# JSSI 30th Anniversary Commemorative Special Issue

# SEISMIC ISOLATION STRUCTURES WORLDWIDE

March 2024

The Japan Society of Seismic Isolation

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# PREFACE

Welcome to the JSSI 30th Anniversary Commemorative Special Issue on Seismic Isolation Structures Worldwide.

In recent decades, seismic isolation technology has emerged as a crucial tool in mitigating the devastating effects of earthquakes on structures and infrastructure worldwide. This special issue serves as a platform for researchers, engineers, and practitioners to share their insights, innovations, and experiences in the field of seismic isolation.

Earthquakes remain one of the most unpredictable and destructive natural disasters, posing significant risks to human life and infrastructure. Traditional methods of earthquake-resistant design often involve making structures stronger and stiffer, but this approach has limitations and can be prohibitively expensive. Seismic isolation offers a complementary strategy by decoupling structures from ground motion, thereby reducing the forces transmitted to the building and its occupants.

The adoption of seismic isolation technology has grown steadily across the globe, with applications ranging from critical facilities such as hospitals and nuclear power plants to cultural heritage sites and residential buildings. As interest in seismic isolation continues to expand, so too does the need for a comprehensive understanding of its principles, design considerations, and performance characteristics.

This special issue aims to contribute to the advancement of seismic isolation technology by providing a platform for the exchange of knowledge and ideas. Through the publication of cutting-edge research, case studies, and technical reviews, we seek to foster collaboration and innovation in this rapidly evolving field.

We would like to express our gratitude to the authors for their contributions. We hope that this special issue serves as a valuable resource for researchers, engineers, and practitioners working in the field of seismic isolation, and we look forward to further advancements in this critical area of earthquake engineering.

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March 2024

# Research and Development Activities on Seismically Isolated Buildings

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## ABSTRACT

This paper reviews the research and development activities on seismically isolated (SI) buildings of Architectural Institute of Japan (AIJ). Analysis of the number of summaries presented at AIJ annual meetings, the number of technical papers on transactions of AIJ, and research trends in relation to the number of SI buildings constructed in Japan was conducted. It also describes "Design Recommendations for Seismically Isolated buildings" published by AIJ and the current activities of the Sub Committee for Seismically Isolated Structures of AIJ.

**KEYWORDS:** Architectural Institute of Japan, Sub Committee for Seismically Isolated Structures, Trends in research

## 1. INTRODUCTION

In Japan, research and development of modern seismically isolated (SI) buildings has been underway since the early 1980s. About 40 years have passed since 1983, when a modern SI building in Japan was constructed using laminated rubber bearings. The subsequent history of seismic isolation in Japan is presented in previous technical papers[1), 2)].

This paper reports the number of summaries in annual meeting of AIJ and peer-reviewed technical papers (Transactions of AIJ).

In addition, keywords mentioned in the technical paper will be picked up and trends in research and development will be introduced. It also introduces "Design Recommendations for Seismically Isolated buildings" published mainly by Sub Committee for Seismically Isolated Structures of the AIJ and the recent activities of the subcommittee.

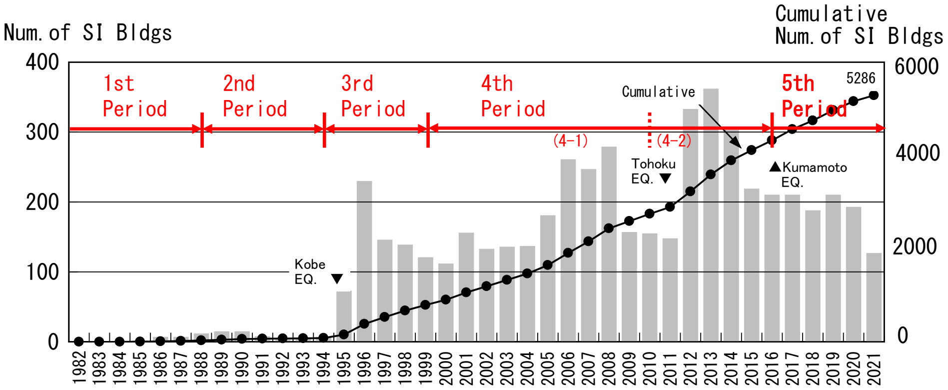
## 2. Dating the transition of seismic isolation in Japan

### 2.1 Number of seismically isolated buildings in Japan

Figure 1 shows the annual number and cumulative number of SI buildings in Japan. The number of SI buildings increased sharply after the 1995 Southern Hyogo Prefecture Earthquake (Kobe EQ.). Also, after the 2011 Off the Pacific Coast of Tohoku Earthquake (Tohoku EQ.), the number of SI buildings exceeded 300 per year, but the number is gradually decreasing after the event. A total of over 5,000 SI buildings have been constructed by 2021.

The first modern SI building in Japan was a two-story house built in 1983 using 800mm diameter laminated rubber bearing and friction dampers. Since then, SI buildings have been applied mainly to technical research institutes of construction companies and to in-house buildings of seismic isolation device manufacturers.

Although there have been cases where it has been applied to general buildings, we have heard that in some cases there were concerns from clients at the time as to whether buildings could be built on rubber bearings.



according to a survey by the Japan Society of Seismic Isolation (JSSI)

Figure 1 Annual number of seismically isolated buildings

The chronology of SI buildings is set up by looking back at the transition of SI buildings in Japan and categorized as "the 1st to 4th period of SI buildings".

The 1st to the 4th period of seismic isolation is the chronological classification used in "Structural Response and Performance for Long Period Seismic Ground Motions" published by the Architectural Institute of Japan (AIJ) in 2007 3).

The dating of the 4th period is also divided into two periods by Prof. Furuhashi : Early (4-1) and Late (4-2) for the 4th period 4).

In addition, the 5th period has been additionally established firstly in publications edited by the Japan Society of Seismic Isolation (JSSI) 5) and Kobayashi et al. also show for the 5th period by a survey of SI building design trends based on performance sheets 6).

The above chronological settings are classified mainly based on the number of SI buildings constructed and their relationship to the earthquake damage, the Building Standard Law and other legislation, and social background.

Characteristics of these period categories are listed following.

1st period (～1988） Beginning stage

Application of seismic isolation by pioneering designers and researchers
Application to own facilities of construction companies, seismic isolation device manufacturers.

2nd period (1989～1994) Before Southern Hyogo Prefecture Earthquake (Kobe EQ.)

Application to housing building, Application to Mid-story SI buildings
Examination of input earthquake exceeding design level

3rd period (1995～1999) After Southern Hyogo Prefecture Earthquake (Kobe EQ.)

Rapid increase in the number of SI buildings.

Diversification of applications and isolation system

4th period (2000～2016) Revision of Building Standards Law

Designated seismic isolation devices as designated building materials
Application to high-rise building

5th period (2017～) Countermeasures against long-period earthquake

Mandatory countermeasures against long-period earthquake caused by Nankai Trough
Consideration of characteristic changes of seismic isolation devices due to cyclic deformation

### 2.2 Number of technical papers of field of seismic isolation at the annual meeting of the AIJ

The annual meeting of AIJ is usually held in autumn. At the annual meeting the latest studies, findings and information are exchanged through technical sessions, panel discussions, lectures, and exhibitions. Figure 2 shows the number of submitted summaries in the field of seismic isolation at the annual meeting of AIJ.

The statistical data shown in Figure 2 indicates that while the number of SI buildings was very small between 1988 and 1991(1st and 2nd period), about 75-100 summaries were submitted.

At that time, research topics included experiments and modeling of laminated rubber bearings and dampers, vibration table tests of SI buildings, simulation analysis methods, and SI buildings design methods. The research and development during this period may have supported the rapid increase in SI building construction since 1995.

Although the number of summaries submissions will increase further in the 3rd period (1995-1999), the growth in the number of SI buildings constructed in a year is slowing.

In the second half of the fourth period (4-2: 2010-2016), both the number of summaries and the number of SI buildings tended to be high, indicating that research and development actual applications during this period were active.

Considering that the number of applications in the most recent 2018-2023 period was around 120-140, there has been a lot of seismic isolation-related research and development in recent years. In the last six years, about 120 summaries have been submitted per year, making it one of the most active areas of research related to the vibration field.

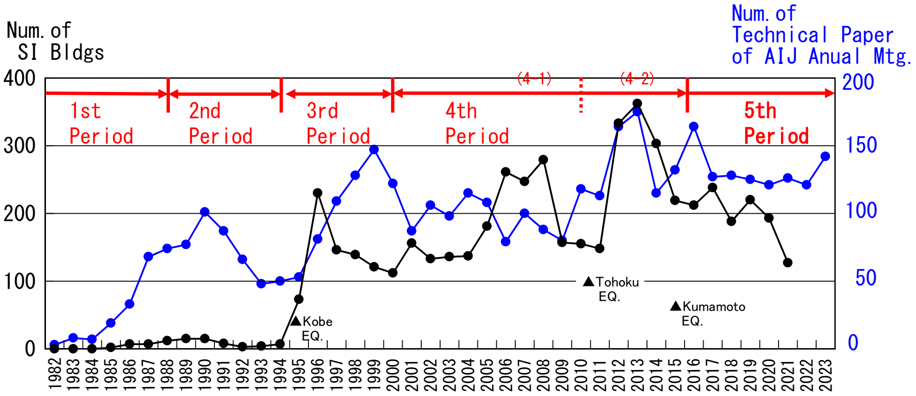


Figure 2 Annual number of seismically isolated buildings
and number of summaries of AIJ annual meetings

Figure 3 shows the classification of summaries of the recent six-year (2018-2023) AIJ annual meetings. About 30~40% of the research topics are related to seismic isolation devices, and about 30~40% are related to response evaluation.

"Devices" include laminated rubber bearings, sliding bearings, dampers, etc.

"System" includes development of frame structures with seismic isolation, 3D seismic isolators, floor isolation systems, displacement control systems, etc.

"Response Evaluation" includes the response evaluation of the seismic response as well as the response evaluation considering changes in the characteristics of the seismic isolation system under long-period earthquake, the response evaluation under strong winds, and the setting of external forces and their response evaluation when subjected to a Tsunami.

"Observation records" show the effectiveness of SI buildings based on observation records after major earthquakes.

In recent years, there have been studies related to large input earthquake such as research on the phenomenon of collisions with retaining walls of SI buildings, and research related to braking to control large deformations of SI layers. In addition, seismic isolation effects have been verified through seismic observation of SI buildings.

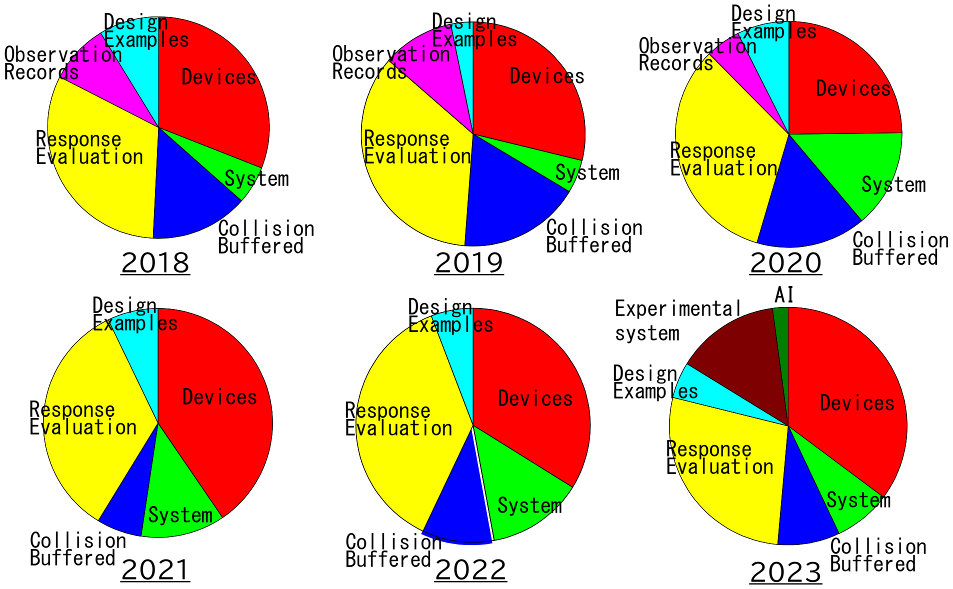


Figure 3 Classification of Technical paper of AIJ annual meetings

Most recently, in 2023, a series of summaries were published on the full-scale seismic isolation test facility "E-Isolation" [7)].

## 2.3 Trends in research published in Transactions of AIJ

Figure 4 shows a classification of technical papers in the field of seismic isolation published in the Transactions of AIJ during the recent six-years (2018-2023). The total number of papers is 43.

Transactions of AIJ is a peer-reviewed collection of technical papers. The trend of technical paper is similar to that seen in the summaries at AIJ annual meetings, with a large proportion of papers on large earthquakes.

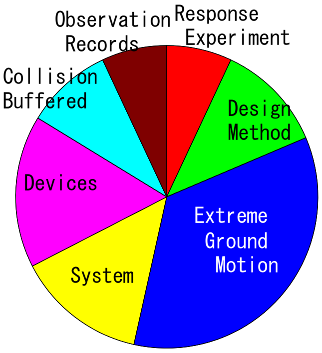


Figure 4 Classification of Transactions of AIJ

Table 1 shows the extracted keywords in the technical papers in each classified category.

Table. 1 Keywords of Transactions of AIJ

| Category | Keywords in paper |
|---|---|
| Response Experiment | Substructure real-time online test<br>Shaking Table tests |
| Design Method | Building Mass Damper, Mid-story isolated system<br>Cost Minimization |
| Extreme Ground Motion | Multi-Cyclic loading tests, Analysis of Heating Interaction Behavior<br>Fail Safe mechanism, Seismic safety evaluation,<br>Response Spectrum Method, Ultimate Property,<br>Long-period ground motion<br>Repeated deformation |
| System | Pile Top Seismic Isolation System, Multi-story isolation<br>High-rise seismic isolation, Vertical seismic isolation<br>Displacement control system<br>High-Static-Low-Dynamic-Stiffness (HSLDS) |
| Devices | Oil Damper, Steel Damper Deformation capacity<br>Elastic sliding bearing, Flare-like structure |
| Collision,Buffered | Collision analysis, Retaining Wall |
| Observation Records | Strong motion record, Torsional response |

Regarding large input earthquake, keywords of technical papers on multi-cyclic loading tests, analysis of heating interaction behavior, fail safe mechanism, ultimate property can be found, and it is assumed that the research is being conducted against the background of a large earthquake in Japan.

Although the Transaction of AIJ is written in Japanese, The AIJ now publishes international academic journals covering architectural design, planning and construction, including structural and environmental engineering. Japan Architectural Review (JAR).
https://onlinelibrary.wiley.com/journal/24758876

## 3. Design Recommendations for Seismically Isolated buildings

Design Recommendations for Seismically Isolated Buildings" was firstly published in 1989 which was just after the 1st period of seismic isolation in Japan.

The preface in the first edition states that the design recommendations have been prepared with an emphasis on the development of objective decision-making materials to assist the designer in making decisions, and that they can be augmented and revised as appropriate to meet future technological developments.

The subsequent editions of this publication follow that editorial policy, and the same editorial policy has been followed in the subsequent editions of this publication.

Each edition of the “Design Recommendations for Seismically Isolated Buildings” includes a section on input earthquake in Japan.

This is based on the understanding that although the estimation of input earthquake is the basis for seismic design (design of SI buildings), at present it is nearly impossible to accurately predict input earthquakes at the construction site of a building, and that structural designers have been designing under uncertain conditions. The reason for this is that structural designers have been designing under uncertain conditions, and it is necessary to understand input earthquake.

For the most current English translation of the latest version is following,
Published May 25, 2016
Design Recommendations for Seismically Isolated Buildings
(JPY1,650)
https://www.aij.or.jp/ppv/productId/428856/

## 4. Recent activities of Sub Committee for Seismically Isolated Structures of AIJ

A Sub Committee for Seismically Isolated Structures has been established within the Architectural Institute of Japan since 1986.

In the most recent four years (2021-2024) of activity, the author has served as the chairperson of the subcommittee, and the objectives of the subcommittee's research activities are as follows,

“Conduct research and studies that contribute to the appropriate dissemination of SI buildings by examining applied technologies and research related to SI buildings in light of time transitions.”

Based on the recent social background, the subcommittee has been studying 1. The performance evaluation index of SI buildings, 2. The contribution of SI buildings to carbon neutrality, 3. Business Continuity Plan (BCP) and Life Cycle Cost (LCC) of SI buildings.

Research activities are also being undertaken in anticipation of future revisions to the latest edition of the Design Recommendations for Seismically Isolated Buildings. We also consider it necessary to disseminate information on the guidelines in English.

## 5. Conclusion

Given the advanced and important nature of seismic isolation technology in Japan, it is considered important to disseminate research activities and developed technologies globally.

Seismic isolation is one of the most important structural technologies in Japan, a country prone to large earthquakes. It is necessary to continue to promote research and development in cooperation with AIJ and other related organizations such as the Japan Society of Seismic Isolation (JSSI), Japan Structural Consultants Association (JSCA).

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# PERFORMANCE BASED DESIGN OF SEISMICALLY ISOLATED BUILDINGS IN JAPAN

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## ABSTRACT

Experts often employ nonlinear time history response analysis to assess the building's and isolation layer's reaction to earthquakes in non-residential seismically isolated building design. The analysis must accurately reflect the seismic isolators' performance variations, as these elements affect the building's vibration behavior. Meanwhile, a 2000 Ministry of Construction notice enabled simpler design approaches using the single mass equivalent linearization method, streamlining the process compared to the previously obligatory nonlinear analysis. This evolution has simplified the engineering workload for designing seismically isolated structures on stable ground. This article reviews Japan's seismically isolated building design progress, highlighting nonlinear time history response analysis and single mass equivalent linearization. It also discusses the future prospects for the surrounding situation of seismic isolation building design.

**KEYWORDS:** JSCA performance design, seismic isolation, Japan, current state

## 1 INTRODUCTION

In Japan, seismic isolation is understood as the most effective means of upgrading buildings' seismic performance and seismic grade. The application of seismic isolation to buildings that will serve as disaster prevention facilities after a large earthquake (government buildings, fire stations, police stations, core hospitals, etc.) is a natural demand for improving seismic performance since those buildings are expected to have the performance of immediate occupancy after a large earthquake. However, in addition to the effect of reducing seismic forces through the use of seismic isolation, from the perspective of the building owner, the value of seismic isolation lies in the sense of secure feeling gained from the response acceleration reduction of the superstructure, or in the prevention of damage to expensive medical equipment in advanced medical facilities, for example. Some developers are trying to differentiate their office buildings from their competitors by the high performance of seismic isolation. In addition, seismic isolation in logistics centers, data centers, and other facilities that form the foundation of social infrastructure has become a common practice.

# 2 PERFORMANCE OF SEISMIC ISOLATION BUILDINGS

## 2.1 Performance Criteria

Figure 1 and Figure 2 illustrate the seismic grade and structural type that the author uses to agree with a building owner. Figure 1 illustrates the recommended structural type based on the required seismic grade and the building height. Figure 2 is a detailed explanation of each structural type's seismic grade and expected performance.

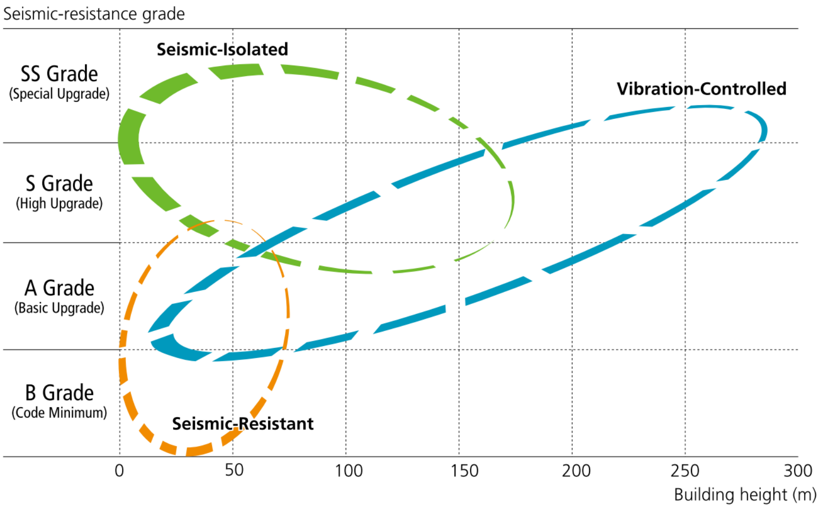
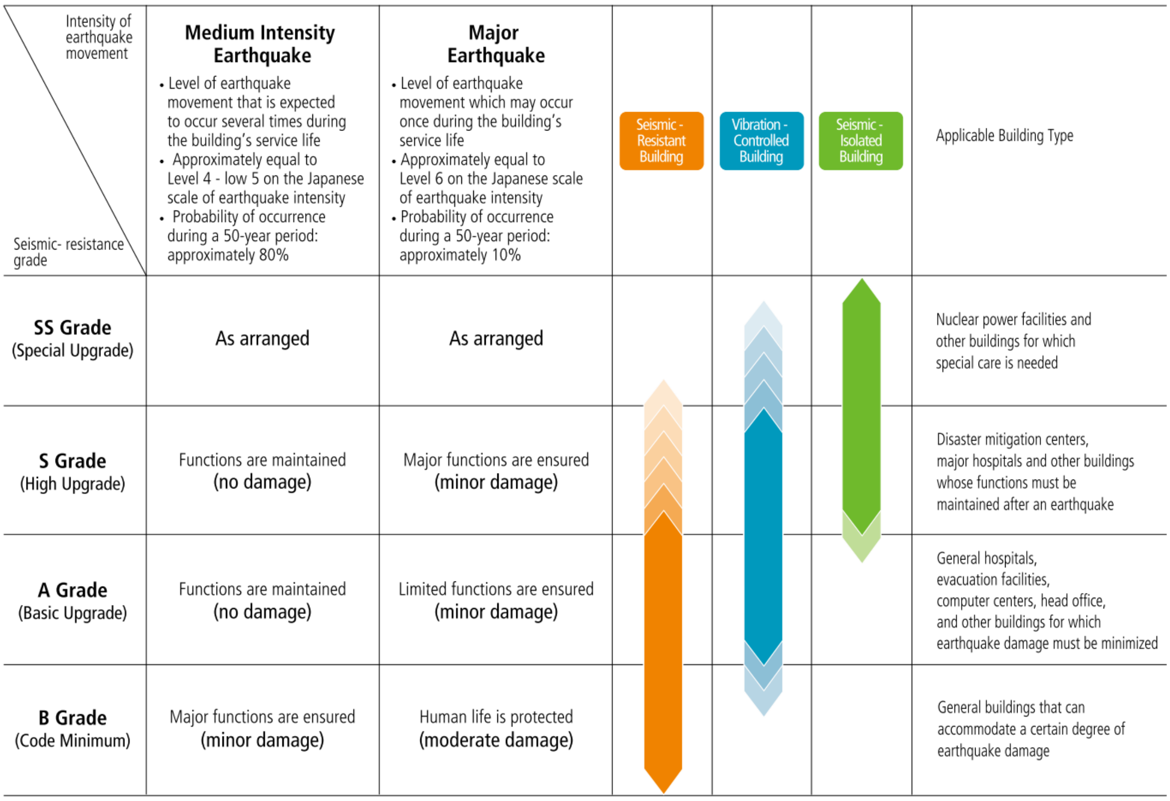


Figure 1 Seismic resistance grade and recommended structural type per the height



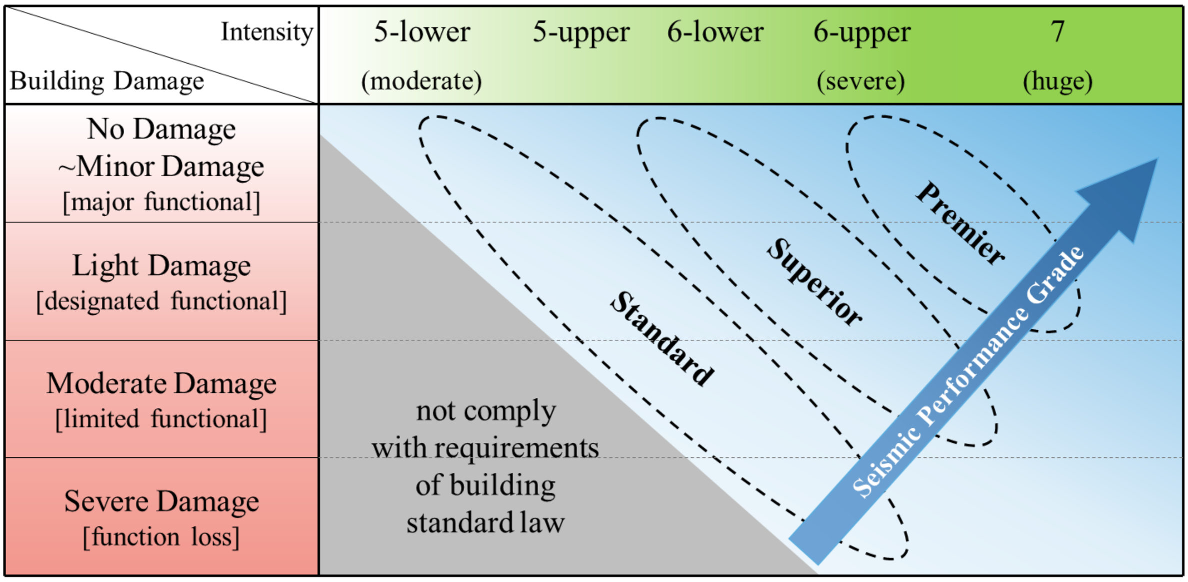
| Intensity of earthquake movement / Seismic- resistance grade | **Medium Intensity Earthquake**<br>• Level of earthquake movement that is expected to occur several times during the building's service life<br>• Approximately equal to Level 4 - low 5 on the Japanese scale of earthquake intensity<br>• Probability of occurrence during a 50-year period: approximately 80% | **Major Earthquake**<br>• Level of earthquake movement which may occur once during the building's service life<br>• Approximately equal to Level 6 on the Japanese scale of earthquake intensity<br>• Probability of occurrence during a 50-year period: approximately 10% | Seismic - Resistant Building | Vibration - Controlled Building | Seismic - Isolated Building | Applicable Building Type |
|---|---|---|---|---|---|---|
| **SS Grade** (Special Upgrade) | As arranged | As arranged | | | | Nuclear power facilities and other buildings for which special care is needed |
| **S Grade** (High Upgrade) | Functions are maintained (no damage) | Major functions are ensured (minor damage) | | | | Disaster mitigation centers, major hospitals and other buildings whose functions must be maintained after an earthquake |
| **A Grade** (Basic Upgrade) | Functions are maintained (no damage) | Limited functions are ensured (minor damage) | | | | General hospitals, evacuation facilities, computer centers, head office, and other buildings for which earthquake damage must be minimized |
| **B Grade** (Code Minimum) | Major functions are ensured (minor damage) | Human life is protected (moderate damage) | | | | General buildings that can accommodate a certain degree of earthquake damage |

Figure 2 Detailed performance of each seismic resistance grade and structural type

JSCA, Japan Structural Consultants Association, also published the commentary brochure on building performance design in 2018, promoting public understanding and awareness of seismic grade. In the brochure, as part of the building performance menu, it is explained that seismic isolation structures can achieve higher performance in reducing seismic damage than vibration control or general aseismatic structures. (Table 1 and Figure 3)

Table 1. Target performance menu per seismic grade [1]

| | EQ<br>Grade | Rare<br>(5-lower) | Very Rare<br>(5-upper) | Extremely Rare<br>(6-upper) | for Verification<br>(approx.7) |
|---|---|---|---|---|---|
| **General Bld.<br>Vibration Control Bld.** | **Premier** | No Damage<br>(Functional) | No Damage<br>(Functional) | Light Damage<br>(Major Functional) | Small Damage<br>(Designated Functional) |
| | **Superior** | No Damage<br>(Functional) | Light Damage<br>(Major Functional) | Small Damage<br>(Designated Functional) | Moderate Damage<br>(Limited Functional) |
| | **Standard** | No Damage<br>(Functional) | | Moderate Damage<br>(Limited Functional) | |
| **Seismic Isolated Bld.** | **Premier** | No Damage<br>(Functional) | No Damage<br>(Functional) | Light Damage<br>(Major Functional) | Light Damage<br>(Major Functional) |
| | **Superior** | No Damage<br>(Functional) | No Damage<br>(Functional) | Light Damage<br>(Major Functional) | Small Damage<br>(Designated Functional) |
| | **Standard** | No Damage<br>(Functional) | | Light Damage<br>(Major Functional) | |



| Classification of Input | Rare<br>(R≈30~50 year) | Very Rare | Extremely Rare<br>(R≈500yrs) | for Verification |
|---|---|---|---|---|
| Assumed Intensity | 5-lower | 5-upper | 6-upper | approx. 7* |
| Scale Factor of Input | x0.2 | x0.5 | x1.0 | x1.5 |

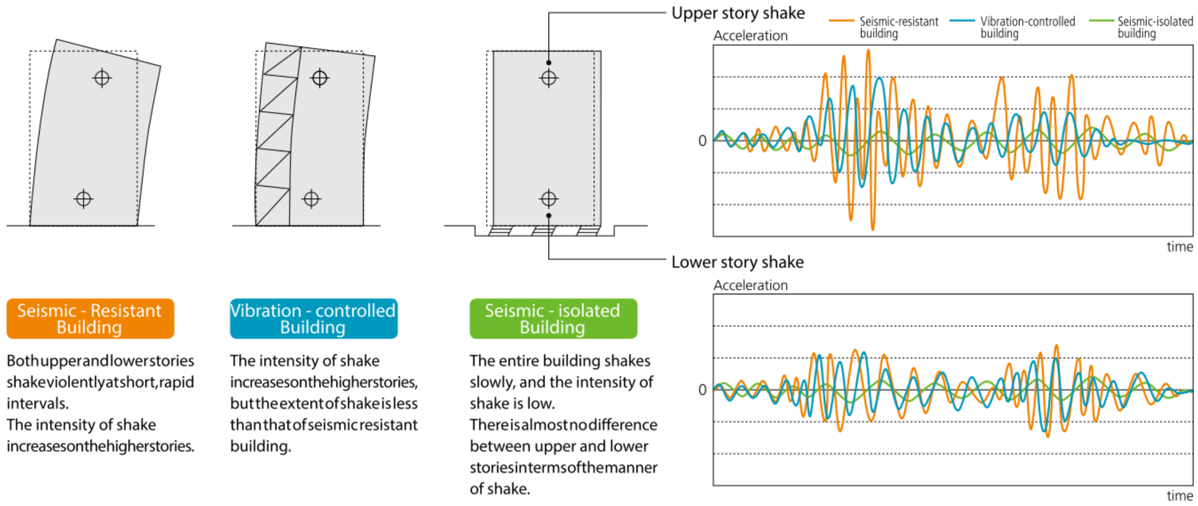
*) "The assumed intensity of 7" means the ground motion of the 1995 Southern Hyogo Prefecture Earthquake

Figure 3 The concept of relationships, the earthquake intensity vs. the building damage [1]

## 2.2 Effectiveness of Seismic Isolation in Large Earthquake

Observation records in past large earthquakes have shown that the response acceleration of the superstructure of seismically isolated buildings was reduced by half to one-third compared to a general aseismatic building.

Figure 4 shows the outline comparison of response differential regarding floor acceleration among general aseismic, vibration-controlled, and seismically isolated buildings.



Both upper and lower stories shake violently at short, rapid intervals. The intensity of shake increases on the higher stories.

The intensity of shake increases on the higher stories, but the extent of shake is less than that of seismic resistant building.

The entire building shakes slowly, and the intensity of shake is low. There is almost no difference between upper and lower stories in terms of the manner of shake.

* The horizontal axis (time) indicates the progress of building shake during an earthquake.
* The vertical axis (acceleration) indicates the severity of the shake.
* The two graphs above show the shake on upper and lower stories, respectively, during the same earthquake.

Figure 4 Comparison of response acceleration in building types

Figure 5 shows the actual acceleration record of several seismic isolation buildings in the past. The red lines denote the observed acceleration at the top of the building, and the black (or gray) line indicates the acceleration on the ground or the base of the building.

These records show that the seismic isolation system reduces the floor response acceleration by around half to one-third compared to the earthquake input. Because of the large displacement of the seismic isolation layer in seismically isolated buildings, it is important for building maintenance to install a recording board and accelerometers to record the response during earthquakes.

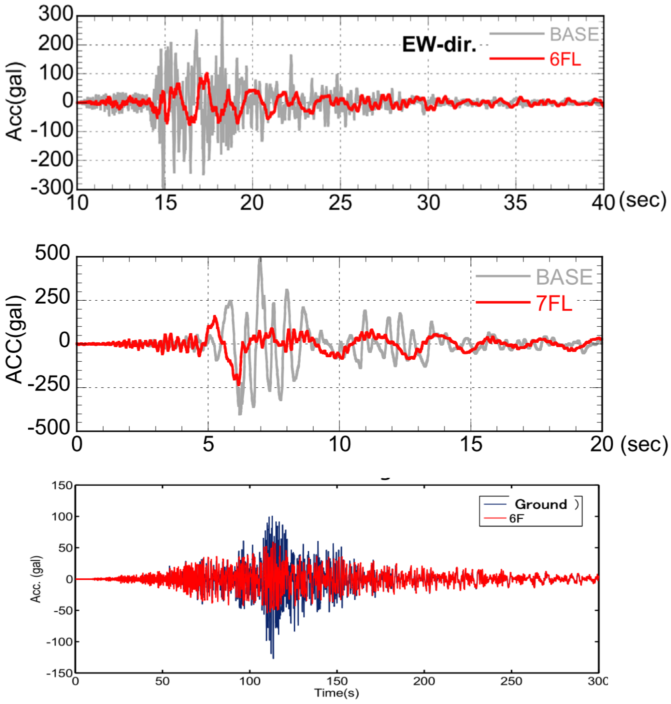


Figure 5 Sample records of acceleration[2]

# 3 DESIGN PROCEDURE OF SEISMIC ISOLATION BUILDINGS IN JAPAN

## 3.1 Time History Analysis Method

In Japan, the construction permission process requires that for buildings exceeding 60 m in height or seismically isolated buildings on soft ground, the engineer in record should execute time history analyses to prove that the response values satisfy the design criteria.

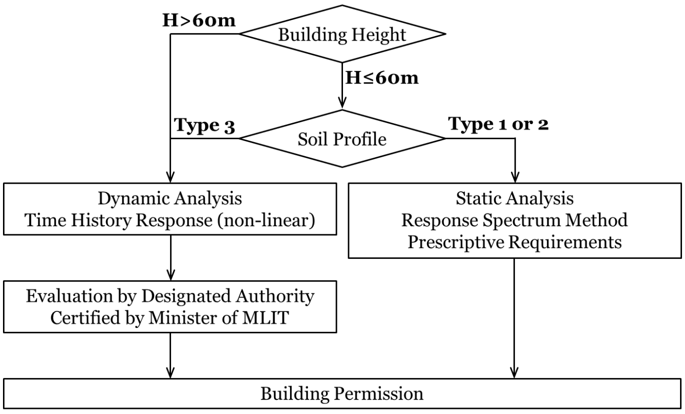


Figure 6 Building permission process

Figure 6 shows the required analysis type in the construction permission process per design conditions and the design flow based on time history response analysis. Figure 7 shows the flow of confirming the response results of the time history analysis and determining the structural members. In practice, a preliminary time history response analysis is performed initially to set a slightly conservative design seismic force, and a confirmatory time history analysis is executed during the detailed design stage.

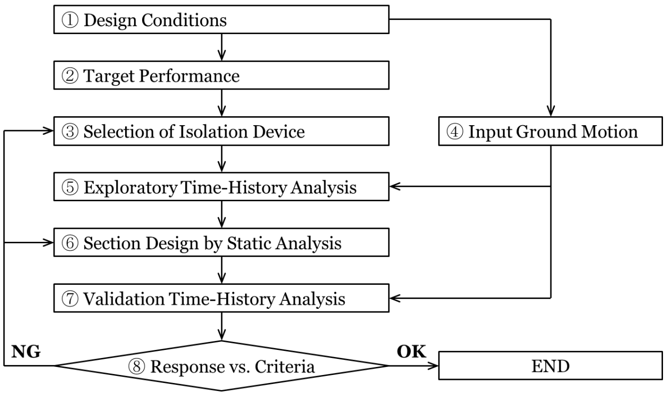


Figure 7 Flow of analysis and design

Figure 8 shows typical design criteria, and the time history analysis output will be directly compared to the criteria. Input ground motions adopted in the time history analysis shall equal to or more than seven (including long-period earthquake motions mentioned in section 4.1) as extremely rare earthquakes. The maximum response values shall be compared with the design criteria.

| | |
|---|---|
| 1. Story Shear Force: $Q_{max}$ | $Q_{max} < Q_d$ (extremely rare EQ)<br>$Q_d$: Design story shear force |
| 2. Story Drift Angle: $R_{max}$ | $R_{max} \leq 1/300 \sim 1/400$ (rare EQ)<br>$R_{max} \leq 1/150 \sim 1/200$ (extremely rare EQ) |
| 3. Drift at Isolation Layer: $\delta_{max}$ | $\delta_{max} \leq \delta_a$<br>$\delta_a = \delta_u/\alpha$<br>$\delta_u$: Smaller value of<br>• Deformation limit of device<br>• Clearance at isolation story<br>$\alpha$ : Safety ratio of 1.5~2.0 |
| 4. Axial Stress of Isolators: $\sigma_{max}$ | Tension: : No tension stress<br>Compression: $\sigma_{max} \leq \sigma_a$<br>$\sigma_a$ : Allowable stress of each device |

Figure 8 Typical performance criteria utilizing time history analysis results

### 3.2 Code Prescript Procedure (Single Mass Equivalent Linearization Method)

When the building height is 60 m or less, the predominant period of ground is 0.6 sec or less, and there is no risk of liquefaction, the notice provides a method to calculate the response value of the seismic isolation layer using the equivalent linearization method.

In general, the stiffness of the superstructure is sufficiently stiff compared to the seismic isolation layer, so it is often possible to treat the superstructure as a single mass in the evaluation of the dynamic properties of the entire building. Basically, the superstructure plan is to be simple shape and does not exhibit complex dynamic properties.

As shown in Figure 9, the relationship between shear force and deformation of the seismic isolation layer can be denoted by a bilinear curve, and the isolation layer displacement can be predicted by considering various types of damping. The notice instructs us to consider variations in product properties and other factors and take an appropriate safety factor in the calculated values.

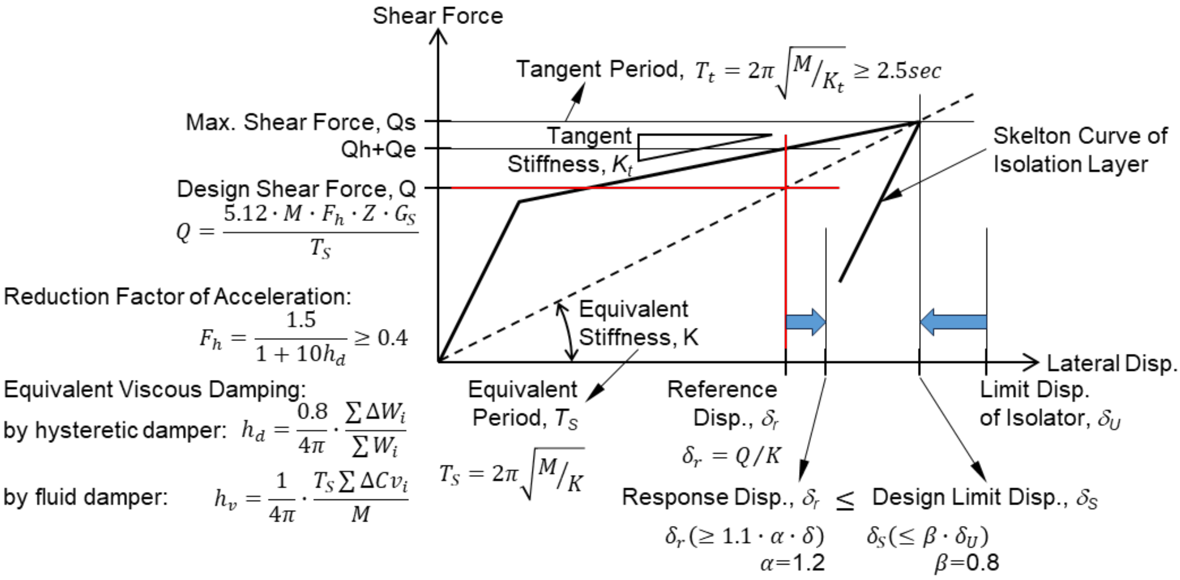


Figure 9 Calculation method for shear force and deformation of isolation layer [2]

### 3.3 Feature of Isolation Layer Design

One of the critical issues in the design of seismically isolated buildings is how to set the ultimate state of the entire structure. In the design of seismically isolated buildings, plasticity of the superstructure is not assumed in principle. On the other hand, it is the engineer's responsibility to set the state of the entire building in the event of a larger-than-expected earthquake. Generally, the final state is often set to prevent failure of seismic isolation bearing in a larger-than-expected earthquake. Then, the seismic isolation layer displacement exceeds the clearance, i.e., the building collides with a retaining wall.

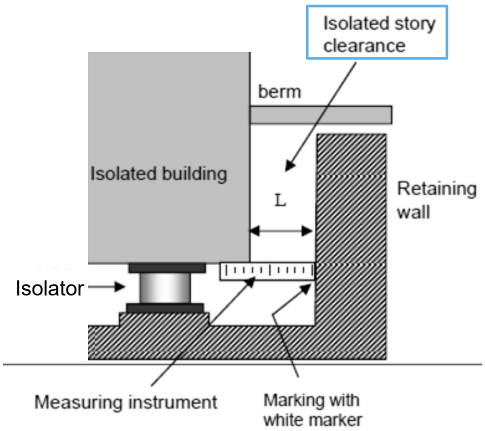


Figure 10 Perimeter of isolation layer

## 4 FUTURE PROSPECTS

(Please note that the following represents my thoughts as an structural engineer and is not the consensus of my company or organization.)

### 4.1 Problems induced by geological structure of metropolitan areas in Japan

The oil tank fire in the 2003 Tokachi-oki Earthquake triggered research on the effects of long-period seismic motion on high-rise buildings and seismically isolated buildings with long natural periods. In particular, the significant shaking observed in high-rise buildings in the Tokyo metropolitan area and Osaka Bay area during the 2011 off the Pacific coast of Tohoku Earthquake has increased momentum to incorporate long-period and long-lasting seismic motion (so-called "long-period seismic motion") into structural design, and in 2017, the long-period seismic motion became a mandatory seismic input for design within specified urban areas. Because Kanto Plain, Nobi Plain, and Osaka Plain, the major metropolitan areas in Japan, are all sedimentary basins, and their ground structures tend to amplify long-period seismic motions due to their long excitation periods, the building law specifically mandated to consider long-period seismic motions in those metropolitan areas.

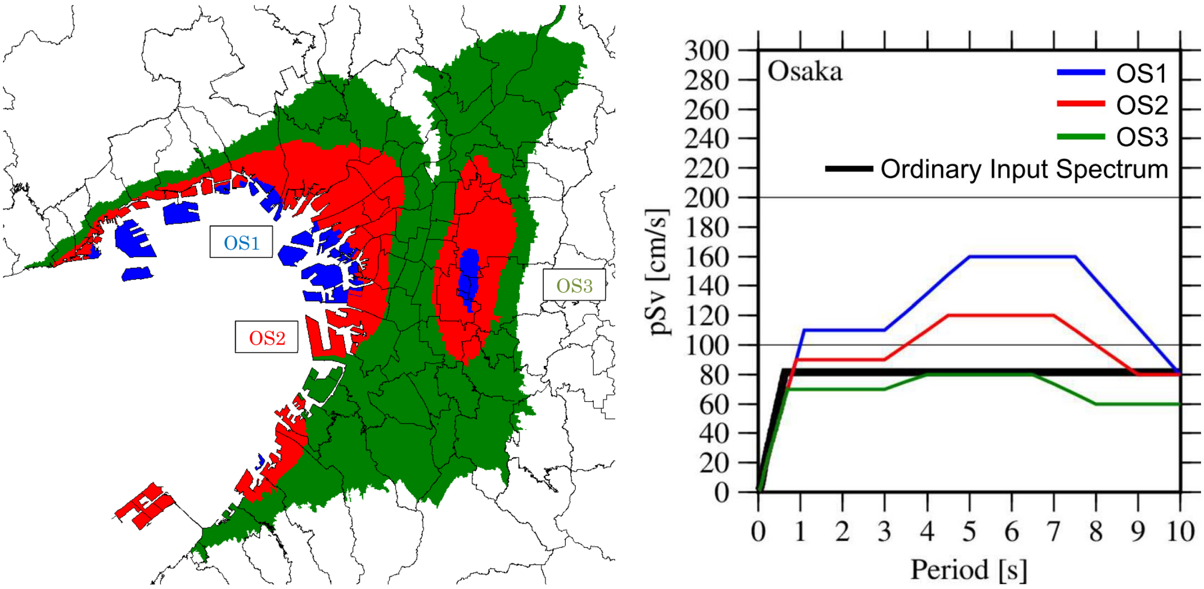


Figure 11 Pseudo velocity response spectrum of long-period earthquake input in Osaka[3]

As shown in Figure 11, the specified spectrum is much larger than the ordinary input spectrum in the region of long period. Long-period seismic motion with a predominant long-period component and long duration has a huge maximum velocity amplitude of 120 to 150 cm/sec compared to the design input seismic motion used in ordinary seismic isolation design, so it is important to study the response characteristics of seismic isolated buildings to a ground motion that exceeds the level specified by building law and the margin to the limit. Depending on the level of long-period seismic motion, the margin of energy absorption capacity in the seismic isolation layer may be reduced or even exceed the horizontal clearance.

### 4.2 Reliability of seismic isolation products

The system of designated building materials for seismic isolation components, which was institutionalized with the establishment of the public notice, contributed to the spread of products under Japan's type approval system. However, it is still fresh in our memories that data falsification scandals involved seismic isolation rubber products and oil damper products in 2015 and 2018, respectively. These scandals undermined the confidence of "designated building materials" system under the government notice. The society suffered doubts about the quality assurance system based on manufacturers' in-house testing under the ministerial certification system, and structural engineers at the time felt anger that they had nowhere to go.

As a design engineer, it is desirable to be able to employ a wide variety of seismic isolation products to increase the means to meet the owner's requirements on the building performance. The full-scale seismic isolator experimental device, E-isolation in Miki City, Hyogo Prefecture, was constructed in 2023. This facility is reassuring to practitioners who can obtain proof of the reliability of the products those they adopt. Practitioners need to fulfill their accountability so that there is a social consensus on the testing cost burden for the benefits of seismic isolation.

## 5 CONCLUSION

Japan is located at the complex intersection of four plates, and the frequency of earthquakes is much higher than in other countries and regions. 20% of the earthquakes of magnitude 6.0 or greater between 1994 and 2003 occurred around Japan. Although seismic isolation structures have rapidly become popular since the 1995 Southern Hyogo Prefecture Earthquake, according to the JSSI report, the number of newly constructed seismically isolated buildings is about 200 per year, which is less than 1% of the total number of new buildings constructed in Japan each year.

There are several reasons why the number of seismically isolated buildings has not increased much even though Japan is a highly seismic country: (1) the cost of seismic isolation layers is close to a simple increase of 1-story cost for low-rise buildings, (2) nonlinear response analysis is required which requires more design time and effort, (3) securing seismic isolation clearance in urban areas reduces land use efficiency, especially in urban areas. For Owners, it is logical to prioritize investment in comfortable facilities and beautiful design over spending money on measures against earthquakes that may occur at any time. It is desirable that structural engineers propose the adoption of seismic isolation to building owners more actively.

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# ACTIVITIES OF JSSI FOR THE PROMOTION AND DISSEMINATION OF SEISMICALLY ISOLATED BUILDINGS

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## ABSTRACT

This paper describes the activities of the Japan Society of Seismic Isolation and the status of the spread of seismically isolated structures. In Japan, seismically isolated buildings have rapidly become popular since the 1995 Southern Hyogo Prefecture Earthquake. In recent years, it has been widely used in skyscrapers. It is important to design seismically isolated structures not only against earthquakes, but also against wind. It is also necessary to take care to prevent the seismic isolation expansion joint from being damaged during an earthquake. Seismically isolated structures need to be properly constructed and maintained to ensure their full potential in the event of an earthquake. The Japan Society of Seismic Isolation publishes various standards and guidelines regarding design, construction, maintenance, and management, contributing to the healthy spread of seismically isolated structures.

**KEYWORDS:** JSSI , Status of SI

## 1. INTRODUCTION

In Japan, the first building with a seismically isolated structure was constructed in 1983, and approximately 40 years have passed this year.

During the 1995 Southern Hyogo Prefecture Earthquake, two seismically isolated buildings in Kobe City were undamaged, and the effectiveness of seismic isolation was confirmed based on records from accelerometers installed in these buildings. This led to the rapid spread of seismically isolated (SI) buildings in Japan.

Since the Southern Hyogo Prefecture Earthquake, Japan has frequently been struck by large earthquakes, such as off the Pacific coast of Tohoku Earthquake and the Kumamoto Earthquake. Through experiencing many earthquake damages, we have accumulated knowledge regarding the design, construction, and maintenance of seismically isolated structures.

Sharing this kind of knowledge is essential for the development of SI structures.

The Japan Society of Seismic Isolation (JSSI) collects a variety of information regarding these structures and vibration controlled (VC) structures, and publishes various standards and guidelines.

This paper introduces JSSI and the current status of SI structures in Japan based on various data collected by JSSI, also introduces various guidelines and standards published by JSSI.

## 2. ABOUT JSSI

The JSSI was established in 1993 with the aim of popularizing SI structures in Japan.

Since its establishment, it has conducted numerous surveys and studies on SI structures and formulated many standards regarding design, construction, materials, and maintenance.

In 2000, “The Qualification System for SI Construction Management Engineers” was established to train engineers who can properly construct and maintain. Additionally, in 2003, inspection for SI buildings, “The SI Inspection Engineer Qualification System" was established.

In 2004, JSSI was designated as a performance evaluation organization by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and conducts performance evaluations of seismic isolation materials and buildings.

Currently, JSSI consists of 87 regular members (corporations), 233 regular academic members (individuals), and 115 supporting members (corporations).

Figure 1 shows the organization of JSSI. The technical committee conducts various research studies on SI structures and VC structures, and publishes standards and guidelines.

The committee for foreign affairs disseminates and collects information outside of Japan through workshops for SI and VC, and other activities.

The dissemination committee conducts dissemination activities such as holding seminars, publishing journals and books.

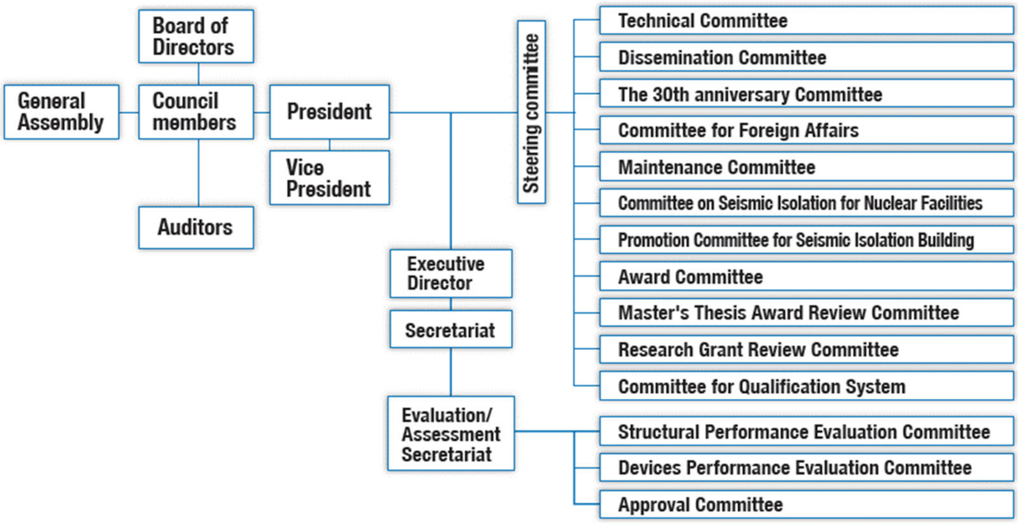

Figure 1 Organization Chart of JSSI

## 3. CURRENT STATUS OF SI BUILDINGS IN JAPAN

Every year, JSSI receives information from member companies. JSSI compiles, analyzes and publishes the data.
Based on this data, the current status of SI buildings in Japan is reported.

### 3.1 Number of SI Buildings

Figure 2 shows the number of SI buildings other than single-family houses constructed in Japan. Analytical research on SI structures has been conducted in Japan since the 1960s, and in 1983 the first SI structure was constructed, a two-story reinforced concrete building using laminated rubber bearings with a diameter of 30 cm and friction dampers.
However, the use of SI structures has mainly been limited to technical research laboratories of construction companies and buildings owned by SI device manufacturers.
At that time, public awareness of SI was low, and its use was limited.
After the 1995 Southern Hyogo Prefecture Earthquake, the number of buildings increased rapidly, with around 150 buildings being built each year.
In the wake of the 2011 Tohoku Pacific Coast Earthquake, the number of cases increased again to over 300 per year, but has since gradually decreased.
A total of more than 5,000 SI buildings will be constructed by 2021.
Approximately 500,000 buildings are constructed annually in Japan, of which approximately 400,000 are single-family homes.
Of these, approximately 15,000 buildings require earthquake-resistant structural calculations, and only 1% have SI structures[4)].
JSSI hopes that SI structures will become more widespread in the future.

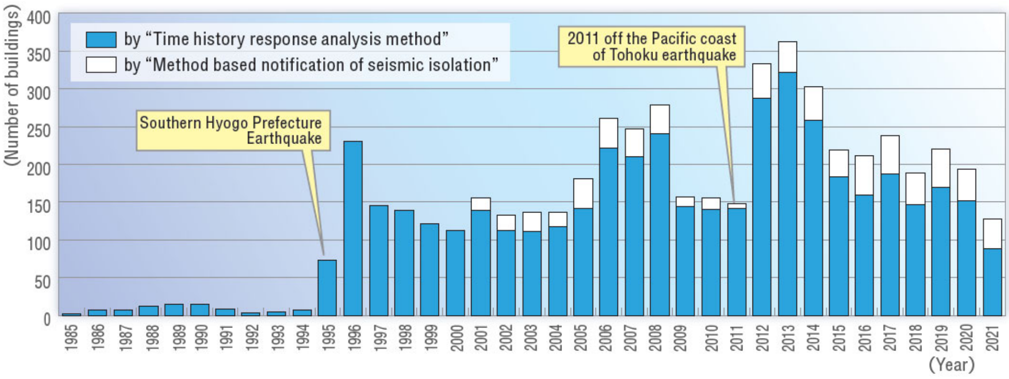

Figure 2 Number of SI buildings in Japan. by year

### 3.2 Usage

Figure 3 shows the usage ratio of SI buildings for the five years from 2017 to 2021.
The most common uses are condominiums and office buildings.
SI condominiums have the added value of ensuring building functionality and preserving property in the event of major earthquakes, and are popular despite slightly expensive.

Furthermore, since the 2011 Tohoku Earthquake, there have been concerns about a future earthquake directly hitting the Tokyo metropolitan area or a mega-Nankai Trough earthquake of similar magnitude.

In addition, SI structures are increasingly being adopted in government buildings, disaster base hospitals, and other facilities as disaster prevention facilities in the event of earthquakes.

On the other hand, the adoption of SI structures in schools is limited.

In the case of public facilities such as schools, budget constraints and lack of funds are obstacles to the adoption of SI structures.

Hospitals need to treat patients during disasters, and are required to continue functioning even after earthquakes.

According to a survey conducted by the Ministry of Health, Labor and Welfare in 2023, only about 8% of the 8,160 hospitals in Japan are seismically isolated.

JSSI would like to work to increase the number of SI hospitals in Japan in the future.

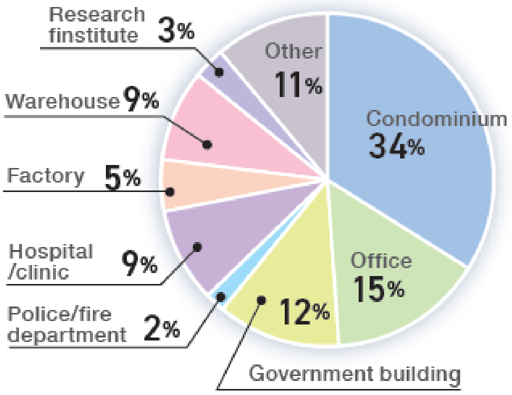

Figure 3 Usage ratio of SI buildings (from 2017 to 2021)

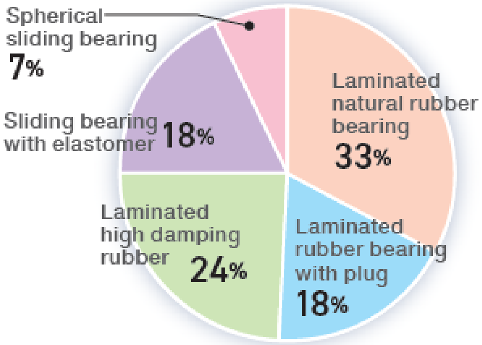

Figure 4 Usage ratio for isolation divices (from 2017 to 2021)

### 3.3 SI Devices

As shown in Figure 4, most seismic isolation members in Japan are laminated rubber bearings such as NRB (natural rubber bearing), LRB (lead rubber bearing), and HDR (high damping rubber bearing).

Sliding bearings with elastomer are also often used to extend the natural period of SI buildings.

In recent years, spherical sliding bearings have also come into widespread use.

Laminated rubber bearings have very low tensile resistance, and sliding bearings have no tensile resistance.

For these reasons, when tensile force during an earthquake acts on the bearings of high-rise buildings, linear rotating ball bearings, which have tensile resistance and a very small coefficient of friction, are sometimes used.

Furthermore, in the case of laminated natural rubber bearings that do not have damping performance, steel dampers, oil dampers, or viscous dampers are used as dampers.

In a SI structure, the isolator supports the weight of the superstructure while deforming significantly in the horizontal direction.

Since the performance of a SI structure depends on the quality of each isolator, it is important to verify and confirm the dynamic characteristics of the isolators and ensure their quality.

In order to verify and understand the performance of large-scale SI devices, it is necessary to conduct full-scale dynamic tests that reproduce the conditions in which a full-scale SI device is exposed to earthquakes.

Until now, there was no large-scale dynamic test equipment in Japan that could verify the dynamic characteristics of actual large-scale SI devices.

In 2023, a “full-scale SI experimental device E-Isolation” was completed in Miki City, Hyogo Prefecture, which allows experiments on full-scale SI and VC devices under velocity and displacement conditions during major earthquakes.

It is expected that the active use of this facility will further increase the reliability of Japan's SI and VC technology.

### 3.4 SI Retrofit

Figure 5 shows the annual number of existing buildings that have been retrofitted with SI structures.

Renovations to SI structures not only have high earthquake resistance, but can also be done while the building is still in use, so the usability of the building will not be compromised either during or after the renovation.

Transferring the weight of buildings to SI bearings is extremely difficult and expensive, but to date approximately 200 buildings have been retrofitted to be earthquake resistant, more than half of which are government facilities.

SI retrofits are also often used in historic buildings with high architectural evaluation and low earthquake resistance.

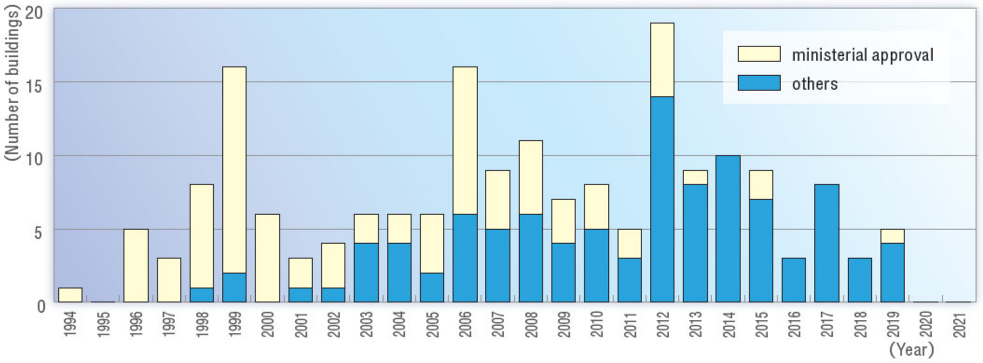

Figure 5 Number of buildings retrofitted for seismic isolation. by year

### 3.5 Application to High-rise Buildings

According to Japan's Building Standards Law, buildings with a height of 60m or more are classified as super high-rise buildings.

For super high-rise buildings, it is mandatory to confirm seismic performance through time history response analysis method, and the seismic design must be reviewed by a performance evaluation facility designated by the MLIT.

Additionally, there are no height restrictions for SI buildings.

In other countries, it is common for SI buildings to have height restrictions, so these regulations are unique to Japan.

Figure 6 shows the annual number of SI super high-rise buildings in Japan.

Initially, SI technology was not applied to high-rise buildings because their natural period was already long.

However, the benefits of using SI structures in improving safety have been recognized, and since 2000, the use of SI structures in super high-rise buildings has increased.

To date, more than 700 SI super high-rise buildings have been constructed, of which more than 500 are condominiums.

Japan's tallest SI building seismically isolated at mid-story is 228m high.

The tallest SI building, with a seismic isolation layer in the foundation, is 192 meters high.

Super high-rise buildings have long natural periods, so in order to exhibit sufficient SI effects, it is necessary to lengthen the SI period.

In addition, structural measures must be taken to prevent the generation of tensile forces in the bearing during earthquakes.

In addition, as the building is high-rise, it is greatly affected by wind, so countermeasures must be considered to the case of strong winds.

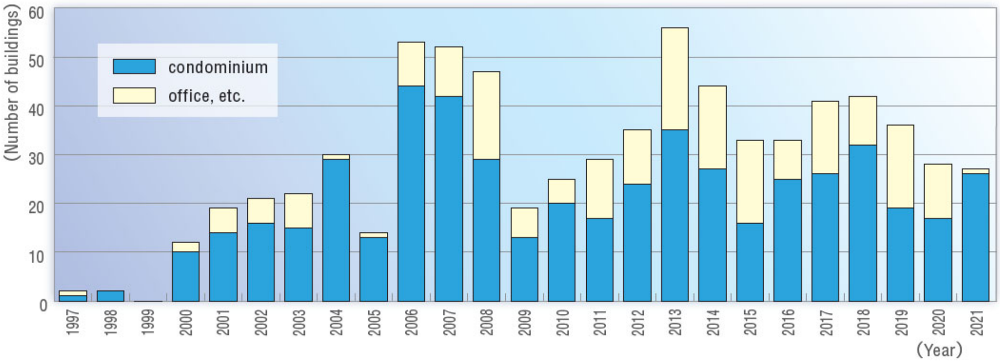

Figure 6 Number of SI super high rise buildings. by year

## 4. STANDARDS ISSUED BY JSSI

### 4.1 Wind Resistant Design Guidelines

In Japan, tropical cyclones called typhoons come several times a year from summer to autumn.

Typhoons hit buildings over a long period of time with strong winds with a maximum instantaneous wind speed of 30 to 60 m/s.

The higher SI building becomes, the greater the impact will be.

When designing high-rise buildings, it is necessary to confirm that the horizontal displacement of SI buildings does not become excessive during strong winds.

Wind load has an average component and a fluctuating component, but laminated rubber bearing with lead plug and laminated high-damped rubber bearing, creep deformation occurs due to the average wind component, so countermeasure must be taken.

Sometimes a mechanism is used that includes a rod (shear pin) that cannot be broken by wind, but can be broken by a slightly larger earthquake.

Additionally, some systems have a mechanism to stop the oil damper from moving during strong winds based on information from anemometers.

JSSI publishes wind resistant design guidelines.

As shown in Figure 7, JSSI's seismic design guidelines classify the response state of SI layer due to wind loads into three levels (ranks A, B, and C), and consider the creep and fatigue characteristics of SI devices.

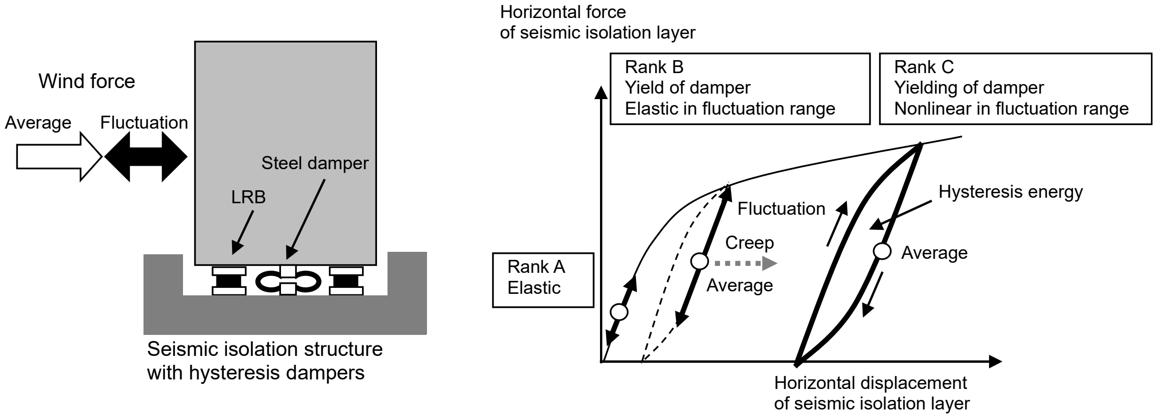

Figure 7 Design of seismically isolated buildings[2)4)]

### 4.2 SI Expansion Joint Guidelines

During the 2011 Tohoku Earthquake, SI buildings were fully effective, and there was no damage to the building's main structure or finishing materials such as ceiling materials.

However, many SI expansion joints (Exp) were damaged. According to a survey conducted by JSSI after the earthquake, some of the SI expansion joints were damaged in 30% of the buildings surveyed.

Even if the building itself can continue to function, damage around the SI expansion joints make it difficult for people and vehicles to enter and exit, affecting the continued functioning of the building.

Damage to SI expansion joints can occur even in small to medium earthquakes and is costly to repair.

This is a serious problem for the widespread use of SI structures, as it gives the impression that buildings with SI structures have inferior performance in small to medium earthquakes than normal buildings.

JSSI has created guidelines that summarize points to keep in mind when designing, manufacturing, constructing, and maintaining SI expansion joints.

Table 1 shows the design target performance of SI expansion joints, and there are three grades: Type A, Type B, and Type C.

Type A, which has the highest performance, maintains its functionality even after a major earthquake and can continue to be used without repair, whereas Type B and Type C are subject to "damage level 1" when shaken by a major earthquake, or become "damage level 2".

Damage level 1 means that there are no major deformations, inclinations, or gaps, and it is possible to continue using the expansion joints after an earthquake by adjusting and repairing them.

Damage level 2 is a more serious condition, where there is no falling off, but there are steps in the floor and protrusions in the wall, and large-scale repairs and parts replacement are required before the SI expansion joint can be used again.

Building designers are required to set target performance in agreement with the building owner and clearly state the performance indicators in the design documents.

Table 1. Performance Classification of Seismic Isolation Expansion Joints[1)4)]

| performance index | Under moderate earthquake | Under large earthquake | Confirmation method | Location of use |
|---|---|---|---|---|
| A | Functional | Functional | Shaking table test | Areas with heavy pedestrian traffic |
| B | Functional | Damage Level 1 | Shaking table test or static test | Areas with moderate pedestrian traffic |
| C | Damage Level 1 | Damage Level 2 | Confirm by drawing | Areas with little or No pedestrian traffic |

**4.3 Maintenance and Management Standards for SI Buildings**

In order to properly perform SI buildings, it is necessary to properly maintain and manage them. JSSI has published “Maintenance and Management Standards for Seismically Isolated Buildings”, so that what maintenance and management should be carried out at the time of design should be described in the design documents.

Many buildings have maintenance plans based on these standards.

As shown in Table 2, the maintenance management standards specify the timing, types, and items of inspections.

Additionally, JSSI has established a “Seismic Isolation Inspection Engineer Qualification System” to certify inspection engineers.

Approximately 2,700 engineers have this qualification, 2023.

Inspections of SI buildings are to be carried out by engineers who have this qualification.

Table 2 Classification of inspection [3)]

| Classification of inspections | When | How | Items | Control values | Contents |
|---|---|---|---|---|---|
| **Inspection at completion** | Upon building completion | Visual inspections and measurements | All items | To be decided by the designer: inconsistencies are corrected | SI devices, piping for equipment, electrical equipment, SI layer, outer periphery of building, seismic gap, fireproofing, expansion joints, marks for maintenance, others (structures in which SI devices are set, signboard indicating SI building, scratch plate to record displacement, separately-placed isolator for tests) |
| **Inspection after renovation** | After work related to SI functions | Visual inspections and measurements | All items related to SI functions | To be decided by the designer | Area of renovation construction and affected peripheral area |
| **Inspection** | Annually | Visual inspections | All items | To be decided by the designer | Those listed in inspection upon completion |
| **Periodic inspection** | 5 and 10 years after completion, then every 10 years | Visual inspections and measurements | All items (visual inspection), Some items (measurement) | To be decided by the designer | The number of items is fewer than that in inspection at completion. (This is based on the premise that inspection at completion was carried out by IE) |
| **Emergency inspection** | After a major earthquake, strong winds, flood, fire | Visual inspections | All items | To be decided by the designer | The purposes of this insppection is to identify damaged parts and to quickly notify the building manager and the designer of said damage:<br>contents are the same as the annual check. |
| **Detailed inspection** | When unusual conditions to be dealt with are recognized during other inspection | Visual inspections and measurements | Damaged items decided by the designer | To be decided by the designer | Damaged portions are selected for inspection |

## 4.4 Construction Standards

There are many elements in the construction of SI buildings that are different from those of conventional buildings. In the construction of SI layers, the installation accuracy (horizontal, vertical, slope) of the base plate on which the SI devices are installed and the filling rate of concrete under the base plate are important.

In addition, in preparation for earthquakes that may occur during construction, it is important to install restraints to prevent the SI devices from horizontally displacing, and to install external scaffolding that can follow the displacement of the SI layer during an earthquake.

JSSI has published “Seismic Isolation Structure Construction Standard”, which indicates points to keep in mind when constructing SI buildings.

Additionally, JSSI has established a “Seismic Isolation Section Construction Management Engineer Qualification System” to certify SI building construction engineers.

Approximately 6,500 engineers have this qualification, 2023.

## 5. CONCLUSION

Although SI structures are becoming more popular in Japan, the proportion of SI buildings among all buildings is extremely small.

The SI structure is undamaged even in large earthquakes, furniture inside the building will not fall, and equipment will not be damaged, making it an excellent building that can continue to be used even after an earthquake.

The Japan Society of Seismic Isolation is conducting various promotional activities with the goal of making all buildings seismically isolated.

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# SEISMIC ISOLATION, ENERGY DISSIPATION, AND CONTROL FOR STRUCTURAL RESILIENCE ENHANCEMENT IN CHINA: STATE-OF-THE-ART REVIEW AND APPLICATIONS

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## ABSTRACT

Currently, there are nearly 16,000 seismically isolated structures and about 14,000 structures with passive energy dissipation or hybrid control in China. This study presents a state-of-the-art review on design rules and innovative devices of seismic isolation, energy dissipation, and hybrid control for civil engineering structures. The basic concepts of seismic isolation and energy dissipation are briefly introduced, and the technical rules, testing and design, important design codes, and applications to new strategic and public structures are shown, pointing out the excellent seismic behavior of the seismic isolation and energy dissipation systems during real seismic events. The most interesting applications on existing building structures, rural buildings, bridges, underground structures, tank structures, and transmission tower structures point out the specific challenges for each case. Finally, recordings obtained during the seismic events in China are presented and discussed. The findings are useful for analyzing the seismic behavior of isolation and energy dissipation systems and their effectiveness during earthquakes. This study also discusses the development trends for future energy dissipation and hybrid control techniques in China.

**KEYWORDS:** seismic isolation, energy dissipation, hybrid control, structural application, seismic retrofitting, seismic monitoring

## 1. INTRODUCTION

The civil infrastructure in China, located around Euro-Asia and Pacific seismic zones, has suffered serious damage and failure due to being frequently subjected to earthquakes in past decades (Zhou 2023; Ou 2023). To overcome these challenges, the vibration control system for civil infrastructure in China has been widely developed (Zhou and Tan 2017; Zhang et al. 2017), specifically passive control systems, such as seismic isolation, damping system, and shock absorption (tuned mass damper). Seismic isolation means the isolator is designed between the bottom of the superstructure and the top of the substructure to mitigate the seismic energy transferred to the superstructure and reduce the seismic responses of the superstructure. Seismic isolation is generally suitable for structures with middle and low height and structures with large stiffness. The seismic responses of the structures can be effectively mitigated when the isolation system is appropriately designed (Tang et al. 2015; Zhang et al. 2016). Seismic isolation is an effective measure to enhance the seismic resilience and mitigate structural damage (China Journal of Highway and Transport, 2021; Zhu et al. 2020, 2022).

Compared with the passive control system, the active control system, which needs an external power supply, can effectively mitigate structural dynamic responses by actively adding the external instantaneous force or instantaneously changing structural dynamic characteristics when subjected to external excitations. In view of the fact that the added control force is adaptive based on the structural dynamic responses, the active control system is much better than the passive control system in terms of continuously and automatically adjusting structural dynamic properties, especially for wind-induced structural vibration control. Semi-active control systems, which require only low external energy, achieve the mitigation targets by adjusting the working state of the control system based on the input or responses and providing the control force to change structural stiffness and damping. The semi-active control system combines the advantages of the passive and active control systems. It mainly includes the active variable stiffness system, active variable damping system, magnetorheological damper, piezoelectric friction damper, and eddy-current damper.

Hybrid control systems, which generally comprise two or more control systems working in parallel in a structure, can utilize the advantages of the passive control system to dissipate the vibration energy and that of the active control system to achieve better response mitigation effectiveness (Xu et al. 2014), e.g., the hybrid mass-damping system with AMD, hybrid isolation system with active system, and hybrid mass-damping with liquid mass control system. The hybrid isolation system shows the advantages of achieving performance requirements in terms of displacement response, acceleration responses, and force responses for engineering structures. Several studies have been conducted to investigate and validate the hybrid isolation system incorporating TMDs and inerter damper, optimal design methods, and response control effectiveness (Zhu et al. 2019; Ye et al. 2019; Wang H et al. 2021; Zhao et al. 2019).

Since the construction of the first isolation building in China in 1990, the modern structural isolation technology marked by the application of laminated rubber bearings has been developed for over 30 years in China. As of September 2022, there are more than 16000 isolation buildings, including houses, schools, hospitals, offices, and museums, and 1950 bridges have been constructed in China (Zhou 2023), making China one of the countries having the largest number of seismically isolated buildings in the world. In particular, after the *Regulations for Management of Seismic Protection of Building Constructions* was issued in 2021, the number of isolation buildings increased remarkably. The total number of newly constructed isolation buildings reached at least 2000 or more during half a year in 2022. Isolation technology has experienced rapid developments from systematic experimental investigations to real structural applications, and from natural rubber bearings, lead rubber bearings, high-damping rubber bearings, friction pendulum bearings to SMA-rubber bearings, adaptive variable frequency and friction pendulum bearings, and hybrid 3D isolation bearings.

Seismic isolation has been developed as a relatively reliable technology accepted by the engineering community and the public.

However, seismic isolation has experienced severe challenges during its development. During the $M_s$ 7.0 Lushan earthquake in 2013, two non-isolated buildings in Lushan County Hospital were significantly damaged, as shown in Figures 1 and 2. However, the isolated outpatient buildings in Lushan County Hospital successfully withstood the destructive earthquake effects, playing a critical role in the rapid promotion of the seismic isolation technology, as shown in Figures 1 and 3.

Figure 1 Lushan County Hospital, including three buildings

Figure 2 Two damaged non-isolated inpatient buildings in Lushan County Hospital

Figure 3 One isolated outpatient building in Lushan County Hospital

In contrast to the completely undamaged isolator of the isolated buildings during the Wenchuan and Lushan earthquakes, during the $M_s$ 6.8 Luding earthquake on September 5, 2022, seismic damage and failure were observed in the isolation bearings and auxiliary dampers in two different isolated buildings (Dai et al. 2022; Pan et al. 2023; Qu et al. 2023), as shown in Figures 4 and 5. The main difference is that there was no seismic damage in the isolated residential buildings of the Beishan Post Office during the Wenchuan earthquake since the distance to the epicenter was approximately 300 km. In contrast, the distance of the isolated outpatient building of the Lushan Hospital from the epicenter was approximately 20 km; only the isolation configurations were damaged, and the main structure remained intact during the Lushan earthquake, as shown in Figure 3. During the $M_s$ 6.8 Luding earthquake, one of the isolated buildings showing damaged isolators was located in Moxi town, and the distance to the epicenter was 6.9 km. The other isolated buildings showing failed dampers were located at the junction between Yanzigou Town and Moxi Town, and the distance to the epicenter was 8.9 km, i.e., the two isolated buildings were closer to the epicenter.

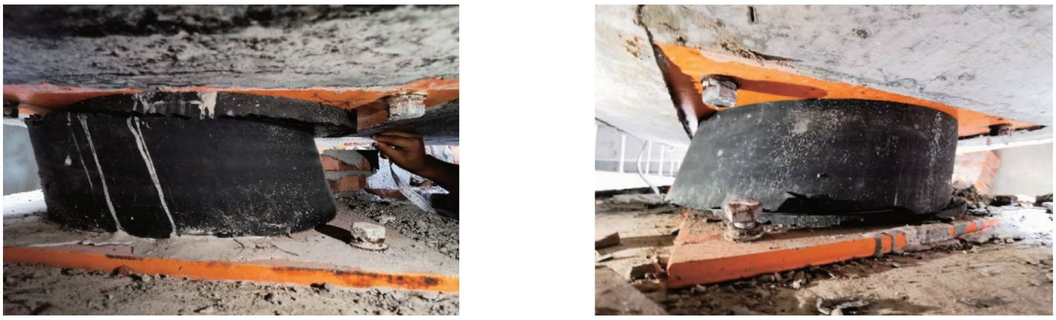
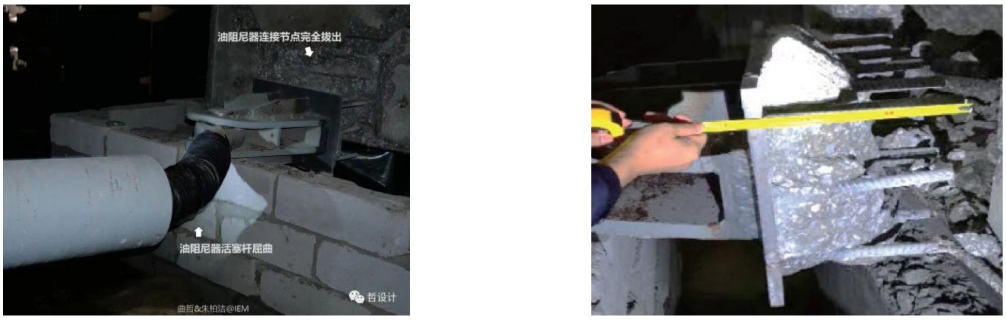


Figure 4 Damage of the rubber bearings in the #1 building



(a) Buckling failure of the viscous damper (b) End connection failure of the damper

Figure 5 Damage of the rubber bearings in the #2 building during the Luding earthquake

In this paper, a state-of-the-art review of seismic isolation, energy, and hybrid control for engineering structures in China is presented. The evolution of seismic technical specifications and design codes is traced, and an overview of the typical investigations and applications of seismic isolation, mitigation, and retrofitting are subsequently provided. The importance of seismic monitoring to improve knowledge under different loading conditions is emphasized. Finally, the urgent engineering demands of structural seismic isolation, energy dissipation, and hybrid control technologies are suggested.

# 2. TECHNICAL RULES FOR SEISMIC ISOLATION AND ENERGY DISSIPATION SYSTEMS IN CHINA

There are several sets of technical rules for seismic isolation and energy dissipation systems in China.

## 2.1 Technical Specifications

- **Technical specification for seismic isolation with laminated rubber bearing isolators (CECS 2001)**. This is a recommended association technical specification for the design and construction of buildings and bridges with seismic isolation, issued in 2001 in China.

- **Technical specification for seismic energy dissipation of buildings (JGJ 297-2013)**. This is the industry standard for the design and construction of buildings and bridges with energy dissipation, issued in 2013 in China.

- **Seismic isolation design code for bridges** (Chapter 10 in the national code for seismic design of bridges, **JTG/T 2231-01-2020**). This is part of the Specifications for the Seismic Design of Highway Bridges updated and issued in 2020 in China.

- **Standard for structural design of urban over-track buildings (T/CECS 1035- 2022).** To provide a reliable basis for the design of urban railway systems in China, the standard clarifies the design requirements of laminated rubber bearings with thick rubber layers and three-dimensional combination isolators for isolated and non-isolated structural design and comfortability evaluation methods (CECS. 2022).

- **Technical standard for dual control of engineering vibration and seismic vibration of building engineering (T/CECS 1234-2023).** This is also association technical specification that guides the effect analysis and response check, design method, and auxiliary measures for the dual control of engineering vibration and seismic vibration, which is based on the technical progress and practical experience in China (CECS. 2023).

- **Guideline for seismic technology to maintain functionality of buildings in earthquakes (RISN-TG046-2023).** This is the national technical guideline that outlines the basic regulations, seismic effects, seismic checks, nonstructural components, attached mechanical and electrical equipment, and functional facilities (MHURD. 2023).

## 2.2 Design Codes

- **Seismic design code of buildings with isolation and energy dissipation** (Chapter 12 in the National Code for Seismic Design of Buildings, **GB50011-2001 and 2010**). This is part of the national code for the seismic design of buildings issued in 2001 and 2010 in China.

- **Standard for seismic isolation design of buildings (GB/T 51408-2021).** This is the national code for the seismic isolation design of building structures, issued in 2021 in China.

### 2.3 Standards for Isolators and Energy Dissipation Dampers

- **Standard of laminated rubber bearing isolators (GB 20688-2006).** This is the national standard for laminated rubber bearing isolators, issued in 2006 in China.

- **Standard of energy dissipation dampers (JG/T 209-2011).** This is the industry standard for energy dissipation dampers issued in 2011 in China.

- **Friction pendulum isolation bearings for buildings (GB/T 37358-2019)**. This is the national standard for friction pendulum isolation bearings for buildings issued in 2019 in China

## 3. TESTING AND DESIGN OF SEISMIC ISOLATION SYSTEMS

Several types of seismic isolators have been employed in real engineering structures in China. Rubber isolator and sliding friction isolator are the most widely used for structural seismic protection. Hence, based on the structural application requirements, testing devices for large-scale isolators, dampers, and seismic isolation and mitigation of structural systems have been developed in recent decades.

### 3.1 Testing System for Seismic Isolators and Dampers

(1) **Worldwide advanced seismic isolation and mitigation device test system**, which was constructed by the Earthquake Engineering Research & Test Center at Guangzhou University, China, as shown in Figure 6. The test system can be used to test seismic isolators and dampers, etc., provide reliable testing results for the optimal design and quality inspection of seismic isolation and mitigation devices, and directly serve the development of national seismic isolation and mitigation technologies. The overall testing indices reach the international leading level. In particular, the vertical capacity is 100000kN in compression and 30000kN in tension, and the maximum horizontal loading forces reaches 10000kN in longitudinal direction and 5000kN in transverse direction, which meet the testing requirements of most large-scale isolators such as friction pendulums. The maximum vertical loading velocity reaches 254mm/s, and the maximum horizontal loading velocity reaches 1000m/s, which meets the real velocity simulation of earthquakes. Simultaneous tension-compression and bidirectional horizontal shear testing for isolators and performance testing for high-speed dampers can also be conducted.

Figure 6 10000-ton tri-axial testing system for seismic isolator and damper

**Multi-functional testing machine for seismic isolator**, which was constructed by the Wuhan Hirun Laboratory. The main objective of the testing machine is to test sliding pendulum isolators, which require dynamic control of one horizontal axis and the vertical axis simultaneously. The maximum vertical and horizontal loads are 75000kN and 6000kN, respectively. The maximum vertical and horizontal displacements are 120mm and 1200mm, respectively. The maximum horizontal peak velocity is greater than 1000 mm/s.

(2) **Most advanced shake table test system**, which features three directions and six degrees of freedom for comprehensive performance testing of large-scale seismic isolators, was constructed by the Earthquake Engineering Research & Test Center at Guangzhou University, China, as shown in Figure 7. The shake table consists of three subtables, sized 8m×10m, 4m×4m, and 4m×4m, respectively. The shake table tests of the large-scale bridge, building structural model, prototype seismic simulation, and vibration test of the industrial equipment and product can all be conducted. The advanced laser displacement sensor, acceleration transducer, dynamic strain measurement system, spectrum analysis and advanced data acquisition system, and matched software are arranged.

Figure 7 Advanced shake table test system

### 3.2 Three Types of Experimental Testings

Several experimental tests have been conducted, and an extensive analysis theory of seismic isolation systems has been widely developed in China, including three types of isolator testing as follows.

(1) **Mechanical characteristics tests of isolators**, which include compression tests to quantify the vertical stiffness and cyclic compression-shear tests to quantify the horizontal stiffness, damping ratio, and maximum horizontal displacement. The test results show that the maximum compression stress of the isolators can reach 90 MPa when the horizontal strain is zero or 35 MPa when the horizontal strain is 400%. Therefore, it is safer to use a maximum compressive stress of less than 15 MPa.

(2) **Durability tests of isolators**, which include low-cycle fatigue failure, creep, and ozone aging tests. It can be observed from the rubber aging tests that the maximum thickness of rubber ozone was 5 mm when exposed to sunlight and air for 105 years. Hence, the working life of the rubber isolator could reach over 100 years for a 10 mm coverer layer to protect it from air and sunlight.

(3) **Shake table tests on large-scale structural models**, including isolation structures with different isolator locations shown in Figure 8, long-span bridges. The results revealed that the effectiveness was dependent on the mass ratio of the superstructure to the substructure, and base isolation showed the best effectiveness, in which the accelerations of an isolated structure could be reduced to 1/12–1/4 compared with a fixed-base structure.

Figure 8 Shaking table test for different configurations of isolation bearing layers

### 3.3 Integrated Design Method for Isolation System

To fully consider the non-proportional damping characteristics of the isolated structure, an integrated design method (Tan et al. 2022), as shown in Figure 9, which converts a nonlinear seismic isolation structure into a linear seismic isolation structure using the equivalent linearization method, was proposed and issued in the *Standard for seismic isolation design of buildings (GB/T 51408-2021)*. The convergence principle was based on the maximum displacement error of the isolation layer. The equivalent parameters of the bearings were determined through repeated iterative calculations. The principle of complex modal decoupling was applied to linear seismic isolation structures. The peak response caused by the magnitude of a specific seismic excitation was calculated using the CCQC rule. Finally, a nonlinear response history analysis was conducted, including the maximum considered earthquake (MCE), to verify the design requirements.

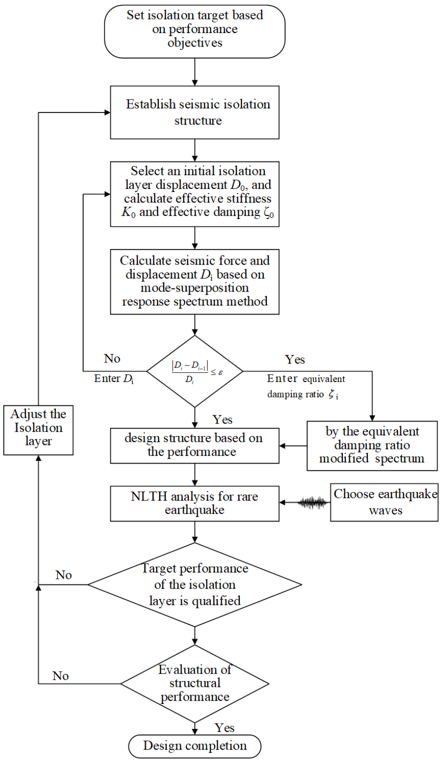


Figure 9 Integrated design method for seismically isolated structures

## 4. OVERVIEW OF RESEARCH PROGRESS AND TYPICAL APPLICATIONS

As of July 2023, there were more than 16000 isolation buildings of different heights (3 and 31 stories), including houses, schools, hospitals, libraries, and museums, and 1950 isolation bridges had been constructed in China, which is one of the most seismically isolated structures in the world. Sand or graphite lime mortar isolation layers for rural buildings, laminated rubber bearings, high-damping rubber bearings, lead rubber bearings, sliding friction isolators, friction pendulum isolators, roller isolators, and SMA high-damping rubber bearings have mainly been employed in real structures. The use of seismic isolation systems has become widespread in China (Zhou 2016; Dai et al. 2022).

### 4.1 Seismic Isolation for Residential Buildings

Several studies have investigated the performance of different types of isolators in residential buildings. In particular, the temperature dependencies of the yield force, stiffness, damping ratio, loading cycles, shear frequency, and aging properties of laminated rubber bearings, lead rubber bearings, and high-damping rubber bearings have been investigated for rubber isolators (Zhuang et al. 2009; Li et al. 2009; Li et al. 2021; Ge et al. 2022). The high temperature accelerated aging testing of rubber bearings (Shen et al. (2020), isolator thermal displacement and dynamic characteristics variations of isolation buildings and temperature dependency models for performance evaluation (Du et al. 2015,2017), hysteretic strength degradation effect of lead rubber bearing and its effects on seismic performance (Qin et al. 2017; Zheng 2022; Liu 2022), fatigue performance testing of the lead rubber bearing (He et al. 2019), constitute model for rubber bearing (Yuan et al. 2020), aging-seawater corrosion on the performance of rubber bearings (Ma et al. 2020,2021), have been widely investigated. Seismic isolation and energy dissipation technologies have been widely investigated for mid- to high-rise modular steel constructions (Deng et al. 2020). The modules can be preserved for reuse after earthquake excitations to establish a damage-controllable system, which is preferred for incorporating modules or inter-module connections and should be replaceable.

In addition, reasonable tectonics of isolated buildings is particularly important to ensure that the design requirements of isolated buildings are met. The main tectonics of the isolated buildings is the gap between the isolation layer and the ground. According to the requirements of the *Code for Seismic Design of Buildings (GB 50011-2010)*, the gap in the vertical direction should be no less than 20 mm, and the gap in the horizontal direction should be no less than 1.2 times of the peak displacement when subjected to a rare earthquake, which is less than 200 mm. The *Code for Construction and Acceptance of Building Isolation Engineering (JGJ 360-2015)* was issued in 2015. Corresponding local regulations related to the design and construction of seismically isolated buildings have been prepared for issuance in the Yunnan, Gansu, and Fujian provinces. The *Code for Construction and Acceptance of Rubber Seismic Isolation Bearing and Device for Building Isolation Engineering in Fujian (DBJ/T 13-252-2016)* was issued (Wu et al. 2018).

In recent decades, several novel friction pendulum bearings have been developed and investigated. The friction coefficient, curvature radius of the sliding surface, re-centering and seismic isolation performance, and response control effectiveness of friction sliding isolators, for example, single, double, and quadruple friction pendulums, vertical tensile resistant friction pendulums (Liu et al. 2016; Zhang et al. 2021), variable friction pendulum isolators (Zhang et al. 2020; Shang et al. 2021a,b,2022), variable frequency friction pendulum isolators (Tsai et al. 2003; Lu et al. 2011; Han et al. 2012; Hong et al. 2018; Tan et al. 2023).

Several studies have been conducted to incorporate traditional isolators with superelastic shape memory alloy (SMA) dampers, such as cables and U-type dampers, which are arranged around the isolators and connected to the upper and lower steel plates (Xue et al. 2004; Ren et al. 2010; Fang 2022; Fang et al. 2023; Wang et al. 2018). The seismic isolation performance of SMA-cable-controlled sliding isolators (Liang et al. 2020) and SMA-lead rubber bearings (Wang et al. 2020, 2023; Chen et al. 2022) for building structures such as residential buildings, has been widely investigated.

Typical structural applications of the seismic isolation in residential buildings are introduced as follows:

**Example 1: Reinforced concrete (RC) seismically isolated apartment building**, which is a residential apartment building group constructed in Beijing, China, and includes 24 high-rise buildings (31 stories). The total floor area is 980,000 m$^2$ and is the largest area of an isolated apartment building in the world, as shown in Figure 10. Several similar isolated residential buildings were constructed in Xinjiang Province, Yunnan Province, and other areas in China.

Figure 10 Seismically isolated residential apartment buildings

**Example 2: RC frame seismically isolated buildings.** In an isolated school building constructed in 2008, during the Lushan Earthquake $M_s$ 7.0 on April 20, 2013, the peak structural acceleration of the isolated school building was reduced to 1/6 of that of the fixed-base buildings. Teachers were able to instruct the young students as quoted: ‘When an earthquake happens, keep inside of the room, don’t run out! This is a base isolated building; inside this building is safer than outside!’ No damage was observed, and no students were injured after the earthquake, as shown in Figure 11.

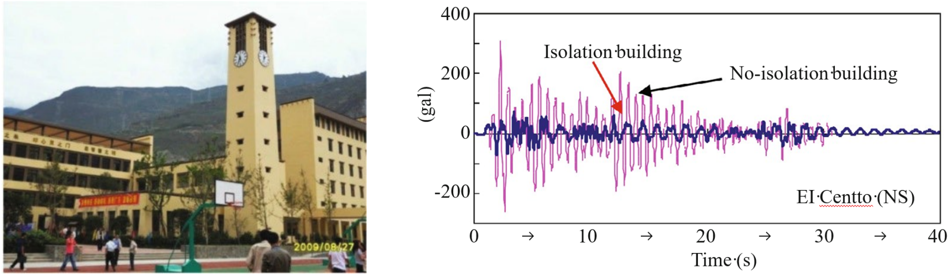


Figure 11 Seismically isolated building school in Wenchuan County and recorded acceleration response

**Example 3: RC inter-story isolated frame with 2-story platform and 9-story residential structure**. The large platform (2 stories, RC frame), with a width of 1500 m and a length of 2000m, is the largest area with 3D isolation worldwide, as shown in Figure 12. It covers a railway area in Beijing City. 48 isolated residential buildings with a total floor area of 240,000 $m^2$ were constructed on top of the 2nd story platform. These residential buildings are 7 to 9-story RC frames and feature 3-dimensional isolations for seismic motion and railway vibration.

Figure 12 48 inter-story isolated buildings with 3D isolation on RC Platform

## 4.2 Seismic Isolation for Large-span Space Structure

Several studies have investigated the seismic performances of different types of isolators in large-span space structures (Shu et al. 2019; Deng et al. 2019; Han et al. 2020; Pan et al. 2022). In particular, the seismic performance and effectiveness of different types of isolators for large-span space structures have been investigated and demonstrated, for example, SMA rubber bearings (Xue et al. 2004), vertical tensile-resistant friction pendulum bearings (Liu et al. 2016), laminated rubber bearings (Nie et al. 2020), and double friction pendulums with SMA cables (Zhuang et al. 2021) for space reticulated shell structures.

The typical structural applications of seismic isolation in residential buildings with large-span space structures are as follows:

**Example 4: Seismic isolation of new Kunming airport terminal (2007-2012).** The new Kunming airport terminal, which is one of the largest isolated structures (10 km) near seismic faults globally, is isolated using 1,892 rubber bearings (ϕ1200 mm) and 108 oil dampers to protect the column with curved shapes, large glass facades, large ceiling, and critical facilities during an earthquake, as shown in Figure 13. The total floor area was 500,000 m$^2$. The dynamic responses of the airport terminal under *Ms* 4.5 Chonmin Earthquake on March 9, 2015, were recorded. The response of the terminal floor F3 was 1/4 that of the base.

Figure 13 Seismic isolation of new Kunming airport terminal (2007-2012)

**Example 5: Seismic isolation of new Daxing airport terminal (2015-2019).** The new Beijing airport terminal has a super long irregular structure, and its length is larger than 300m. The total isolated floor area is 700,000 m$^2$. A high-speed railway or subway crossing under an airport terminal may induce significant vibrations. The isolation system, which consists of lead rubber bearings, laminated rubber bearings, elastic sliding bearings, and velocity-type dampers, uses 1,118 rubber bearings (ϕ1200mm, 1500 mm), sliding bearings, and 160 velocity-type dampers aimed at enhancing seismic resilience, as shown in Figure 14.

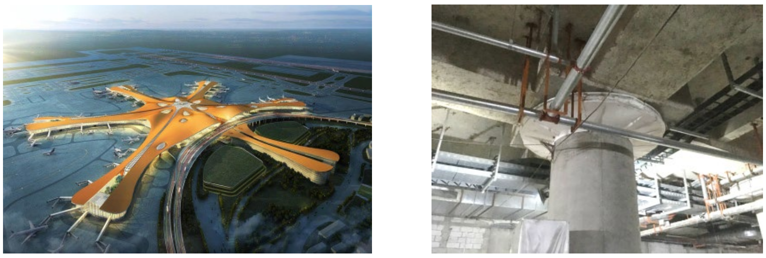


Figure 14  Seismic isolation of new Daxing airport terminal (2015-2019)

**Example 6: Seismic isolation of new Meilan airport terminal (2016-2019)**. The new Hainan airport terminal with an isolated floor area of 300,000 $m^2$ was constructed. The isolation bearings effectively accommodated the thermal deformation caused by the structural concrete shrinkage of the floor slab. The structural plane of the airport terminal is irregular, with a structural length of 300m. The rubber isolation bearing, lead-core rubber isolation bearing, and elastic slide bearing were combined, as shown in Figure 15. Many new airports with base isolation are being planned or designed in China.

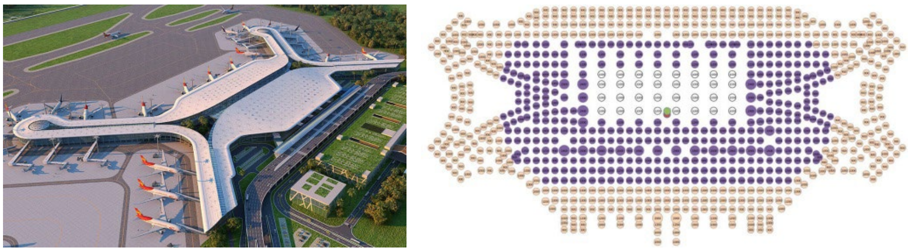


Figure 15  Seismic isolation of new Meilan airport terminal (2016-2019)

**Example 7: Seismic isolation of new Sanyi airport terminal.** The new Sanyi airport terminal, one of the largest isolated buildings, was isolated using friction pendulum bearings. The single span of the airport terminal reached 69m. The total floor area is 100,000 $m^2$, as shown in Figure 16.

Figure 16 Seismically isolation of new Sanyi airport terminal

### 4.3 Seismic Isolation for Low-rise Rural Buildings

Several structural damages and failures have occurred in large rural regions; for example, several rural buildings have collapsed, and heavy casualties have occurred. On May 12, 2008, the $M_s$ 8.0 Wenchuan earthquake caused serious damage and failure of buildings, most of which were village houses. On April 14, 2010, the 7.1 Yushu earthquake caused the failure and collapse of a number of rural buildings. Under the same earthquake, rural buildings showed much more serious damage than city structures. Hence, seismic isolation and mitigation technologies used in rural buildings should be considered (Shang et al. 2016; Yin et al. 2018; Huang et al. 2019; Li et al. 2021).

Hence, a novel isolation technology was employed in rural buildings. In particular, reinforced asphalt composite isolation systems (Shang et al. 2009, 2013), slide-limited friction base isolation (Ma et al. 2011), spring asphalt three-dimensional isolation bearings for low-rise buildings (Shang et al. 2012; ), glass-bead graphite rolling isolation systems (Cao wanlin et al. 2010), and sand cushion sliding isolation (Li et al. 2010; Han. 2013; Qian et al. 2013; Shi et al. 2014; Li et al. 2017), laminated rubber isolation systems for rural masonry structures (Wang et al. 2014), and novel fiber-reinforced plastic plate rubber isolation bearings (SFRPB) (Tan et al. 2012,2013,2017), have were experimentally and theoretically investigated. The seismic isolation performance of the novel isolation strategies for real rural structural applications, considering cold regions, frequent and rare earthquakes, and frost-heaving resistance, was demonstrated and validated through experimental tests. Further field tests showed that the seismic responses of the superstructures of rural buildings can be effectively mitigated. The '*Technical Specification for Steel Bar-asphalt Base Isolation Technology in Multi-story Building (DBJ43 /T304-2014)*' has been issued for the design of steel bar-asphalt isolated rural buildings. Low-cost isolation strategies for rural buildings show promise for structural applications. Rural structural isolation systems should be further investigated to enhance the seismic performance.

Typical applications of seismic isolation in low-rise rural buildings are introduced as follows:

**Example 8: Low-rise rural buildings with "elastic isolation brick."** To enhance the seismic performance of low-rise rural buildings, which are always low-cost, simple designs constructed simply, a new isolation system called "elastic isolation brick" has been developed and employed in large countryside areas in China (Tan et al. 2014, 2017) as shown in Figure 17. Compared with the isolation rubber bearing, the cost of this elastic isolation brick was reduced by 75%. The elastic isolation bricks have a simple design and construction. The seismic performance of the low-rise rural buildings isolated by elastic isolation bricks has been demonstrated using shake table tests. The results revealed that the elastic isolation brick system could withstand very strong earthquakes, and no damage was observed when the peak ground accelerations reached 0.80 g. The rural buildings with elastic isolation bricks could become the 'safety island' in a very strong earthquake.

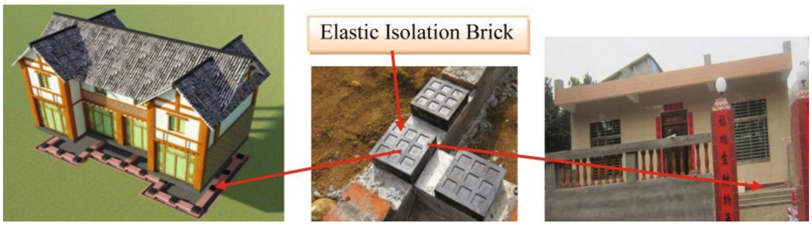


Figure 17 Low-rise residential building with "elastic isolation brick"

### 4.4 Seismic Isolation for Bridges

Seismic isolators and dampers, which dissipate seismic energy by deformation and lengthen the isolation period by reducing the horizontal stiffness or enhancing the damping capacity, have been widely used in bridges (Tan et al. 2009; Jia et al. 2021). Lead rubber bearings have been used in the Buguzi railway bridge (Zhang et al. 2002) in Xinjiang Province and the Shijin Canal bridge in Heibei Province, China.

The seismic performance, e.g., lead rubber bearing (Wu et al. 2016; Wang et al. 2019; Zheng et al. 2020), high damping rubber bearing, sliding bearing (Peng et al. 2019;), friction pendulum (Xia et al. 2014; Li et al. 2015; Zhang et al. 2018; Wang et al. 2019; Shi et al. 2018; Huang et al. 2016; Liu et al. 2019; Jiang et al. 2019; Wei et al. 2019; Zeng et al. 2020; Chen et al. 2020), novel function separation isolation system (Wen et al. 2017; Yang et al. 2020), polyurethane elastomeric bearings (Yuan et al. 2020; Wang et al. 2023) for bridges have been investigated and proposed different design strategies to promote the applications of seismic isolation in real bridge applications (Zhao et al. 2020,2021).

Several studies have been conducted to incorporate superelastic SMA devices with isolators to enhance seismic resilience. The seismic performance, energy dissipation mechanism, dynamic behavior, and design methods of the different novel isolators for bridges were systematically investigated by numerical experiments or shake table tests (Li et al. 2007; Han et al. 2008; Yuan et al. 2008; Guo et al. 2009; Yi et al. 2019; ), including the SMA rubber bearing (Li et al. 2002; Miao et al. 2012; Wang et al. 2019; Zheng et al. 2020,2021; Cao et al. 2020,2022; Deng et al. 2022), SMA-high damping rubber bearing (Fang et al. 2023), damping enhanced re-centering seismic isolator (Zheng et al. 2022); SMA friction pendulum (Zheng et al. 2019, 2021,2022; ); 3D seismic isolator (Jia et al. 2017), SMA-cable-controlled sliding bearings (Fang et al. 2020), superelastic variable stiffness friction pendulum (Han et al. 2020; Zheng et al. 2022,2023), SMA cable-based negative stiffness seismic isolator (Cao et al. 2022,2023), and superelastic conical friction pendulum (Zheng et al. 2023a,b).

Typical applications of the seismic isolation in bridges are introduced as follows:

**Example 9: HK-MACAO-ZHUHAI seismically isolated bridge.** A high-damping rubber bearing with cable restrainers was employed in the HK-MACAO-ZHUHAI bridge to enhance the seismic performance, which crosses the South China Sea with a length of 26 km, as shown in Figure 18. The piers of bridges in seawater are effectively protected from cracking and are elastic during earthquakes. The seismic isolation system protects the bridge against strong earthquakes and wind and reduces the seismic response to 1/4 of the response of the traditional bridge.

Figure 18 Seismically isolated HK-MACAO-ZHUHAI bridge

**Example 10: Seismically isolated highway bridge.** The developed SMA cable-restrained high-damping rubber bearings were employed in the Datianba #2 highway curved bridge (curve radius of 500m) located in Yunnan Province, China, as shown in Figure 19 (Fang et al. 2022). This was the first study to adopt the proposed SMA-cable-restrained high-damping rubber bearings in the world. The bridge is 368.76 m in length, and the nine-span prefabricated T-section RC girders were simply supported by either column-type or wall-type piers and abutments.

Figure 19 Datianba #2 highway bridge with SMA-HDRs in Yunnan Province, China

### 4.5 Seismic Isolation for Underground Structures

Several studies have revealed that urban underground structures experienced serious damage during the Chi Chi earthquake (Wang et al. 2000) and Wenchuan earthquake (Wang et al. 2009). The seismic safety of urban underground structures has attracted considerable attention. In 2014, the *Code for Seismic Design of Urban Underground Structures (GB 50909-2014*) in China was issued (MHURD, 2014).

Seismic isolation has been widely employed to enhance the seismic resilience of urban underground structures and is an effective measure for transferring the shear deformation of the main components. The effectiveness of different types of seismic isolators, such as friction pendulum isolators (Du et al. 2019; Xu et al. 2020), roller friction pendulum bearings (Tao et al. 2016; Ma et al. 2018), laminated rubber bearings (Zheng et al. 2020; Liu et al. 2020), and lead rubber bearings (Huang et al. 2011; Chen et al. 2016) has been investigated and demonstrated through numerical, experimental, and shake table tests.

Most seismic technologies focus on reducing the earthquake-induced damage to improve the seismic resilience of underground structures. Research on the restoration of the function of underground structures after earthquakes is generally insufficient. Future studies should focus on restoring the function of underground structures after earthquakes, particularly the degree and speed of restoration. Moreover, new structural systems and large-scale model tests, which form the basis of seismic behavior assessments, should be further developed. Seismic design standards and codes for earthquake-resilient underground structures should be established to promote further applications.

**Example 11: Seismically isolated urban over-track buildings.** To effectively utilize the space of urban over-track buildings and enhance their serviceability and seismic performance, friction pendulum three-dimensional isolation bearings were utilized in over-track buildings at the Beianhe station of Beijing metro Line 16. The urban overtrack building consisted of reinforced concrete and steel frames, as shown in Figure 20.

Figure 20 Seismically isolated urban over-track buildings

### 4.6 Seismic Isolation for Tank Structures

Owing to the high requirements of liquefied natural gas (LNG) tanks, several studies have focused on the search for an appropriate isolation system for tank structures. In particular, the seismic performance of the plate-shell integrated concrete tank structures with different isolation systems, including lead rubber bearings, sliding bearings, friction pendulum bearings, and SMA devices, has been investigated (Sun et al. 2013; Qu et al. 2014; Shan et al. 2018; Jing et al. 2019; Tang et al. 2021; Qi et aet al. 2022; Zhu H. et al. 2023; Zhang et al. 2023) through theoretical and experimental studies.

**Example 12: Seismically isolated LNG tank structure.** To effectively enhance the seismic performance, base isolation was employed in an LNG tank structure with a capacity of two million tons and 200,000 tons in Caofeidian, Tangshan City, Hebei Province. Lead-rubber bearings were used, as shown in Figure 21. Seismic isolation can also effectively enhance the load-carrying capacity of large tank structures.

Figure 21  Seismically isolated LNG tank structure

### 4.7 Seismic Isolation for Cultural Relic

**Example 13: Seismically isolated historic statue and stone tablet (1200 years history).** Historical relics, thousands of years old in China, play an important role in providing public cultural services and meeting the needs of spiritual and cultural life. Base isolation is employed in historical relics such as statues, tablets, or pictures to protect cultural relics from earthquake damage. Base isolation can reduce the horizontal response of the relics to 1/12 of the ground motion and ensure safety during earthquakes, as shown in Figure 22.

Figure 22 Seismically isolated history statues and stone tablets

### 4.8 Seismic Isolation for Structural Retrofitting

**Example 14: Seismic isolation retrofits for old structures.** Several old structures, including buildings and bridges such as schools, office buildings, hospitals, girder bridges, and other critical facilities, lack seismic resistance in China. Therefore, it is necessary to employ seismic isolation for retrofitting and enhancing the performance during strong earthquakes. Seismic isolation retrofitting of school buildings was successfully conducted in the Shanxi Province. The government extended this demonstration activity through a national meeting, as shown in Figure 23.

Figure 23 Base Isolation and 1st story isolation retrofit in Shaanxi Province

**Example 15: Seismic isolation retrofits for historical buildings.** A historical building located in Nanjing City was uplifted by 3m in 2013 and then retrofitted using seismic isolation, as shown in Figure 24 (Du and Wang et al. 2022). Lead and laminated rubber bearings are used. Historical buildings are culturally protected. A real-time monitoring system was built to record the static and dynamic behaviors of the isolation bearings and provide real-time warnings. This was the first monitoring system in China for seismically isolated historical buildings.

Figure 24 Panorama of the historical building and sensor layout

## 5. ENERGY DISSIPATION DEVICES

By the end of 2022, different types of energy-dissipation devices were employed in over 14,000 actual buildings. An energy-dissipation system consisting of several energy-dissipation devices is particularly effective in enhancing damping capacity, thereby mitigating seismic energy and protecting the structure from damage and failure under earthquakes. Different types of energy dissipation devices, such as braces, walls, joints, connections, restrainers, nonstructural elements, and suitable spaces (Qian et al. 2016; Qiu and Zhu. 2017; Zhang et al. 2020; Qiu et al. 2020; Ke et al. 2023; Dong et al. 2023), also contribute to the stiffness against wind loads for safety requirements. The structural responses can be mitigated by 50%-70% using energy dissipation devices, which are reliable, simple, and suitable measures for aseismic structures, including six typical types of energy dissipation devices used in China: (1) Steel yielding dampers, (2) Lead yielding dampers, (3) Oil dampers, (4) BRB bracing, (5) SMA dampers, and (6) Eddy-current dampers (ECD).

**Example 16: Eddy-current damper developed by Chen Zhengqing in China.** The eddy-current damper, a new generation of noncontact energy dissipation devices, can provide large damping for response mitigation and exhibit better durability. To effectively mitigate the wind-induced response, an eddy-current damper was employed in the Shanghai Center building with a height of 606m, as shown in Figure 25, which reduced the wind-induced response by 30%-50% during strong wind events. The eddy-current damper is more effective, durable, and economical than other types of dampers and has also been used in bridges.

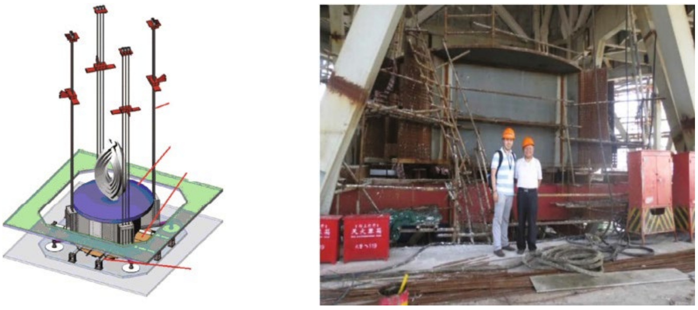


Figure 25 Eddy-current damper in Shanghai Center Building

**Example 17: Shear wall with SMA damper.** A novel Fe-SMA shear damper was developed and employed in actual shear wall structures (Fang et al. 2021), as shown in Figure 26. Seismic performance was investigated both numerically and experimentally. The Fe-SMA shear damper exhibits superior performance in low cycle fatigue, and its low-cycle fatigue life is 10 times that of a traditional mild steel damper.

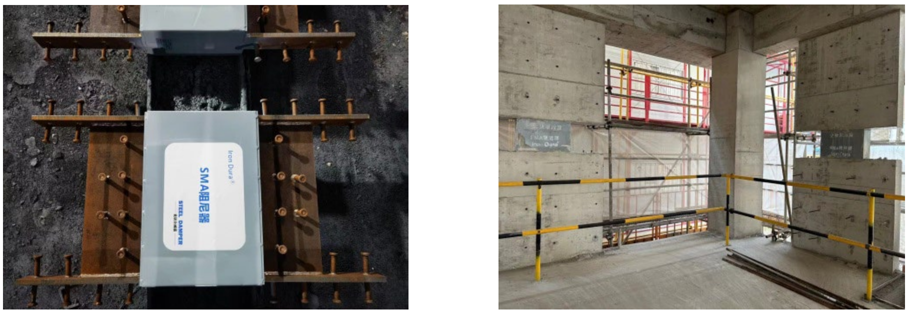


Figure 26 New Fe-SMA shear damper for shear wall structures

**Example 18: Tunnel with SMA soft connection.** Tunnels always cross rivers or seas, and the tunnel joints may open during an earthquake, which means that water may enter the tunnel and induce serious disasters. To address this problem, soft joints incorporating SMA devices were developed and employed in a 6 km-long tunnel below sea located in a seismic area with a seismic intensity of 0.40 g in Southern China, as shown in Figure 27. SMA devices aim to close tunnel joints after an earthquake and ensure that tunnel joints are watertight. The effectiveness of the SMA soft connection system has been demonstrated theoretically and by test results for being waterproof during very strong earthquakes, and the tunnel response can be reduced by approximately 30%-50%.

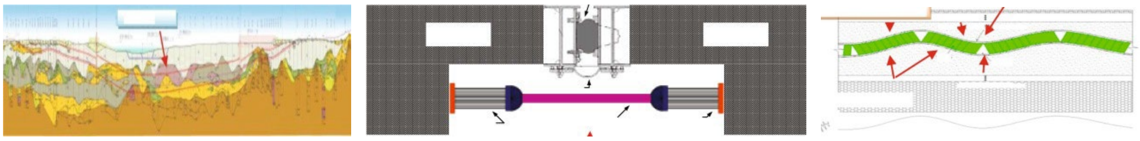


Figure 27 New SMA soft connection for tunnel joints

## 6. HYBRID CONTROL DEVICES FOR STRUCTURES

Structural hybrid control has been employed in approximately 30 buildings and bridges (Lu et al. 2001; Fan et al. 2007; Tan et al. 2011). TMD devices with favorable stability and low cost hardly satisfy the requirements for earthquakes or winds. Compared with TMD devices, AMD are more effective, require external energy input, and increase costs. Hence, a low-cost hybrid control system, which consists of a TMD and AMD, was developed and can satisfy the requirements for response control under earthquakes or strong winds. Hybrid control systems are among the best options for controlling structural vibrations in China.

**Example 19: Hybrid control system of Canton Tower with a height of 600 m.** The advantages of the hybrid control system for the Guangzhou Tower are as follows.

(1) The Guangzhou tower, with a height of 600 m, is sensitive to long-period ground motion and strong winds; hence, the earthquake- and wind-induced vibration responses are significant in terms of the requirements of comfort and safety.

(2) The torsion effects under an earthquake or wind are significant because the structural plan is an ellipse.

(3) The slender conformation was not achieved under strong winds (Figure 28).

(4) The TMD is low-cost, but it hardly satisfies the safety and comfortability requirements. AMD is effective for earthquake- and wind-induced response mitigation, but its cost is excessively high. As a result, the hybrid control system consisting of two water tanks, as TMD and two AMDs, may provide the best balance, as shown in Figure 28, effectively enhancing the control performance and reducing costs.

Figure 28 Hybrid control system consisting of two water tanks as TMD and two AMDs for Canton Tower

## 7. MONITORING OF SEISMICALLY ISOLATED STRUCTURES

**Example 20: Monitoring of isolated hospitals.** The hospital, located in the west of China, consists of three sub-towers with plane sizes 32.7m×18.6m, 64.0m×18.6m, and 32.4m×18.6m and a large podium. Each sub-tower had six stories. The seasonal climate changed significantly. Ambient temperature, initial displacement of isolation bearings, and dynamic characteristics were monitored from construction to the service period (Du et al. 2015, 2017). The overall layout of the hospital building sensors is illustrated in Figure 29. The variations in ambient temperature and frequency during the operation period are shown in Figure 30.

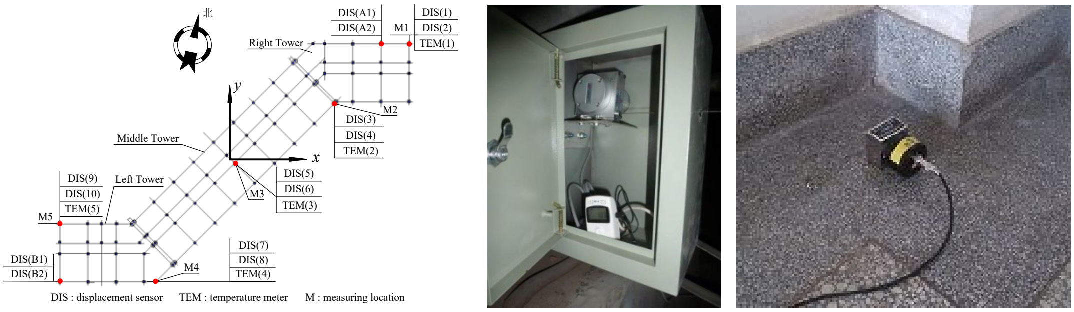


Figure 29 Sensor layout of a hospital building (Du et al. 2015, 2017)

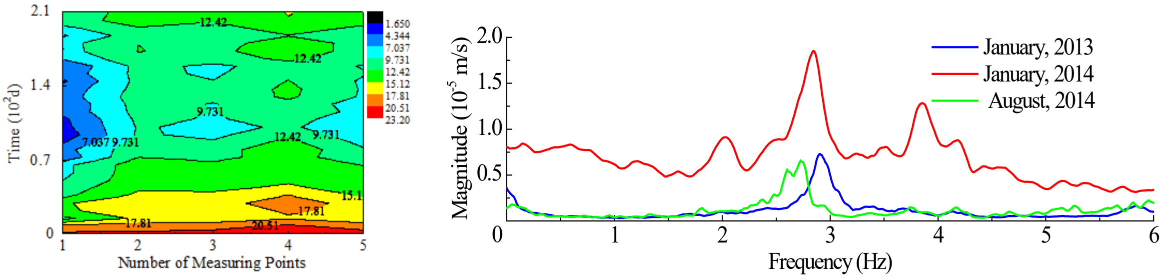
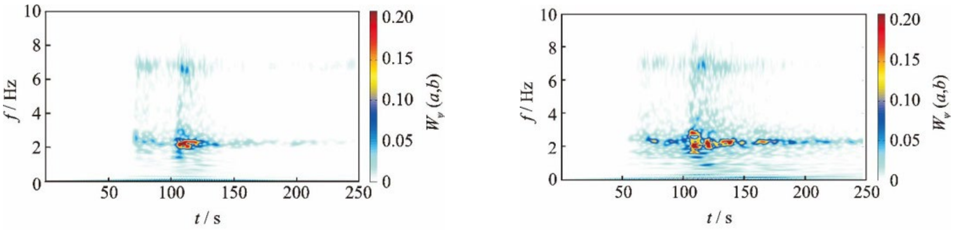


Figure 30 Variations of ambient temperature and frequency in operation period

**Example 21: Monitoring of isolated school buildings.** Teaching Building #1 of the school was based on isolation using rubber bearings and was located in western China. The height of the school building was 27.3m with five stories, as shown in Figure 31. To achieve service conditions and investigate the performance of the isolation system, the dynamic characteristics of an isolated school building were monitored using acceleration sensors (Du et al. 2018). Two earthquakes, the Qilian earthquake in 2016 and the Menyuan earthquake in 2017, and their corresponding seismic responses were recorded. The time–frequency distribution of the seismic response of an isolated school building under the two earthquakes is shown in Figure 32.

Figure 31 Acceleration sensor layout of a school building (Du et al. 2018)



(a) Qilian earthquake in 2016 (b) Menyuan earthquake in 2017

Figure 32 Time-frequency analysis of seismic response of isolated school

**Example 22: Monitoring of large-span complex buildings.** A huge seismically isolated steel framework is shown in Figure 33. Base isolation is employed in this steel framework, and the seismic isolators were installed at the foot of the steel column. The steel columns provided reliable stiffness to ensure the cooperation of the rubber isolation bearings. The sensor arrangement of the huge steel framework is shown in Figure 33. The isolator displacement, ambient temperature, structural acceleration, and wind speed were mainly monitored (Zhu et al. 2014).

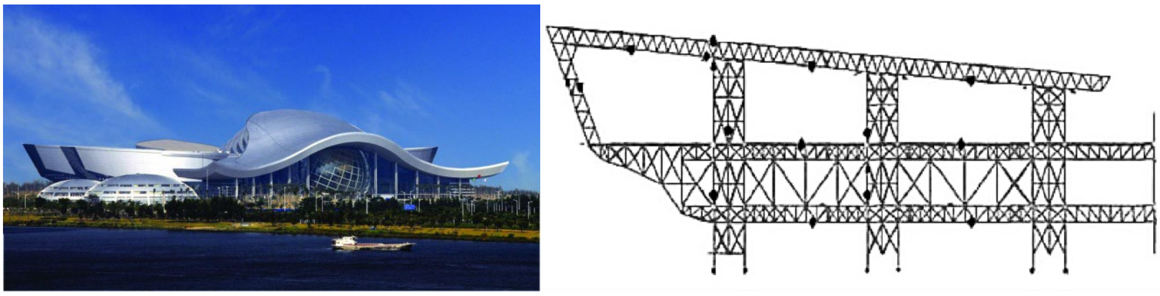


Figure 33 Sensor arrangement of huge steel framework

## 8. URGENT ENGINEERING DEMANDS FOR SEISMIC ISOLATION

In recent decades, the isolation technology in China has experienced strong earthquakes thrice, i.e., the $M_s$ 8.0 Wenchuan earthquake in 2008, $M_s$ 7.0 Lushan earthquake in 2013, and $M_s$ 6.8 Luding earthquake in 2022. Some shortcomings have also been observed after the earthquake, for example, the energy dissipation components also behaved serious damage and failure and the connection of the isolation configurations was failed. Possible reasons include the quality of the isolator products, management, and supervision. From a technological perspective, related standards and specifications are required to ensure reasonable products, design, and construction quality indices.

The severe damage and failure of the laminated rubber bearing and viscous dampers revealed the reliability of the isolator under earthquake excitation with a large-velocity pulse. The ground motions vary from short-time micro-vibrations to large-velocity pulses, in which the structural components, for example, the dampers for energy dissipation, rapidly work directly with high velocity without a certain response time to normal activation. Notably, no specific targeted measures are adaptable to the sampling inspection tests and construction site installation of the current isolation products, which is particularly important in terms of whether the seismic performance of the isolators and dampers can be achieved under pulse-type near-fault earthquakes.

According to the standard *Rubber bearing 1st part: Testing method of rubber isolation bearing* (GB/T 20688.1-2007), the requirement, ‘minimum loading frequency is 0.001 Hz’, is hardly apply to the rapid response demand of the isolator corresponding to the structural behavior under earthquake. On the other hand, the requirement, ‘reference loading frequency should be 0.5 Hz’, is relatively higher for most isolation bearings in structures. This is because besides a few early constructed brick-concrete or masonry structural isolation buildings, the basic isolation period of the isolation structures, e.g., isolated multi-story reinforced concrete frame, frame-shear, and shear wall structure, mainly ranges from 2.5s to 4.5s, i.e., from 0.2 Hz to 0.4 Hz. The requirement, ‘Reference testing values should be the values of the third cycle,’ which is selected as the measured performance parameters, the adaptability of the reference testing values to the near-fault earthquake with large velocity pulses should be open to discussion.

According to *Dampers for vibration energy dissipation of buildings (JG/T 209-2012)*, the experimental method for viscous dampers clarifies that the basic structural frequency, defined as the reference testing frequency, is reasonable. However, the experimental loading procedure involves step-by-step loading from small to large displacements. The method, by which the measured damping coefficient and damping index corresponding to the third cycle are selected as the design values, is limited. It is still a challenge to meet the demand for near-fault pulse-type earthquakes remains challenging.

To overcome these challenges, the following suggestions are provided.

(1) When designing a seismic isolation system, the maximum velocity response of the isolation system corresponding to the acceleration levels of different fortification intensities should be provided for isolator development, production, and inspection.

(2) It is more reasonable and feasible to add the testing method of benchmark detection indices for related guidelines, including the base frequency of the targeted building and the maximum velocity.

(3) To adapt to the rapid response requirements of the isolator and viscous dampers under near-fault ground motions with large velocity pulses, particularly for near-fault isolation structures, it is necessary to investigate the feasibility of using the test value of the third cycle as the measured performance parameters of the isolators and dampers.

(4) According to the damage and failure reasons, it is also necessary to add the test method of the torsion-tension-shear coupling of isolation bearings into relevant product inspection standards.

Furthermore, to address the challenges of on-servicing isolation buildings, e.g., the compatibility of the real performance of existing isolators and matched viscous dampers, unreasonable isolator configurations degrade the service function. To avoid the unreasonable design and construction of the isolator configurations, the relevant isolation equipment production, design, construction, and acceptance standards need to be improved, and a reliable basis for developing the isolation technology should be provided.

To enhance the structural seismic resilience, post-earthquake function recoverability, repairability, It is an effective measure to develop the resilience-based structural system and design method. For many near fault or crossing fault building and bridge structures, such as the bridges along the Sichuan-Tibet railway, the impulse effect, slip effect, and strong vertical earthquake effect pose a severe challenge to the existing seismic isolation and mitigation theory, technology and design method.

It is needed to accurately predict the dynamic behavior of the structures under near-fault earthquakes by using advanced technologies such as real-time dynamic substructure test. Urgent demands for developing more adaptable resilient systems and protecting the bridge structural safety, traffic safety, and even post-earthquake function recoverability under near or crossing fault earthquakes, should to be addressed for the engineering structure construction.

## 9. CONCLUSIONS

Seismic isolation, energy dissipation, and hybrid control are the most effective and reliable measures to achieve the resilience goals of engineering structures. This study conducts a state-of-the-art review of seismic isolation, energy dissipation, and hybrid control in China, and the typical structural applications have been presented, demonstrating that seismic isolation and mitigation technologies are now advancing as the most effective measures to enhance the structural seismic resilience against strong earthquakes all over the world. The technical rules, experimental testing system, and design method of seismic isolation and mitigation devices have been widely developed, and the structural applications in residential buildings, low-rise rural buildings, bridges, underground structures, tank structures, cultural relics, and structural retrofitting have increased remarkably in recent years. Different types of isolators, e.g., laminated rubber bearing, lead rubber bearing, high damping rubber bearing, friction pendulum isolator, variable stiffness and friction isolator, SMA-rubber bearing, SMA cable-restrained sliding bearing and high damping rubber bearing, SMA lead rubber bearing, superelastic variable stiffness and friction pendulum isolators, and dampers, e.g., Steel damper, TMD, AMD, SMA damper, eddy-current damper.

The laminated rubber bearing, high-damping rubber bearing, and lead rubber bearing are the most widely used for building applications in China. They are incorporated with steel and viscous dampers to optimize the structural seismic performance. The number of existing structures with seismic isolation retrofitting has increased significantly owing to its increased service life advantage. The most interesting applications on reinforced concrete, wood, concrete girder bridges, and historic structures have been conducted. Some applications are in areas that recently experienced seismic events, in which seismically isolated structures showed better performance in protecting structural safety. Meanwhile, some damage cases have also been observed in seismic isolation and mitigation structures.

Several applications have focused on the monitoring of seismic isolated structures with dampers under service and seismic events to reveal the structural static and dynamic behavior. The recordings obtained during the Luding earthquake on September 5, 2022, have been presented and discussed, pointing out that the behavior of isolation and mitigation devices can be quite different under earthquakes with large velocity pulses, which should be further experimentally and numerically analyzed in detail for future developments and seismic monitoring of seismically isolated structures.

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# CURRENT STATE AND FUTURE CHALLENGES OF SEISMIC ISOLATION DEVELOPMENT IN TAIWAN

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## ABSTRACT

Since the 1999 Chi-Chi Earthquake, passive control technology has been widely used in both new construction and retrofitting of buildings and infrastructure to mitigate against seismic attacks in Taiwan. In 2005, the Taiwan Seismic Design Specifications and Commentary of Buildings was upgraded and expanded to include the design for seismically isolated buildings and buildings with damping systems. The specifications promote and facilitate the proper application of passive control technology for buildings. Initially, passive control technology was applied primarily to critical structures, such as hospitals and emergency response facilities, which must maintain full functionality during and after earthquakes. However, since 2009, the use of such technology has been greatly expanded to residential buildings for better seismic protection and quality of life. According to the specific design provisions, there have been more than 200 seismically isolated structures constructed in Taiwan. In this paper, several modern applications of seismic isolation technology for building structures and bridges in Taiwan are presented. Moreover, seismic isolation technology has been developed to protect non-structural components and equipment, including communication and industrial processing equipment. Among the many techniques of seismic isolation for equipment, the sloped rolling-type isolation devices, which feature constant horizontal transmitted acceleration regardless of the intensity and frequency content of input excitations, have been widely applied in the telecommunications industry and high-technique facilities in Taiwan.

Taiwan has established a committee dedicated to regular revisions of the specifications for the design of seismically isolated buildings. Recently, the committee announced two significant provisions for seismically isolated buildings. The first provision involves considering the variability of seismic isolation units in the design stage. The second provision entails implementing a more exhaustive and practical testing and verification process. In this paper, additionally, the latest seismic design code for buildings with isolation systems in Taiwan is briefly introduced. To meet the increasing requirements of domestic and international research and tests for full-scale seismic isolation and velocity-dependent damping devices with long stroke and high velocity, the bi-axial dynamic testing system (BATS), which possesses high-performance lateral and vertical dynamic control capacities, has been established

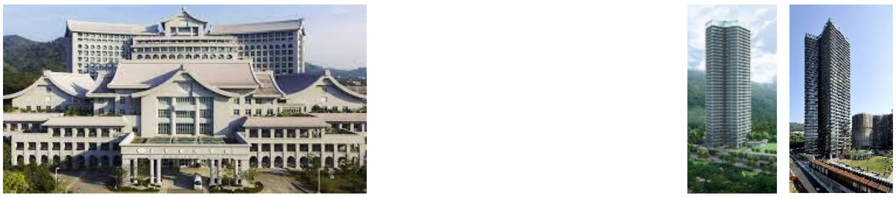
in National Center for Research on Earthquake Engineering (NCREE) in Taiwan. The friction performance of BATS and the feasibility of the direct force measurement strategy is examined in this paper. To practically demonstrate the efficacy of seismic isolation design, the strong motion monitoring of a seismically isolated building in Hualien is examined and compared with numerical analysis in this paper. Some effects induced by near-fault ground motions are raised and discussed accordingly. Lastly, some future challenges, in terms of design and promotion, to the application of seismic isolation technology in Taiwan are addressed in this paper.

**KEYWORDS:** Seismic Isolation, Practical Application, Taiwan Seismic Design Code,
Large-Scale Multiaxial Testing Facility, Strong Motion Monitoring, Future Challenge.

## 1. RECENT PRACTICAL APPLICATION OF SEISMIC ISOLATION TECHNOLOGY IN TAIWAN

Since the 1999 Chi-Chi Earthquake, passive control technology has been widely adopted in both new construction and retrofitting of buildings and infrastructure against seismic attacks in Taiwan. To date, there have been more than 200 seismically isolated structures constructed in Taiwan. Initially, these applications primarily focused on critical structures, including medical facilities and emergency response centers, which must maintain full functionality during and after earthquakes. For instance, several hospitals in Taiwan, including the Taipei Tzu Chi Hospital, the He Xin Building at Hualien Tzu Chi Hospital, and the Taichung Tzu Chi Hospital, have implemented isolation technology to enhance their seismic resistant capacities and seismic performances. The Taipei Tzu Chi Hospital, which began operation in 2005, is a 15-story steel-reinforced concrete (SRC) structure with a 3-story basement, as shown in Fig. 1(a). The installed isolation system beneath the basement comprises 161 lead rubber bearings (LRBs) with a maximum diameter of 1.5 m, 54 natural rubber bearings (NRBs) with a maximum diameter of 1.3 m, 4 flat sliders, along with 82 steel dampers and 48 viscous dampers. The maximum isolation displacement is 60 cm and the separation between the superstructure and the surrounding retaining wall is designed to be 80 cm. The He Xin Building at Hualien Tzu Chi Hospital is an 11-story SRC structure with a 1-story basement, as shown in Fig. 1(b). The isolation system installed at B2F utilizes 74 LRBs, 14 flat sliders, and additional damping devices [1]. This building is noteworthy for being the first base-isolated structure equipped with the strong motion monitoring system of the Central Weather Bureau (CWB) in Taiwan. Its seismic responses measured during previous earthquakes in Taiwan are discussed in detail in Section 4. The Taichung Tzu Chi Hospital, completed in 2008, is a 14-story SRC structure with a 2-story basement, as illustrated in Fig. 1(c). The isolation system implemented at B3F adopts 325 LRBs with a maximum diameter of 1.5 m and 88 viscous dampers. Currently, the tallest base-isolated building is a precast reinforced concrete (RC) residential building with a total height of 133.2 m (B3F~38F) and an aspect ratio of 3.17 [2], as presented in Fig. 1(d). The isolation system installed underneath 1F consists of 43 LRBs with a maximum diameter of 1.5 m. The separation between the superstructure and the surrounding retaining wall is designed to be 50 cm. The elastic period before isolation and the effective period after isolation under the design basis earthquake (DBE) shaking are 3.29 s and 5.18 s, respectively.

(a) Taipei Tzu Chi Hospital (b) Hualien Tzu Chi Hospital



(c) Taichung Tzu Chi Hospital (d) The tallest base-isolated building

Figure 1 Base-isolated building cases using LRBs in Taiwan

In Taiwan, the mid-story isolation technique has been widely implemented for seismically isolated buildings due to its architectural advantages in the aspects of aesthetics and functionality as well as its easy maintenance and inspection after construction. In mid-story isolation design, the isolation system is incorporated into the mid-story (typically installed on the top of the first story, as shown in Fig. 2(a)) rather than at the base of the building. Therefore, it is essential to recognize that the dynamic behavior of a mid-story isolated structure can be more complex compared to that of a base-isolated structure. Assuming the superstructure to be a single-degree-of-freedom system is inappropriate and may not be conservative for the preliminary design of mid-story isolated buildings. The modal response spectrum analysis that appropriately considers the contribution of higher modes, rather than the equivalent lateral force procedure provided for base-isolated buildings, is more applicable. Most importantly, nonlinear response history analyses considering appropriate ground motions for the final design check are required. These findings underscore the necessity for meticulous attention to detail in mid-story isolation design [3–5]. In Taiwan, the highest mid-story isolation system is installed above the fourth story of an RC residential building (B6F~16F), as illustrated in Fig. 2(b). This system utilizes LRBs with a maximum diameter of 1.2 m. Furthermore, the Civil Engineering Research Building at National Taiwan University is a 9-story precast RC structure, featuring a 1-story basement and 2-story penthouses, as depicted in Fig 2(c). Above the first story, there is an isolation system comprising 19 LRBs with a maximum diameter of 0.9 m, as well as 6 viscous dampers with a maximum stroke of ±50 cm and a maximum force of 100 tons. It is noteworthy that the height of the isolation layer is 3.2 m, facilitating educational and engineering visits.

(a) Typical mid-story isolation design (b) The highest mid-story isolation system (c) The Civil Engineering Research Building

Figure 2 Seismically isolated building cases that adopt mid-story isolation design

Concerning the application types of seismic isolators in Taiwan, in addition to the above-mentioned LRBs, high-damping rubber bearings (HDRBs) and friction pendulum bearings (FPBs) are being used increasingly. For example, the Chunghwa Post information center, Fig. 3(a), which will be completed in 2023, is a base-isolated building with an 11-story height and a 2-story basement. The isolation system is composed of 24 HDRBs and 8 viscous dampers that are installed at B1F. Friction pendulum bearings have proven effective in addressing the challenge of eccentricity between the center of mass of the superstructure and the center of rigidity of the isolation system, especially when dealing with considerably irregular structures, due to the feature of their lateral effective stiffness proportional to the imposed axial load [6]. Three iconic irregular buildings in Taiwan have utilized friction pendulum bearings. (1) Taipei Performing Arts Center (Fig. 3(b)): A 12-story steel structure with one basement. The base isolation system is composed of 89 FPBs, in which the maximum type of bearing is 2.2m in diameter. The maximum isolation displacement is 700 mm. (2) Tao Zhu Yin Yuan Mansion (Fig. 3(c)): A 21-story base-isolated structure with a 5m-height roof out-rigger truss, a 3-story roof protrusion, and a 4-story basement. The isolation system consists of 48 FPBs. (3) The Southern Branch of National Palace Museum (Fig. 3(d)): The base isolation system is composed of 210 FPBs, in which the maximum type of bearing is 1.9 m in diameter and the maximum horizontal displacement capacity is 500 mm. The superstructures of these cases are architecturally and structurally complex and irregular, making friction pendulum bearings a valuable choice for the isolation system.

(a) Chunghwa Post Information Center

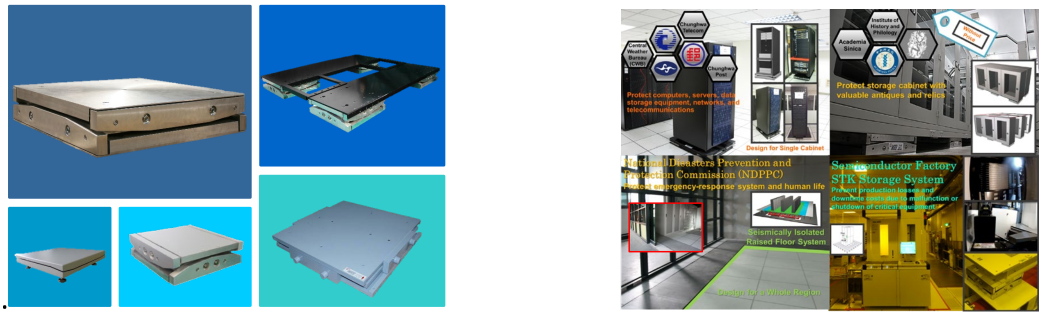
(b) Taipei Performing Arts Center

(c) Tao Zhu Yin Yuan Mansion

(d) The Southern Branch of the National Palace Museum

Figure 3 Seismic isolation design cases using HDRBs and FPBs

In Taiwan, the first seismically isolated bridge was designed and constructed on National Freeway No. 3. Additionally, there are another 8 bridges on the same freeway that have successively implemented seismic isolation design. These isolation systems incorporate the use of LRBs [7, 8]. Moreover, Taiwan's bridge seismic design specifications have undergone several revisions since 1987 [9, 10]. To meet the seismic requirements of the latest specification version, the Freeway Bureau of the Ministry of Transportation and Communications initiated a comprehensive evaluation of the seismic capability of existing bridges and their retrofitting efforts after the 1999 Chi-Chi Earthquake. As a result, the Dong-Shan Bridge on National Freeway No. 3 was retrofitted with the addition of seismic isolation bearings to the existing rigid piers [11]. However, many other critical facilities in Taiwan, such as high-tech factories and emergency centers, have gradually become aware of the effectiveness of seismic isolation technology and have considered adopting such technology for safety and functionality purposes [12]. To achieve a higher performance level for existing aseismic structures, applying seismic isolation technology to the housed critical equipment can yet be regarded as one of the most efficient, practical, and cost-effective strategies. An often-seen case is to incorporate seismic isolators into a raised floor system, i.e., an isolated raised floor system. The sloped rolling-type bearings (SRBs) developed by NCREE, as illustrated in Fig. 4 (a), feature constant horizontal acceleration control performance regardless of earthquake intensities and frequency properties [13, 14]. It has been practically applied in the internet data center of the National Center for High-performance Computing, the internet data center of the National Disasters Prevention and Protection Commission, the antique storage cabinets of the Institute of History and Philology, Academia Sinica, the supercomputer of the Central Weather Bureau, the network and telecommunication servers of Chunghwa Telecom, the data storage equipment of Chunghwa Post, and the high-precision equipment of several semiconductor factories, etc., as shown in Fig. 4(b).



(a) Schematic view of SRBs (b) Practical applications of SRBs

Figure 4 Seismic isolation for equipment or facilities

In the study of SRBs, a review of the literature indicates that SRBs designed with single sloping angles and damping forces face challenges in simultaneously controlling horizontal transmitted acceleration and isolation displacement effectively [15]. Consequently, several strategies have been developed to address this issue. These strategies include passive adjustments with linearly or stepwise variable parameters [16, 17], enhancements in a semi-active manner [18, 19], and integration with earthquake early warning information [20, 21]. Furthermore, certain studies have explored combining SRBs with added inerters to enhance their performance and resilience [22].

## 2. RECENT REVISIONS OF TAIWAN SEISMIC DESIGN SPECIFICATIONS AND COMMENTARY ON BUILDINGS WITH ISOLATION SYSTEMS

In Taiwan, passive control technology has been accepted as a viable means to limit or eliminate earthquake-induced damage by academics, design professionals, and government officials. To properly promote and facilitate the adoption of passive control technology for buildings, the Taiwan Seismic

Design Specifications and Commentary of Buildings was updated and expanded from its previous version to include the design of buildings with seismic isolation and damping systems in 2005 [23]. This design code provided not only analysis procedures for passively controlled buildings but also test requirements for passive control devices.

In the recent two decades, NCREE has formed a committee composed of academics, design professionals, and government officials to continuously revise and update the design code for buildings. At first, in 2011, the design code for buildings with seismic isolation and damping systems was revised toward a more reasonable and practicable goal [23, 24]. The main modified specifications and commentaries for buildings with seismic isolation systems were as follows:

(1) Appropriate design requirements and methods should be considered corresponding to different structural performances.

(2) Mid-story isolation design requires nonlinear dynamic analysis procedures due to the complex dynamic behavior caused by the flexibility of the substructure below the isolation system.

(3) The minimum total lateral force for seismic isolation design at long periods does not need to be limited to the lower bound used in conventional design.

(4) The varied vertical stiffnesses of elastomeric bearings in compression and tension should be considered carefully for the design.

(5) The total design displacement $D_{TD}$ and the total maximum displacement $D_{TM}$ should not be less than 1.1 times the design displacement $D_D$ and the maximum displacement $D_M$, respectively. It is also suggested that $D_{TM}$ should be less than 1.5 times $D_{TD}$, and $D_{TD}$ should be less than the displacement value corresponding to a shear strain of 200% if the isolation system is composed of elastomeric bearings.

(6) Under DBE shaking, elastic base shear force without considering ductile reduction, $V_s$, is used for the design of the superstructure (i.e., the maximum story drift of the superstructure should not exceed 0.005), while 1.25 times the elastic base shear force, $V_b = 1.25\ V_s$, is used for the design of the substructure.

(7) $V_s$ should be distributed rationally over the height of the superstructure using a modified method.

(8) Nonlinear dynamic analysis procedures should use appropriate simulated ground motions. Average response values can be used if at least seven simulated ground motions are analyzed; otherwise, maximum response values should be used.

(9) For elastomeric bearings, vertical compression stresses under usual and instant conditions should be less than $150\text{kg/cm}^2$ and $300\text{kg/cm}^2$. An instant small tensile force response on a few bearings is allowable but should be less than $10\text{kg/cm}^2$.

(10) In prototype testing of elastomeric bearings, vertical stress versus lateral strain can be used in addition to the vertical load versus lateral displacement test if the following conditions are met: (1) the test specimen is an elastomeric bearing, (2) the design compression considering dead and live loads as well as earthquake-induced force is not greater than $200\text{kg/cm}^2$, and (3) $D_{TM}$ is not greater than a lateral displacement corresponding to 250% of the total rubber layer thickness.

More importantly, several significant revisions were considered and adopted by the committee recently, as summarized below:

For seismically isolated structures, the effects of the variability in mechanical properties of seismic isolation units and their influence on the structure are considered in the design code. Since the mechanical behavior of seismic isolation units may vary due to factors such as manufacturing and testing processes, an overall bounding analysis for the isolation system is used to consider variations of design parameters, including the effective stiffness of the isolation system at $D_D$ and $D_M$ ($K_{eD}$, $K_{eM}$), and the equivalent damping ratio of the isolation system at $D_D$ and $D_M$ ($\xi_{eD}$, $\xi_{eM}$) [25]. The variations of ±15%, corresponding to the acceptance criteria for the performance test, shall be analyzed by the design professionals.

The test requirement for seismic isolation units makes a significant revision in the definition and purpose for comprehensively considering quality control, feasibility, and promotion. Three tests are required to verify the quality of a seismic isolation unit before installation, including prototype, production, and performance tests.

(1) The purpose of the prototype test is to verify the production ability of the manufacturer.
  (i) At least two identical seismic isolation units of the same type and size shall be tested to provide the report of the mechanical properties of the specimens. Specimens used for prototype tests shall not be installed in the structure.
  (ii) The prototype test shall be conducted by certified laboratories that are capable of carrying out tests for seismic isolation units in Taiwan.
  (iii) If the seismic isolation units are (1) similar in size as well as identical in material and type, (2) identical in design and manufacturing processes, and (3) the prototype test report of the similar seismic isolation units within the last five years in Taiwan can be provided by the manufacturer and has been approved by the design professionals, the prototype test is not required to carry out again.

(2) The purpose of the production test is to ensure the stability of quality control in each process, from production to final assembly, by the manufacturer.
  (i) Before delivery to the site, the production test requires the assessment of the basic performance of each seismic isolation unit since each unit is essential to structural safety and behavior.
  (ii) Production tests shall be conducted by the manufacturer or certified laboratories that are capable of carrying out tests for seismic isolation units.

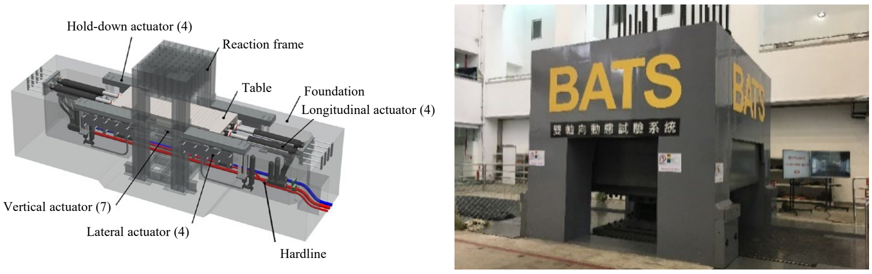
(3) The purpose of the performance test is to verify that the mechanical properties of the seismic isolation unit samples meet the design requirements of the design professionals.
  (i) Before installation to the structure, the performance test requires the test program to follow the characteristics of the seismic isolation unit samples as determined by design professionals.
  (ii) The performance test shall be conducted by certified laboratories that are capable of carrying out tests for seismic isolation units in Taiwan.

## 3. THE LARGE-SCALE DYNAMIC MULTIAXIAL TESTING FACILITIES

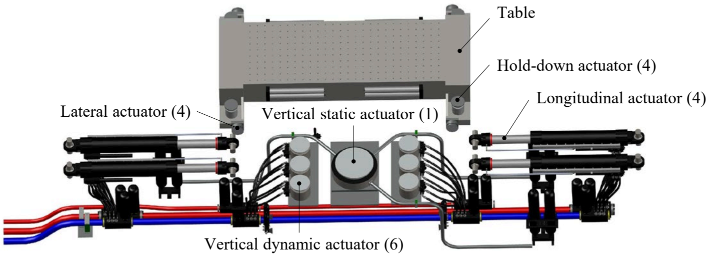
In 2009, NCREE established the Multi-Axial Testing System (MATS) at the Taipei laboratory in Taiwan [26], as shown in Fig. 5. MATS is one of the few global full-scale testing systems for conducting large compression and shear force experiments on specimens such as seismic isolators [27] and wall-type damping devices [28, 29]. To meet the increasing requirement of domestic and international research and tests for full-scale seismic isolation and velocity-dependent damping devices with long stroke and high velocity, the bi-axial dynamic testing system (BATS), which possesses high-performance lateral and vertical dynamic control capacities, was subsequently established at the Tainan laboratory in Taiwan in 2017, as shown in Fig. 6. Recently, BATS has been utilized to investigate various responses due to near-fault ground motions, including the behavior of structural components [30], seismic isolation devices [31], and viscous dampers with long stroke and high velocity.

Figure 5 MATS at the NCREE Taipei laboratory

BATS, as shown in Fig. 6(a), mainly serves to examine full-scale critical structural members, such as columns and seismic isolators, subjected to both horizontal deformation and a vertical compression load in a dynamic manner. It mainly comprises a steel reaction frame, a moveable steel table, four horizontal hydraulic actuators to drive the table longitudinally, seven hydraulic actuators to exert the compression load vertically, four hold-down hydraulic actuators to balance the table to have more redundancy for control, and four lateral hydraulic actuators to guarantee that the table has the desired longitudinal motion during testing. Details of the main components of BATS are illustrated in Fig. 6(b). Four dynamic longitudinal actuators with a maximum force capacity of 2 MN are installed and connected between the table and foundation in the horizontal direction. A static vertical actuator with a maximum force capacity of 30 MN and six dynamic vertical actuators each with a maximum force capacity of 5 MN are mounted on the foundation to support the table in the vertical direction. The maximum longitudinal stroke, velocity, and force capacity of BATS are ±1.2 m, ±1 m/s, and ±4 MN, respectively. The maximum vertical stroke and velocity are ±62.5 mm and ±0.15 m/s, respectively. The maximum vertical compressive force is 60 MN, which includes a total dynamic force of 30 MN and a static force of 30 MN. The stroke and force capacities of each of the four hold-down actuators are ±62.5 mm and +2.0 M, respectively. In other words, BATS also has a vertical tension force capacity of 8.0 MN. For each of the four lateral actuators, the stroke and force capacities are ±5.0 mm and +1.0 MN, respectively.



(a) Overall appearance



(b) Key components

Figure 6 BATS at the NCREE Tainan laboratory

Before making BATS available for public use, it is crucial to determine its key parameters, such as inertial force (effective mass) and system friction force (friction coefficients), and to gain insights into its dynamic performance. Consequently, a series of tests were conducted to comprehend these fundamental parameters and assess the dynamic performance of BATS. To achieve this, the mathematical model and iteration methodology have been proposed to identify and mathematically describe the dependency of the friction performance of BATS on total normal forces (and that of the shear force of the specimen on vertical compression loads) and horizontal excitation rates. This is accomplished by iterating the results of horizontal triangular and sinusoidal reversed loading tests [32, 33]. The vertical compression loads are 0 MN and 10 MN for triangle wave cyclic loading tests with different horizontal displacements and velocities as well as sine wave cyclic loading tests with varied horizontal displacements and excitation frequencies. Based on the results, the average effective mass of the platform was calculated as 96.69 tons and the relationship between the horizontal excitation rates and the system friction coefficients under a specific vertical compression load was obtained, as shown in Fig. 7.

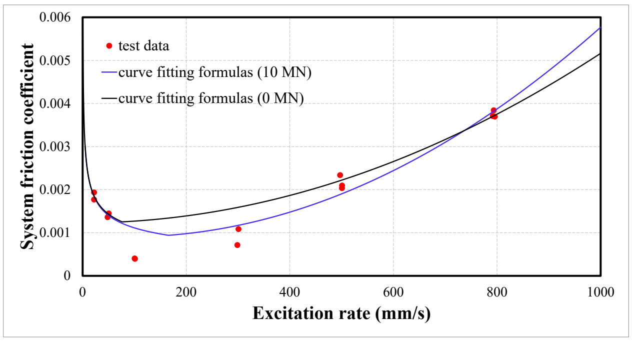
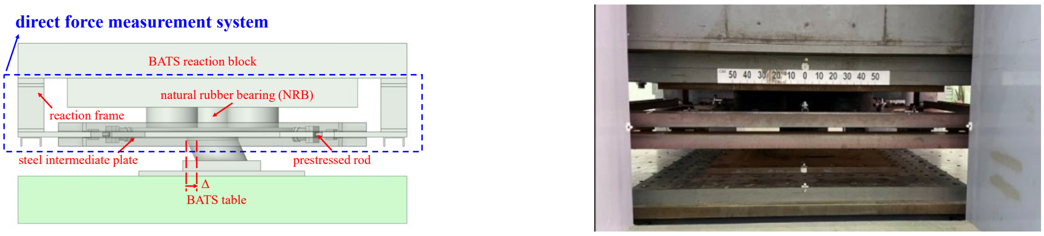


Figure 7 Iteration results for the system friction coefficients of BATS

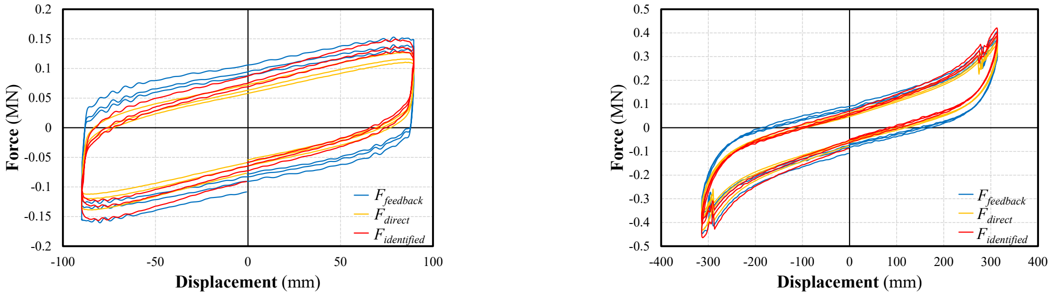
To verify the rationality and applicability of the identified system friction force (friction coefficients) and inertial force (effective mass) of BATS, small-size isolator tests were conducted. The shear force responses were also directly measured using a shear force measurement system [34] to eliminate any interference of friction and inertial force induced by BATS. The shear force measurement system comprises an NRB or several NRBs connected in parallel that transmit the vertical load applied to the specimen, an intermediate plate that connects the system with the specimen, a reaction frame fixed at the top of the BATS reaction block, and four prestressed rods that transmit the horizontal force from the specimen to the reaction frame, as shown in Fig. 8. Therefore, the shear force applied to the specimen is the sum of the force changes of the four prestressed rods and the NRB (or NRBs). In other words, the specimen is connected in series with the parallel prestressed rods and the NRB (or NRBs) in the horizontal direction.



(a) Experimental setup

(b) Overall appearance

Figure 8 The designed direct force measurement system and verification test setup



(a) Vertical compressive Stress: 20 MPa, shear strain: 100%, frequency: 0.25 Hz

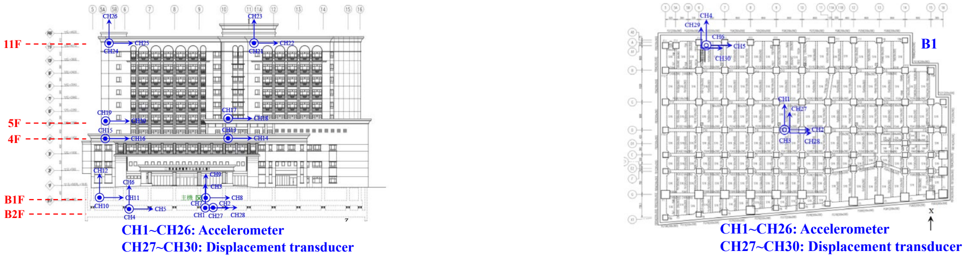
(b) Vertical compressive Stress: 20 MPa, shear strain: 350%, frequency: 0.182 Hz

Figure 9 Comparison of hysteresis loops using different approaches

The specimen used in the measurement system was an LRB with a diameter of 500 mm and a total height of 197 mm. The tests aimed to provide a comparison of the identification results, as shown in Fig. 9. In those figures, $F_{feedback}$ is the force feedback directly from the actuators, $F_{identified}$ is $F_{feedback}$ modified by the identified effective mass and the relationship between the horizontal excitation rates and the system friction coefficients (see Fig. 7), and $F_{direct}$ is the force measured by the shear force measurement system. The comparison illustrates that both the friction force and the inertial force were modified, as depicted in Fig. 9(a). In Fig. 9(b), the comparison with a larger displacement amplitude and higher maximum excitation rate shows that $F_{identified}$ is consistent with $F_{direct}$. This reaffirms the reliability of the proposed mathematical model for BATS and underscores the feasibility of the proposed direct force measurement strategy.

## 4. STRONG MOTION MONITORING OF A SEISMICALLY ISOLATED BUILDING AND NEAR-FAULT EFFECT

Taiwan is seismically active, housing a total of 36 active faults [35]. This geological condition leads to approximately 8.6 million people, comprising one-third of the population, residing within a ten-kilometer radius of these fault lines. The potential impact of near-fault effects on buildings and infrastructure poses a critical concern for human life and property safety in Taiwan. For example, the He Xin Building at Hualien Tzu Chi Hospital was installed with a structural monitoring system, as shown in Fig. 10, which includes 26 accelerometers and 4 displacement transducers [1, 36]. The accelerometers are installed at the center and corners of specific floors and measure both the horizontal responses in the longitudinal and transverse directions. Additionally, the displacement transducers are installed across the isolation interface, monitoring isolation displacement in both horizontal directions between the basement floor (B1F in Fig. 10(a)) and foundation layer (B2F in Fig. 10(a), at the center and corners. On February 6, 2018, an earthquake with a Richter magnitude of 6.0 struck Hualien City and caused an intensity scale of seven. The epicenter was located merely 5.3 km deep and approximately 18.3 km northeast of the Hualien County Government. This earthquake led to the dislocation of the Milun Fault, which is only 2 km from the Hualien Tzu Chi Hospital. Remarkably, there was no structural or facility damage, and malfunction reported for the seismically isolated building. From the acceleration measurement results of the structure in the longitudinal direction, as shown in Fig. 11, the near-fault ground motion phenomenon and the upward transmission of the excitation with an enlarged period, owing to the function of the isolation system, along the structure floors was observed. This evidence practically serves to validate the functionality and efficacy of the seismic isolation design in mitigating the impact of the earthquake.



(a) Front view (b) Plan view

Figure 10 The structural monitoring system

Unfortunately, due to damage to the displacement transducers, the isolation displacement records for the 2018 earthquake are unavailable. Thus, a numerical model was established. Through numerical analysis, the displacement response of the isolation system to the 2018 earthquake is illustrated in Fig. 12. The maximum displacements correspond to the actual record of the pushed distance of the sounding flower nursery, which is contacted by part of the extended paving. As indicated in Fig. 12, the maximum longitudinal displacement is 285 mm, corresponding to a peak ground acceleration of 266 gal. However, according to the original design, the maximum isolation displacement was projected to be 240 mm, at a corresponding effective peak acceleration of 330 gal. This observation suggests that the isolation displacement exceeded the design expectation, underscoring that additional isolation displacement was induced by the near-fault ground motion.

As mentioned above, the seismic isolation design against near-fault ground motions remains challenging, considering that the near-fault ground motions containing long-period velocity pulses may result in a dramatic displacement demand on the isolation system and an unacceptable force transmitted to the superstructure. For example, several studies have suggested the implementation of viscous damping devices to the seismic isolation system to potentially reduce the large displacement and, as a result, the huge inertia force demand on the superstructure. However, on the other hand, the isolation effectiveness against far-field ground motions may be questioned. Thus, some research works have proposed the design method by the isolation system composed of multilinear hysteretic bearings and viscous dampers with various damping exponents against both near-fault and far-field ground motions.

Additionally, considering the huge demand for near-fault ground motions, designing a superstructure by its pure elastic behavior is not rational. The force-controlled concept is then employed to reduce the transmitted force to the superstructure by ductility reduction factors specified in various design codes.

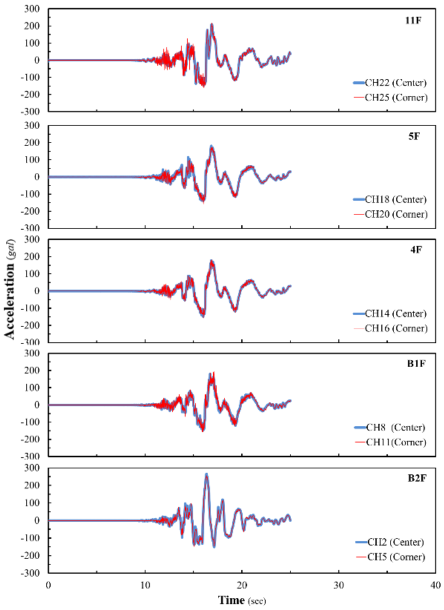


Figure 11 Longitudinal acceleration response histories under the 2018 earthquake

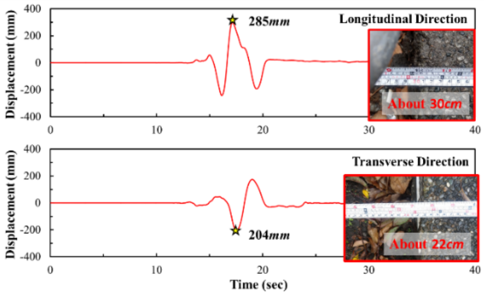


Figure 12 Isolation displacements and their comparisons to the actual surface record

## 5. FUTURE CHALLENGES TO APPLICATION OF SEISMIC ISOLATION TECHNOLOGY

(1) In the aspect of design:

Near-fault ground motions usually cause larger seismic design demands, which is particularly true for structures with long periods of vibration, e.g., high-rise buildings and seismically isolated structures. In Taiwan, at present, for static and dynamic analyses, how to practically determine seismic design demands for which the near-fault effect is reasonably considered is still a critical and debatable issue. Although some seismic isolation design strategies at the expense of a larger isolation displacement demand have been proposed, the sacrifice of property lines due to this issue is still unacceptable to owners and architects, even though the advantages of seismic isolation design over other conventional earthquake-resistant designs are understood. To practically overcome this problem, developing more robust devices and combined systems that can better meet multiple performance objectives at different seismic demands may be still required in the future.

(2) In the aspect of promotion:

In Taiwan, there are many design professionals who have experience in practically designing seismically isolated structures, and NCREE has much experience in dynamically testing project-specific seismic isolation units. Peer design review has also been carried out by nationally credible organizations for years. However, Taiwan still lacks peer review processes for relevant tests and construction, not to mention professional certification. To address this issue, the Chinese Society of Seismic Isolation (CSSI) attempted to establish a certification program of tests of seismic isolation units and construction of seismically isolated structures, of which the expense should be funded by owners. In addition, the establishment of a complete program of regular and irregular (after earthquakes) inspection, maintenance, and management of seismic isolation systems as well as all components passing through the seismic isolation interface after construction has also been attempted, of which the expense should be funded by resident's committees. Currently, CSSI is endeavoring with the relevant government agencies to get an extra floor area ratio bonus for seismically isolated structures if their design and test results, as well as the inspection, maintenance, and management plans, are approved and certified. If feasible, this plan will be beneficial and positive in the promotion of seismic isolation technology in Taiwan in the future.

## 6. CONCLUSIONS

Passive control technologies have been widely implemented in all kinds of structures in Taiwan since the 1999 Chi-Chi earthquake. At present, more than 200 building projects have adopted seismic isolation systems. It is necessary to note that many organizations and industries in Taiwan have adopted seismic isolation technology to safeguard their critical equipment and facilities. In Taiwan, many research projects have been actively launched to further understand the actual behavior of the existing devices and systems, as well as to develop more advanced solutions. Considering feedback from practical engineering experience and reviews from academic communities, the seismic isolation provisions in the Taiwan Seismic Design Specifications and Commentary of Buildings are continuously modified, aiming for a more reasonable and practicable approach.

With the establishment of BATS in Taiwan, the improvements in seismic isolation technology can be supported in the academic community. Additionally, the demand for conducting prototype, production, and performance tests on full-scale seismic isolators in both industry and government can be adequately met. As a result, NCREE is well-equipped to provide superior seismic experimental services to government agencies, academia, and industries both domestically and internationally. This commitment proves beneficial in enhancing public safety and resilience against earthquake disasters.

Moreover, the near-fault effect on buildings and infrastructures is a significant issue of human life and property in Taiwan. The seismic isolation design against near-fault ground motions remains challenging. Therefore, in Taiwan, these issues are currently being addressed through extensive numerical and experimental studies to mitigate the risks associated with the near-fault effect.

Over the past two decades, there has been a significant increase in the application of seismic isolation technology in various structures throughout Taiwan. However, the inspection, maintenance, and management of seismically isolated buildings are still in the early stages of development, with limited practical application in this area. In response to this, CSSI has collaborated with the Japan Society of Seismic Isolation to facilitate the exchange of ideas and information through workshops and training programs. This collaboration aims to further enhance the development of comprehensive inspection, maintenance, and management practices for seismically isolated buildings in Taiwan.

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# APPLICATION OF SEISMIC BASE-ISOLATION TECHNOLOGY IN INDIA

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## ABSTRACT

This document discusses the status of the application of seismic base-isolation (BI) technology in India. The Indian construction industry has slowly started implementing base-isolation technology to safeguard the infrastructure from the looming threat of earthquake events. In India, the pace of application of seismic base-isolation technology is still slow due to a lack of awareness about the performance benefits of the base-isolation technology amongst the stakeholders. However, as an effect of over the time increase in awareness about financial and other advantages of the base-isolation technology and the introduction of design guidelines for base-isolated structures through Indian Standard (IS) codes, it is envisioned that the number of projects in India will be increased soon, especially in the localities of high seismic activities.

**KEYWORDS:** Buildings, Base-Isolation, Base-Isolators, Earthquake, Energy, Sustainable.

## 1. INTRODUCTION

Devastating effects caused by earthquakes have been witnessed by several countries worldwide, including India, in history. Prediction of earthquakes is not possible, being an uncertain event. The inappropriate occurrence of these events causes hindrances to achieving sustainable development goals, slows down growth, and pushes down the economic status of any country. Hence, it becomes essential to safeguard the lives, buildings, and infrastructure from the looming threat of an earthquake.

Base-isolation (BI) is now a well-evolved passive vibration control technology, and through its wide applications worldwide, it has been established that it is one of the few available concepts to mitigate structural responses both at member and global levels (Madhekar and Matsagar, 2022). In seismic base-isolation the damaging effect of the ground motion is absorbed at the isolation plane and hence reduces the force demand on structures sitting above isolators. The period of the structure is primarily lengthened when base-isolated, thus improving its performance during an earthquake event. In the conventional design approach, one needs to rely on the inelastic action of the various structural elements to dissipate the earthquake-caused energy. In addition to safeguarding the primary structure, seismic base-isolation also offers protection of the contents and secondary systems housed in the buildings; since, the seismic forces transmitted to the primary structure are reduced considerably. In view of the effective level of protection offered by base-isolation, the reduction in post-earthquake damages and, hence, a decrease in the post-earthquake repairing cost can be assured.

Looking into the benefits offered by seismic base-isolation technology, the Indian construction industry has also started implementing this mature technology, particularly in areas of high seismicity, through several government, private, and industrial projects in the last few decades. Brief information about some of the base-isolated projects that are completed, under construction, and upcoming in India is to be compiled and disseminated through this document to the scientific and public domain. Perhaps due to lack of public awareness about seismic performance benefits of base-isolation, lack of knowledge on base-isolation technology amongst design engineers and stakeholders, uncertainty regarding the additional financial costs for adopting base-isolation, uncertainty regarding easy availability of base-isolators, non-availability of clear design guidelines through Indian Standard (IS) seismic design codes for base-isolated structures for long time the popularity of application of seismic-base isolation in India remained slow and taking time to elevate.

## 2. BASE ISOLATION DESIGN STANDARDS AND CODES IN INDIA

The International Organization for Standardization (ISO) is an international body involved in the development of international standards. ISO composes experts and representatives from the national standards organizations of member countries. In India, the Bureau of Indian Standards (BIS) is the national standards body that develops and publishes the Indian Standard (IS) codes for their implementation in design practice. In the year 2022, the BIS, India, published the IS code for earthquake resistance design of buildings using base-isolation technology. The objective of this code is to reduce the extent of earthquake damage through base-isolation of buildings. IS 1893 (Part 6): 2022 mainly covers requirements for design of base-isolated buildings. This standard proposes the buildings shall be designed and constructed to resist earthquake induced displacements and forces. The provisions of this standard are applicable only to regular Reinforced Concrete (RC) buildings and steel-frame buildings.

The major part of India's land area is prone to moderate to strong earthquake shaking, and there are several critical structures already built and under construction in these areas. Therefore, the implementation of earthquake-resistant design is of paramount importance and essential, especially in the zones of high seismic activity. The general provisions for earthquake resistance of buildings are laid down in the BIS publication IS 1893 (Part 1): 2016. Figure 1 shows the Seismic Zone Map of India as included in the IS 1893 (Part 1): 2016. As per this map, India's land is categorized into four seismic zones, viz. Zone - II, III, IV, and V. The Highest level of seismic activity is expected in Zone-V; whereas, the lowest level of seismic activity is expected in Zone II, as categorized by the standard.

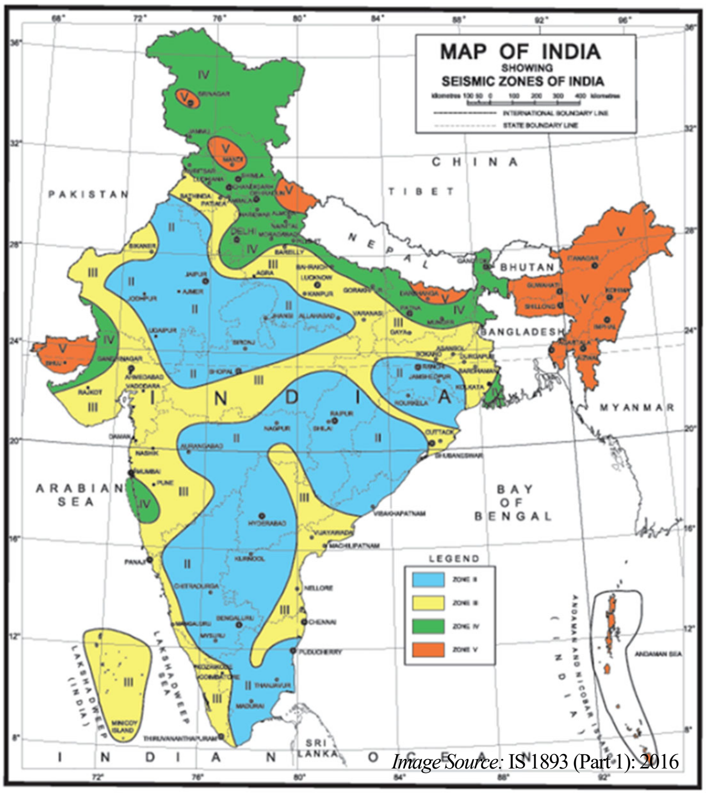


*Image Source:* IS 1893 (Part 1): 2016

Figure 1 Seismic Zone Map of India as per IS 1893 (Part 1): 2016

## 3. BASE-ISOLATION PROJECTS IN INDIA

As discussed herein, the Indian construction industry has started adopting base-isolation technology slowly in view of the benefits offered by this technology to safeguard structures from devastating earthquake effects. In view of the increasing awareness and availability of detailed design guidelines in the form of IS code to help structural design engineers, the construction industry in India is expected to gear up, and more projects with the implementation of base-isolation technology are anticipated to come up in India. Details of some of the building projects that are functional, under construction, and under consideration in India are reported in this document.

### 3.1 Bhuj Hospital Project, Bhuj, Gujarat

On the unfortunate morning of India's 52nd Republic Day, Friday, 26th January 2001, a powerful earthquake (measuring 7.7 on the Richter scale) struck the Bhuj city in Kutch region of the state of Gujarat in India (Sharpe, 2002). The best estimates suggest that at least 20,100 human casualties happened that unfortunate morning. As reported, this earthquake has also destroyed the Bhuj District Hospital, killing almost all of its 178 patients. Hospitals are lifeline structures, and their continuous functioning is always desired; hence, the Government of India has planned to replace a 300-bed hospital and decided to use seismic base-isolation technology while accepting the offer of design expertise from the New Zealand government. Bhuj Hospital became the first base-isolated hospital building in India. A ceremony of laying the foundation stone for the hospital building took place on Tuesday, 2nd October 2001, and the hospital building was inaugurated on Wednesday, 14th January 2004, by the then Prime Minister of India after construction. The Bhuj Hospital building is supported by a combination of 280 lead-rubber and sliding isolation bearings. All the isolation bearings required for this project are manufactured and supplied by Robinson Seismic Limited, New Zealand. Figure 2 shows the pictorial views of the completed Bhuj hospital structure and base-isolation units installed in the structure.

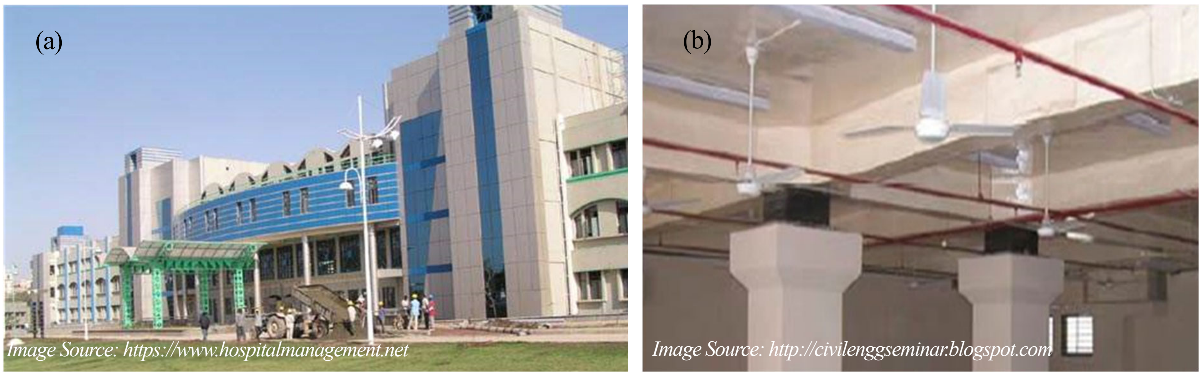


Figure 2 View of the (a) Completed Bhuj Hospital Structure and (b) Base-Isolators Installed in the Structure

### 3.2 Base-Isolated Structures at IIT Guwahati, Assam

Two numbers of three-storied RC framed buildings with identical structural configurations are constructed at the Indian Institute of Technology (IIT) Guwahati campus, one with base-isolation using four lead plug bearings and the other with the conventional foundation to study the behaviour of base-isolated buildings under real earthquakes (Dubey *et al.*, 2008). These structures are the outcome of a collaborative research project between IIT Guwahati and Bhabha Atomic Research Center (BARC), Mumbai, India. Figure 3 shows the pictorial view of the structures and architectural details (plan and front elevation) of the demonstration structures, showing plan dimensions, location of isolators and other relevant details. Different properties of isolators used in the base-isolated structure are described in Table 1.

Table 1: Properties of Lead Plug Isolators (Dubey *et al.*, 2008)

| Model | Property | Value |
|---|---|---|
| Base-Isolated Structure (Lead Plug Isolators) | Mass | 0.5 Ton |
| | Vertical Stiffness | 188960 kN/m |
| | Post-Yield Stiffness | 796 kN/m |
| | Ratio of Post to Pre-Yield Stiffness | 0.0463 |
| | Effective Damping | 0.1056 |
| | Yield Strength | 25.38 kN |
| | Effective Horizontal Stiffness | 1292.085 kN/m |

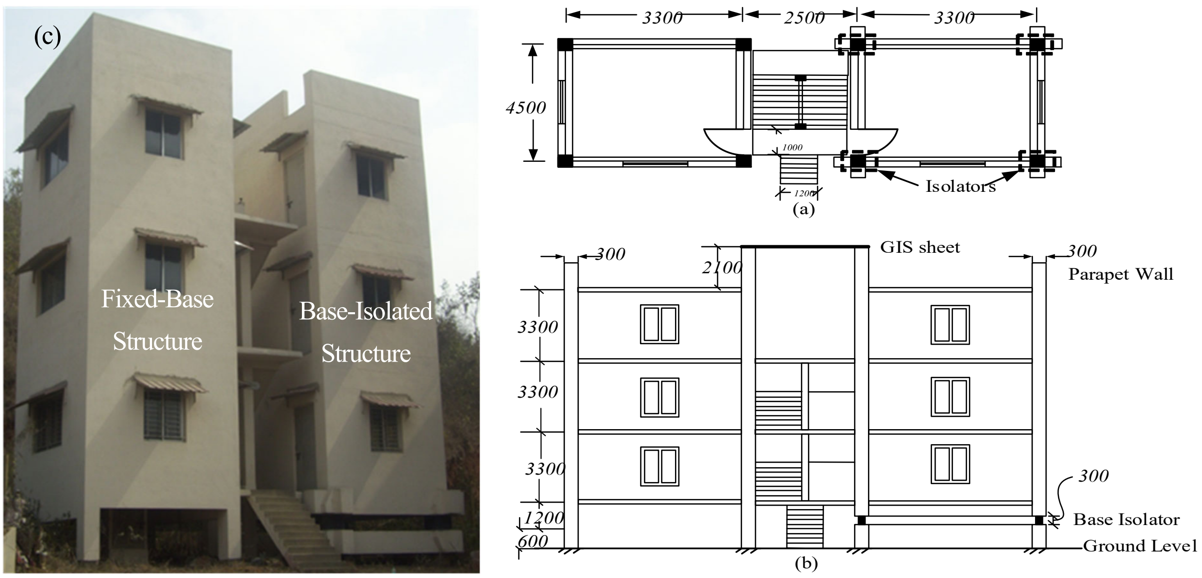


Figure 3 (a)Architectural Details (b) Sectional Elevation and (c) Pictorial View of Structures at IIT Guwahati Campus

### 3.3 Indira Gandhi Hospital Project, Dwarka, New Delhi

Figure 4 shows the photograph of a currently functional 750-bed Indira Gandhi Hospital Project, Dwarka, New Delhi. This project was conceptualized and developed by the Public Works Department (PWD), New Delhi, for the Directorate General of Health Services (DGHS), Government of National Capital Territory (NCT) of Delhi. The Reinforced Cement Concrete (RCC) structure of the hospital building has three interconnected blocks: (i) Outpatient Department (OPD), (ii) ward, and (iii) emergency block. This structure is constructed in Seismic Zone-IV of India, which is one of the most severe earthquake zones in India; hence, the continuous functionality requirement of this hospital structure is achieved by adopting the base-isolation technology. Table 2 summarizes some of the structural details and information of the constructed hospital facility. All the blocks of the hospital structure are base-isolated with a combination of Lead-Rubber-Bearings (LRB) and sliding bearings. In total, 440 numbers of base-isolation units are placed below the structure to decouple it from the seismic forces generated during earthquake events. The details of the isolators, along with their properties considered in modelling, are described in Table 3. Necessary endorsement to the structural design of the base-isolated hospital structure is provided by the communicating author at IIT Delhi. As per the design, the base-isolator units required at a hospital construction site are supplied by Dynamic Isolation Systems, USA. L&T Construction was involved in the execution of construction work at the site.

Table 2 Construction Details of the Hospital Structure

| Sr. No. | Hospital Blocks | Number of Floors | Covered Area |
|---|---|---|---|
| 1 | Emergency Block | 2 Basement (B) + Ground (G) + 5 | 36,226 $m^2$ |
| 2 | Ward Block | 2B+G+8 | 31,455 $m^2$ |
| 3 | OPD Block | 2B+G+5 | 25,325 $m^2$ |

Table 3 Block wise Details of the Installed Base-Isolators

| **Sr. No.** | **Base-Isolator Category** | **Emergency Block** | | | **Ward Block** | **OPD Block** | **Total Isolator Units** |
|---|---|---|---|---|---|---|---|
| | | **Block (A1, A2)** | **Block (A3)** | **Block (A4)** | | | |
| 1 | BG - A | 23 | 2 | 16 | 28 | 0 | 69 |
| 2 | BG - B | 38 | 12 | 0 | 52 | 14 | 116 |
| 3 | BG - C | 46 | 13 | 0 | 43 | 12 | 114 |
| 4 | BG - D | 13 | 0 | 0 | 3 | 54 | 70 |
| 5 | BG - E | 24 | 1 | 5 | 29 | 12 | 71 |
| Total | | 144 | 28 | 21 | 155 | 92 | 440 |


*Image Source: https://twitter.com/AamAadmiParty*

Figure 4 Pictorial View of the Indira Gandhi Hospital Structure, Dwarka, New Delhi

### 3.4 Sardar Patel Bhavan, Patna, Bihar

Sardar Patel Bhavan, Patna, Bihar is the first building in the state of Bihar that is constructed with base-isolation technology. This building utilizes a combination of lead-rubber-bearings (LRB) and sliding bearings to isolate the base of the structure from the superstructure. Patna, the state capital of Bihar, falls in Seismic Zone-IV of India. Sardar Patel Bhavan is planned to house the police headquarters and the state's emergency operation centre; hence, the undisturbed functioning of this building is very important in case of emergency situations such as earthquakes. The main building block of the Sardar Patel Bhawan is a B+S+6 storied RCC framed structure. The entire building of the Sardar Patel Bhavan is supported by a total of 308 number of base-isolators. The Building Construction Department (BCD) of the Government of Bihar led the project activities till its successful completion in the year 2018. Contribution in structural design and production testing services are provided by the communicating author at IIT Delhi for this structure. Dynamic Isolation Systems, USA, has manufactured and supplied the required number of base-isolators, and the construction work of the Sardar Patel Bhavan is completed by Ahluwalia Contracts (India) Limited. Figure 5 demonstrates the structural framing section showing a level of base-isolation of the Sardar Patel Bhavan and a photographic view of the completed and functional structure.

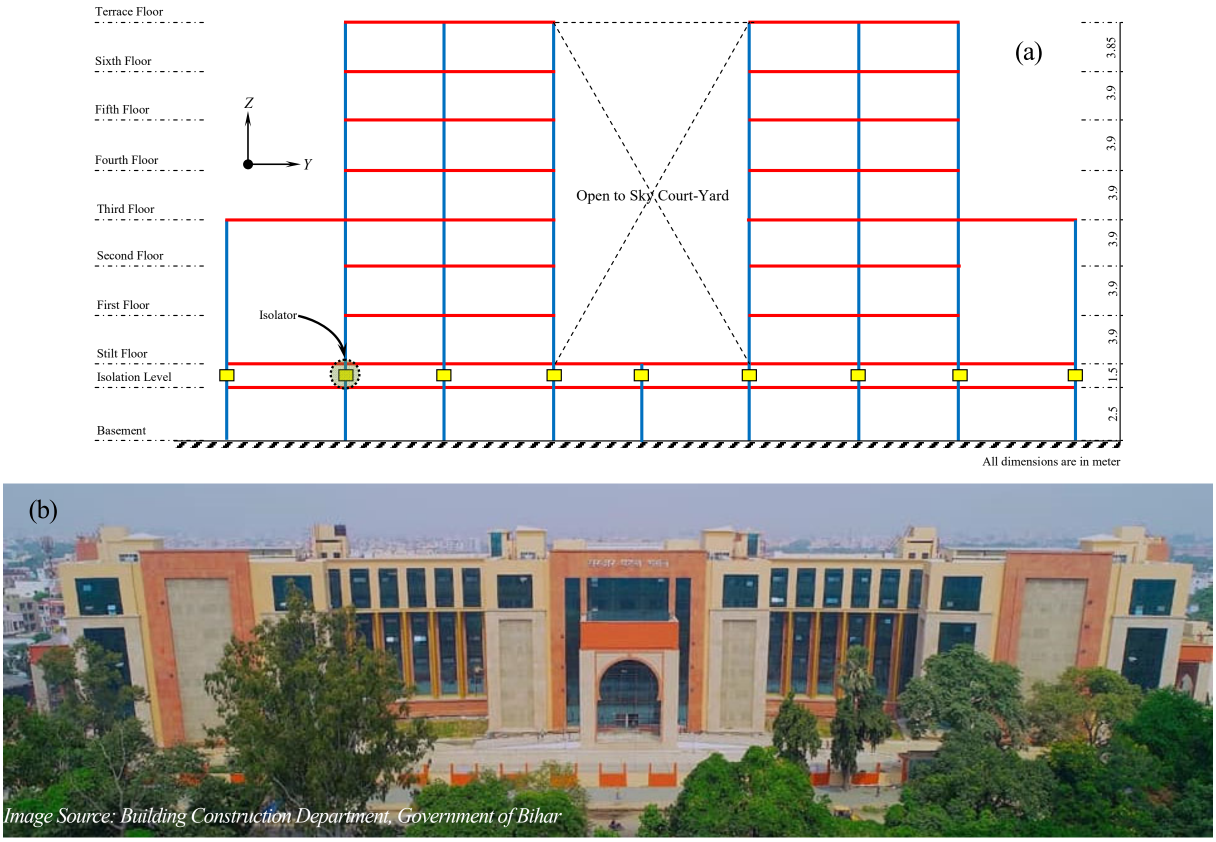


*Image Source: Building Construction Department, Government of Bihar*

Figure 5 (a) Structural Framing Showing Isolation Level and (b) Pictorial View of the Sardar Patel Bhavan, Patna, Bihar

### 3.5 Resistoflex Showcase Building Project, NOIDA, Uttar Pradesh

The recently constructed RC mid-rise (B+S+5) Resistoflex showcase building (Figure 6) located in the National Capital Region (NCR) is entitled India's first base-isolated corporate building structure (plan dimension: 27.78 m × 10.05 m) developed in collaboration with the communicating author at IIT Delhi. The objective of this landmark project is to demonstrate base-isolation technology and provide adequate information among stakeholders to adapt the BI techniques, especially for important structures (located in Seismic Zones IV and V of India). The structure is designed to be operational and will continue to remain functional even in the case of severe earthquakes predicted for Seismic Zone-IV of India (Panda *et al.*, 2023). The showcase building structure is erected on the fourteen number of Double-Curvature Friction Pendulum Bearings (DCFPB). The schematic diagram, picture, and typical force-deformation behaviour of DCFPB is shown in Figure 6. For the considered RC framed building, the base isolators are decided to be placed at stilt level to isolate the superstructure from ground level. The DCFPBs are modelled at the stilt level of the building and are designed for design basis earthquake (DBE) and maximum considered earthquake (MCE) by following the guidelines of the in-force versions of the IS 1893, and ASCE/SEI-7 at the time of design. It is noteworthy to mention that the lift core in the building is designed and constructed as a hanging structure with the provision of appropriate space at bottom and around its periphery to allow the movement of isolation units when active. The showcase building structure is being visited by several national and international fraternities (Figure 6), which serves the intended purpose of this structure, which is to disseminate base-isolation technology.

Figure 6 (a) Pictures of Base-Isolated Resistoflex Showcase Building and (b) Visitors from Several Sectors

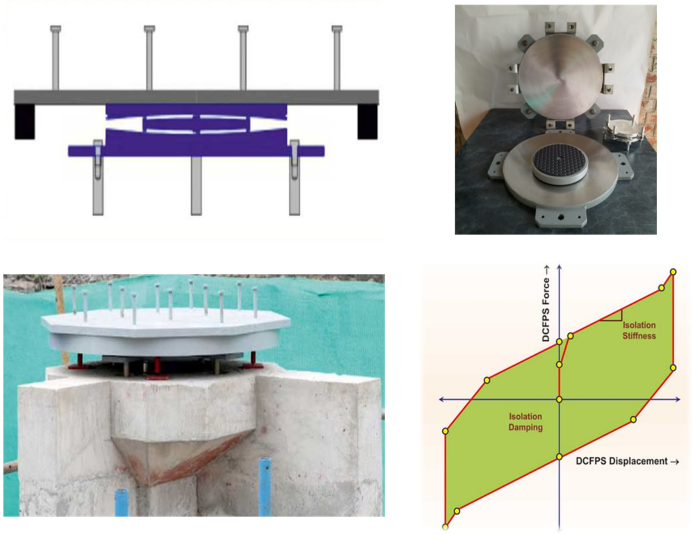


Figure 7 Details of DCFP Bearings Installed at Resistoflex Showcase Building

#### *3.5.1 Seismic monitoring of showcase building*

A unique feature through seismic monitoring is added to the Resistoflex showcase building while integrating the data acquisition system and accelerometer sensors to instantly convey to all stakeholders and occupants through mobiles and the internet about the incoming and happening seismic activity, which in turn makes the building seismically smart. To monitor the response of the base-isolated building, a LabVIEW® GUI code has been developed, where there will be continuous data acquisition (Figure 8) through a series of sixteen uniaxial accelerometers and a data acquisition system. Table 4 presents the installation of uniaxial accelerometers at different locations, i.e., column number, direction, and above or below the isolation level, in the showcase building. This table shows that eight accelerometers are installed below the isolation level, i.e., at the basement and ground floor. Additionally, eight accelerometers are installed above the isolation level, i.e., at the ground, 4th, and 5th floors. The direction of the accelerometers is aligned along both the horizontal directions of the building. Figure 9 shows the recorded forced vibration data at 4th and 5th floors of the Resistoflex building during the recent earthquake activity.

Table 4 Installation of Uni-Axial Accelerometers at Different Locations

| **Location** | **Column Number** | **Accelerometer Nomenclature** | **Direction** | **DAQ Channel** |
|---|---|---|---|---|
| Basement | C14 (BIL) | A01 | Along X | CH0 |
| | | A11 | Along Y | CH1 |
| Basement | C13 (BIL) | A40 | Along X | CH14 |
| | | A41 | Along Y | CH15 |
| Ground Floor | C13 (BIL) | A21 | Along X | CH2 |
| | | A12 | Along Y | CH5 |
| Ground Floor | C13 (AIL) | A02 | Along X | CH4 |
| | | A03 | Along Y | CH3 |
| Ground Floor | C1 (BIL) | A13 | Along X | CH6 |
| | | A14 | Along Y | CH7 |
| Ground Floor | C1 (AIL) | A20 | Along X | CH8 |
| | | A21 | Along Y | CH9 |
| 4th Floor | C13 (AIL) | A22 | Along X | CH10 |
| | | A23 | Along Y | CH11 |
| 5th Floor | C13 (AIL) | A30 | Along X | CH12 |
| | | A31 | Along Y | CH13 |

* AIL = Above Isolation Level; BIL = Below Isolation Level

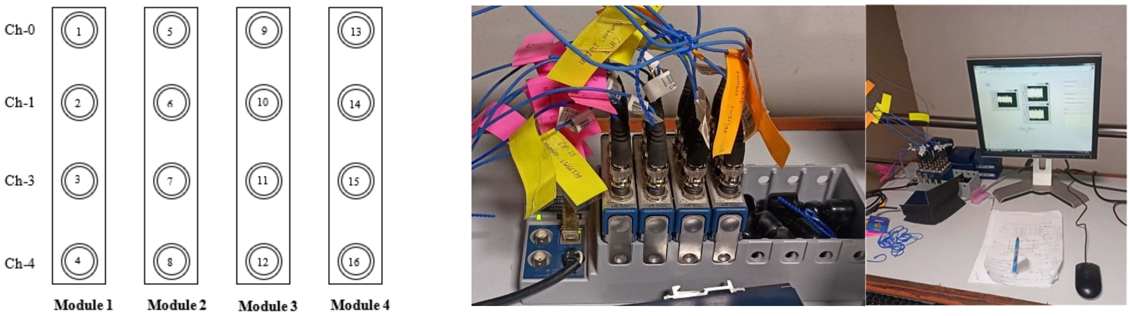
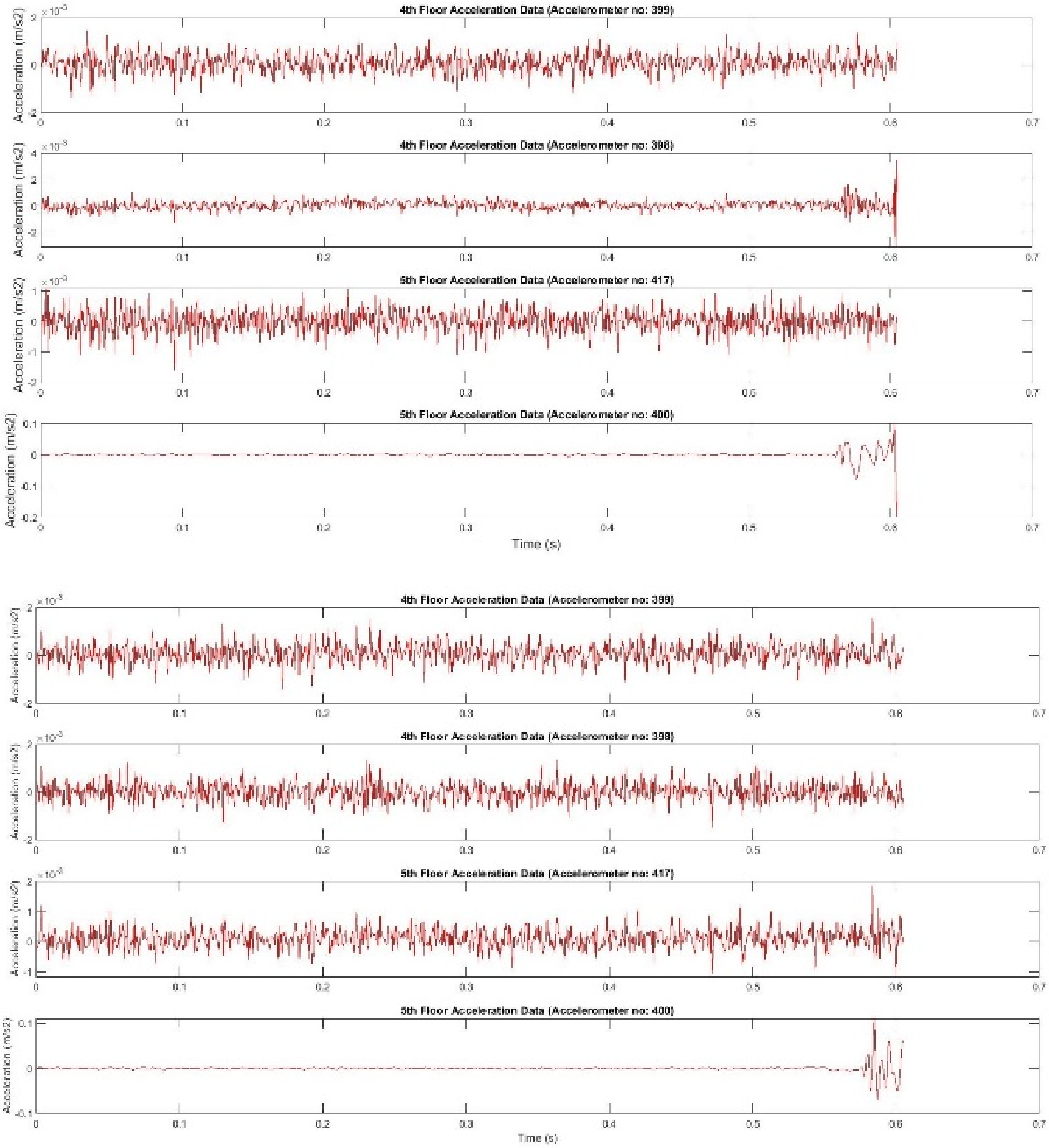


Figure 8 Continuous Data Acquisition through Developed LabVIEW® GUI Code


4th Floor Acceleration Data (Accelerometer no: 399)

4th Floor Acceleration Data (Accelerometer no: 398)

5th Floor Acceleration Data (Accelerometer no: 417)

5th Floor Acceleration Data (Accelerometer no: 400)

4th Floor Acceleration Data (Accelerometer no: 399)

4th Floor Acceleration Data (Accelerometer no: 398)

5th Floor Acceleration Data (Accelerometer no: 417)

5th Floor Acceleration Data (Accelerometer no: 400)

Figure 9 Recorded Forced Vibration Data at 4th and 5th Floor Levels of the Resistoflex Building

### 3.6 Government Lalla Ded Hospital Additional Block Project, Srinagar, Jammu and Kashmir

This is an ongoing G+6 story building project at Srinagar, the summer capital of Jammu and Kashmir. The project was approved in 2017 under the Jhelum and Tawi Flood Recovery Project (JTFRP). This is a critical infrastructure project in Seismic Zone V of India; hence, the World Bank has recommended the use of base-isolation technology and funded the project. When completed, the project will stand as a groundbreaking endeavour in the Jammu and Kashmir region. The functioning of the additional block is anticipated to boost the hospital's capacity from 500 to 900 beds. Under the design stage, the lead-rubber bearings at around 41 locations are proposed to be used to base-isolate the additional block structure. The LD hospital structure is located on the bank of the Jhelum river; thereby, in the event of a river flood, the hospital structure partly submerges into the flood water; hence, to avoid the immersion of base-isolators in flood situation, the level of base-isolation is proposed to be at first-floor level of the structure. The executing agency, Jammu and Kashmir Project Construction Corporation (JKPCC) is coordinating the activity. Endorsement to the design of the base-isolated structure is under process with the communicating author at IIT Delhi. The sectional elevation and numerical model of the additional block structure prepared for design purposes are shown in Figure 10.

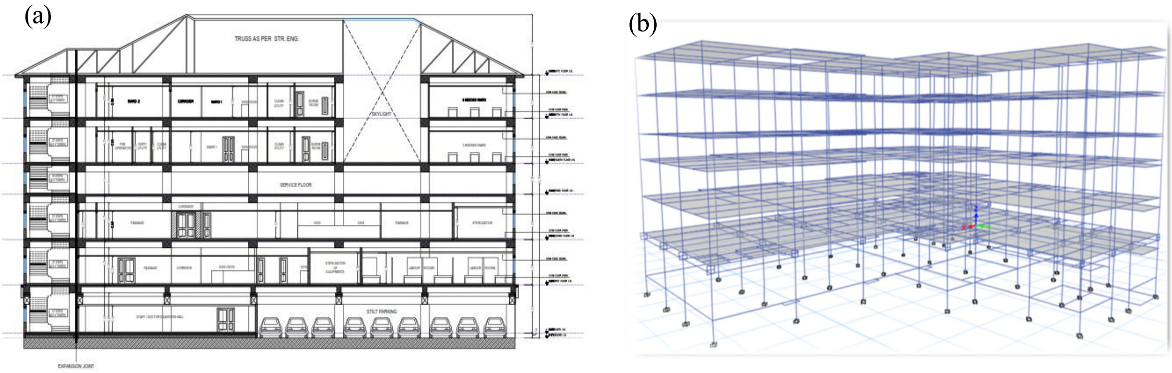


Figure 10 (a) Sectional Elevation and (b) Numerical Model of the LD Hospital Additional Block Structure

### 3.7 Guru Teg Bahadur Hospital Project, Shahdara, Delhi

Guru Teg Bahadur Hospital is a large hospital situated at Dilshad Garden, Shahdara, Delhi, India, and is affiliated with the University College of Medical Sciences, University of Delhi. The 500-bed new ward block with eight stories of RCC framed structure building includes a service basement and has a total floor area of 28,734 m$^2$. It is constructed using base-isolation technology to maintain its continuous functionality even after devastating seismic events. The new ward block structure caters to additional facilities for gynaecology and paediatric services. This additional ward is also connected at all floors with the existing ward block by providing a connecting corridor and ramp. The newly constructed ward also has green building features to make it an energy-efficient building, which improves the quality of the indoor environment. Figure 11 shows the image of the base-isolated hospital structure and a picture of the lead-rubber bearing being installed at the site.

Figure 11 (a) Images of Guru Teg Bahadur Hospital and (b) Lead-Rubber Bearing Installation at Site

### 3.8 Lok Nayak Jai Prakash Narayan (LNJP) Hospital Project, New Delhi

The Lok Nayak Jai Prakash Narayan (LNJP) Hospital, New Delhi, is a multispecialty hospital founded in 1930. As reported, the hospital gets a daily footfall of around 4,000 patients not only from Delhi but from neighbouring states as well, for example, Uttar Pradesh, Bihar, Haryana, Punjab, Rajasthan, Uttarakhand, and Himachal Pradesh. The newly constructed Outpatient Department (OPD) at the LNJP hospital has state-of-the-art facilities comparable with the established private multispecialty hospitals in Delhi. Base-isolation technology is implemented to ensure the continuous functionality of the hospital after earthquake events. Figure 12 shows the picture of LNJP hospital and one of the base-isolator units installed in the hospital structure.

Figure 12 (a) LNJP Hospital Structure and (b) Installed Base-Isolator Unit in the Hospital Structure

### 3.9 Walker Military Hospital Project, Shimla, Himachal Pradesh

The famous Walker Military Hospital, Shimla, Himachal Pradesh, was gutted in an unfortunate fire event in 1998. As it was a wooden structure, the blaze spread quickly, leaving little scope to control the fire. The entire building was engulfed in flames as the thick coating of paint applied to the wood elements made the structure more inflammable. The reconstruction of the 100-bed five-storey hospital was planned while implementing the base-isolation technology and installation of lead-rubber bearings, which makes the hospital structure one of its kind in the state of Himachal Pradesh. Figure 13 shows the model of the planned 100 bedded base-isolated Walker Military Hospital structure.

Figure 13 Model of the Planned 100-Bedded Base-Isolated Walker Military Hospital Structure

### 3.10 Cancer Hospital Projects, Assam

As reported, the Assam Cancer Care Foundation (ACCF) is a joint partnership between the Government of Assam and Tata Trusts. It was set up in December 2017 to create a first-of-its-kind, three-level cancer grid in the state. With a plan to set up 17 cancer hospitals in the state, it is the largest cancer care network in South Asia. The distributed care model was conceptualized by the Trusts and the Government of Assam to create patient-centric cancer institutions to deliver standardized and affordable care closer to patients' homes. The ACCF is expected to benefit 50% of cancer patients in Assam. Most of the part of Assam state falls under a seismically active region, and hospitals are lifeline structures. It is important to safeguard them from the devasting effects of earthquakes; hence, utilization of seismic base-isolation technology is the best fit here. Triple-pendulum base-isolator units are installed in the eight number of completed base-isolated hospital structures as of now at Barpeta, Tezpur, Dibrugarh, Lakhimpur, Jorhat, Darrang, Kokrajhar, and Silchar in the state of Assam. The base-isolator units are designed, manufactured, and supplied by M/s Earthquake Protection Systems (EPS), California, USA. The structural design and construction work of the hospital structures is taken up by the Engineering Design and Research Centre (EDRC) wing of L&T and L&T Construction, respectively. The activity of endorsement of the structural design of the base-isolated hospital structures is facilitated by IIT Madras. Figure 14 shows some of the photographs during construction and after completion of the hospital structures at Dibrugarh and Tezpur.

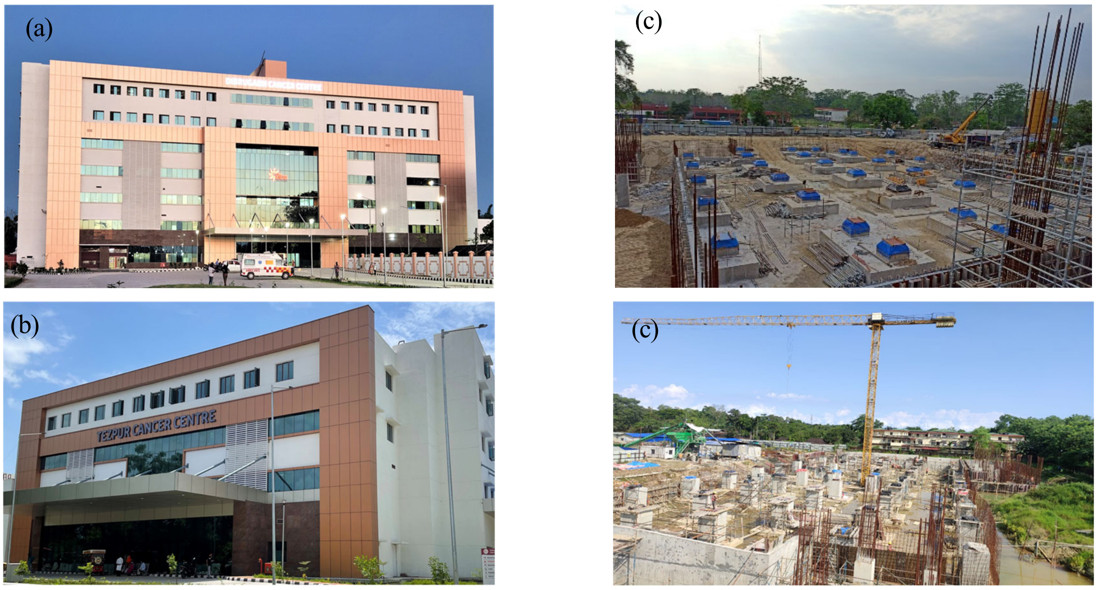


Figure 14 Photographs of the Hospital Structures at (a) Dibrugarh, (b) Tezpur, and (c) During Construction Images

### 3.11 Ireo Business Park Project, Gurugram, Haryana

A 2B+G+6 storied business park structure at Gurugram, Haryana, is a commercial building developed by Ireo Private Limited, Gurugram. The built-up area of the commercial building structure is around 92,903 m$^2$ in plan. The structure primarily contains office spaces and is mainly utilized for commercial activities. Commercial building structures are the places that a significant population visits every day for multiple reasons, such as for employment, important meetings with the senior team, or socializing with colleagues. These spots are important for those who would like to increase their current business operations or begin a new one. Uninterrupted operations of the commercial structures are always anticipated; hence, base-isolation technology is adopted to safeguard the Ireo Business Park structure from uncertain earthquake events. The commercial building structure is constructed using precast construction technology and is supported on 258 DCFPBs located at the upper basement level. The isolator units are designed, manufactured, and supplied at the site by HIRUN International Company Limited, Taiwan. Figure 15 shows some of the photographs of the Ireo Business Park building during and after the construction stage.

Figure 15 Photographs of the (a) Ireo Business Park, Gurugram and (b) Isolator Units and its Installation

### 3.12 Shrem Fairmont Airport Hotel Project, Mumbai, Maharashtra

A premium luxury hotel and commercial building project (3B+G+11) of the Shrem Group is under construction in Mumbai, Maharashtra. The Shrem Group is a developer in hospitality, real estate and infrastructure. The developer has specific project requirements with a focus on high customer comfort and safety standards. Due to increased vibration activities in the metropolitan area and in view of the mission to increase comfort, the developer demanded the use of base-isolation technology to mitigate the local vibrations and protect the structure from unforeseen earthquakes. The building has been under construction as a composite structure since 2018, and its completion is planned for 2024. GERB Vibration Control Systems Pvt Ltd, NOIDA, India, has taken up this project to design, manufacture, and supply the base-isolators. Around 515 steel spring element base-isolators are installed at the upper basement level of the structure, having 92,903 m$^2$ plan area. As of now, most of the major construction activities of the building have been completed, and finishing work is in progress. Figure 16 shows some of the details of the Shrem Fairmont Airport Hotel Project.

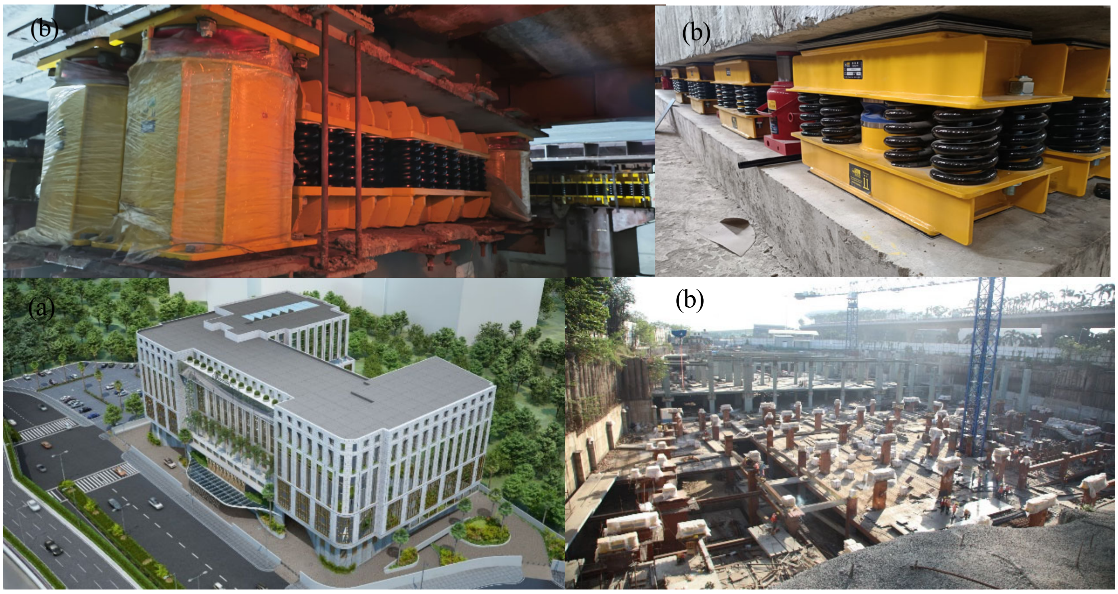


Figure 16 Details of the (a) Proposed Shrem Fairmont Airport Hotel Project and (b) Isolator Units and its Installation

## 4. CONCLUSIONS

Details of some of the critical base-isolated building structures that are functional and under construction are provided herein in this document. Application of base-isolation technology is slowly taking pace in India, especially in the healthcare industry. There is still enormous potential for adopting this technology in residential, commercial, and industrial structures. It is envisioned that due to the availability of Indian standards for the design of base-isolated buildings and an increase in awareness about the financial and other benefits offered by base-isolation technology, the Indian construction industry will adopt this technology more effectively and comfortably, especially in the seismic zones of high severity.

## 5. ACKNOWLEDGMENTS

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# SEISMIC ISOLATION IN TÜRKİYE

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## ABSTRACT

This paper provides a brief survey of the current state and the challenges faced in seismic isolation applications. The utilization of the technique of seismic isolation for new structures and retrofit of existing structures is developing at a high rate in the country. A new seismic isolation design code for buildings is prepared. As of 2023, there are about 200 structures (constructed or under construction) with seismic isolation. The list includes hospitals, buildings, airport terminals, LNG storage tanks, bridges and viaducts, sports arenas, and schools. Most of the recent activity seems to have focused on viaducts and hospital buildings as the Ministry of Health made it mandatory to use seismic isolation for public hospitals in the high earthquake hazard zones of Türkiye. After the recent earthquakes, the interest and demand in seismic isolation applications have substantially increased. The training of engineers for the proper use of seismic isolation techniques is needed for the healthy development of applications.

**KEYWORDS:** Türkiye, Earthquake, Isolation, Codes

## 1. INTRODUCTION

Earthquake is a threat to human lives and assets. Population growth and increasing urbanization in earthquake-prone areas suggest that earthquake impacts on human populations will continue in the coming decades. Although, seismic design codes have been successful in controlling the damage to structures, and in provision of life safety, the non-structural and business losses kept increasing. In most buildings (especially the museums) the contents are generally more costly and valuable than the buildings themselves. The post-earthquake operational continuity of hospitals, communication centers, poliçe, and fire stations and other critical facilities needs to be ensured. Conventional construction techniques that can protect the structure itself, may result in very high floor accelerations that damage non-structural components and contents. As such, the use of seismic isolation techniques is needed to ensure "fully operational" performance.

Türkiye has suffered a high amount of casualties and loss of property due to earthquakes over many centuries. The seismic isolation technology has been applied at an accelerated pace for earthquake protection after the 1999 Kocaeli Mw7.4 Earthquake. Today, there exist about 200 structures (constructed or under construction) with seismic isolation, including hospitals, schools, airport terminals, storage tanks, bridges, viaducts, and sports arena. Most of the recent activity have focused on hospital buildings (Erdik et al, 2015). In 2017, Engineering News Record (ENR)

selected the largest 10 base isolated buildings in the world (https://www.enr.com/articles/42366-the-10-largest-base-isolated-buildings-in-the-world). The ranking was based on the total closed floor area. Three of these largest base isolated buildings are located in Türkiye.
These developments on seismic isolation also necessitated the preparation and enforcement of a national official design code for seismic isolation applications on buildings in 2019.

The 2020 Elazığ earthquake and the catastrophic February 6, 2023 earthquakes served as a test of the performance base isolated hospitals and indicated the problems associated with the state of applications. These earthquakes also served to increase the interest and demand in seismic isolation applications. With a current number of qualified engineers, it is difficult to meet such a demand. The training of engineers for the proper and correct utilization of seismic isolation techniques, as well as licensing, needs to be considered for the healthy development of applications.

## 2. OVERVIEW OF THE SEISMIC ISOLATION IN TÜRKİYE

The status of the seismic isolation applications in Türkiye is documented sevearal publications (e.g. Yenidogan et al. (2014), Erdik et al. (2015, 2018), Erdik (2015, 2017 and 2019) and Sadan (2023). The following overview represents a summary of these papers.

The total number of seismic isolation applications in Türkiye, especially for hospitals, has significantly increased after the 1999 Kocaeli and Düzce and 2011 Van earthquakes, where, a large number of hospitals were damaged beyond repair and have led the Turkish Ministry of Health to enact a regulation in 2013 to enforce that the "Hospital Buildings, located in seismic zones 1 and 2 with a number of bed capacity over 100 should be constructed with base-isolation".

As of 2021, there are 102 isolated structures in Türkiye, of which 65 are hospitals, 8 are bridges, and 3 are industrial facilities (Figure 1) encompassing about 45,000 isolation units (Sadan, 2023). Most of these seismic isolation applications for hospitals involve large buildings encompassing isolation units in the order of 1000. About 60% of these isolation units were curved surface friction and 40% were elastomeric type.

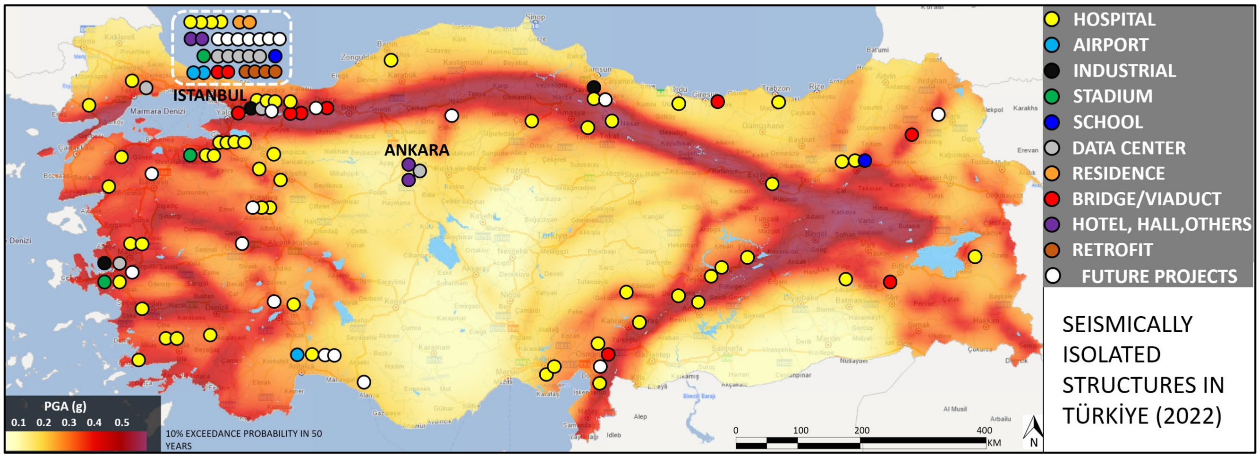


Figure 1. Distribution of the seismically isolated structures in Türkiye (After, Sadan, 2023)

The isolated structures include the Adana Integrated Health Campus which houses 1,550 beds in four building units supported by 1,512 base isolators (Figure 2a). The 790,000 square meter, 2,354-bed Başakşehir Health Campus hospital complex sitting on 2040 isolator units, is currently the largest base-isolated building in the world (Figure 2b). Başıbüyük Training and Research Hospital in İstanbul was retrofitted with seismic isolation (Figure 3a) and currently represents the largest hospital in the world, retrofitted with seismic isolation. The hospital complex is composed of sixteen 2-13 story blocks with a total area of 113.000 meter square and a 750-bed capacity. Recent seismic isolatiıon applications also involve residential/commercial building complexes, such as the Mavera Comfort Apartments, with 16 isolated apartment blocks covering 170,000m2 and encompassing 454 lead rubber isolators (Figure 3b). In addition to numerous bridges and viaducts, there also exist exemplary seismic isolation applications for historical buildings, liquid storage tanks, and jetties.

Figure 2. (a) Adana Integrated Health Campus and (b) Başakşehir Health Campus

Figure 3. (a) Başıbüyük Training and Research Hospital and (b) Mavera Comfort Apartments

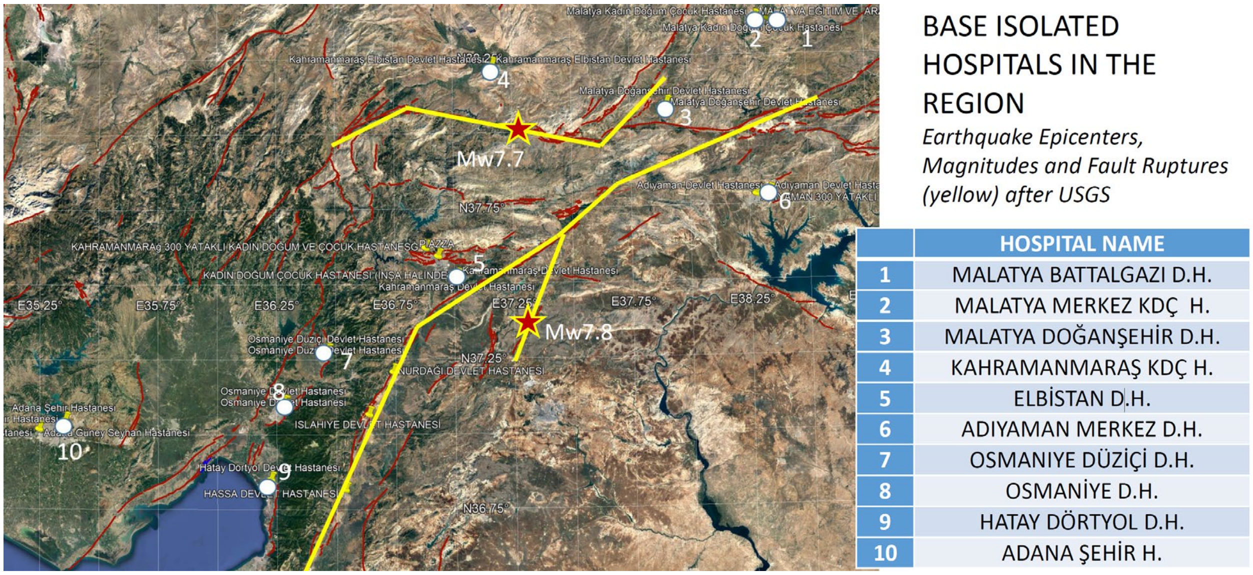
The Turkish Association for Seismic Isolation (TASI - https://did.org.tr/en/) was founded in 2006 with a mission of increasing the awareness and applications of seismic isolation technologies to mitigate earthquake losses. TASI is a member of ASSISi (Anti-Seismic Systems International Society) and has established strong ties with other sister organizations, especially with the Japanese Society of Seismic Isolation (JSSI). The ever-increasing efforts of TASI include several national and regional conferences including the 10th ASSISi World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures held in Istanbul in 2007 and the recent (Nov. 2023) 18th World Conference on Seismic Isolation (18WCSI) in Antalya.

In response to the advances in seismic isolation technology and the increased number of seismic isolation applications, TASI prepared a guideline (TASI, 2008) entitled "Seismic Isolation Design Code for Buildings", which was adopted by the Istanbul Seismic Risk Mitigation and Emergency Preparedness Project (ISMEP, www.ipkb.gov.tr) for the seismic isolation design of new and retrofitted hospitals. In 2018, a design code on Seismic Isolation Design for Building Structures, essentially based on ASCE 7-16 (2016), is prepared by a committee consisting of academicians and professional engineers. The code considers 475-year (DBE-Design Basis Earthquake) and 2475-year (MCE-Maximum Credible Earthquake) ground motion levels for the seismic isolation design. The analysis methods of (a) Equivalent Lateral Force (ELF), Mode Superposition, and Nonlinear Time History Analysis are to be used depending on the properties of the building and isolation system. The code considers different performance objectives of Continued Functionality and Limited Damage / Immediate Occupancy at different earthquake ground motion levels.

Türkiye's first full-scale dynamic seismic isolator testing facility, ESQUAKE was established on the premises of Eskisehir Technical University in 2018. The testing capacity of ESQUAKE accommodates Static Vertical Load of 20,000kN, Dynamic Vertical Load of 15,000kN, Horizontal Load of 2,000kN, Displacement of ±60cm, and Velocity of 1m/s.

There exist several facilities in Türkiye that produces elastomeric and curved surface friction type isolation units. Among them, TIS (tis.com.tr/en/seismic-isolation) has provided seismic isolation units for 64 projects at home and 32 projects abroad.

## 4. PERFORMANCE oOF THE ISOLATED HOSPITALS IN FEB.. 6, 2023 EARTHQUAKES


BASE ISOLATED HOSPITALS IN THE REGION

*Earthquake Epicenters, Magnitudes and Fault Ruptures (yellow) after USGS*

| | HOSPITAL NAME |
|---|---|
| 1 | MALATYA BATTALGAZI D.H. |
| 2 | MALATYA MERKEZ KDÇ H. |
| 3 | MALATYA DOĞANŞEHİR D.H. |
| 4 | KAHRAMANMARAŞ KDÇ H. |
| 5 | ELBİSTAN D.H. |
| 6 | ADIYAMAN MERKEZ D.H. |
| 7 | OSMANİYE DÜZİÇİ D.H. |
| 8 | OSMANİYE D.H. |
| 9 | HATAY DÖRTYOL D.H. |
| 10 | ADANA ŞEHİR H. |

Figure 4. Isolated Hospitals in the February 6, 2023 Earthquake affected region (Erdik, 2023b)

On Feb. 6, 2023, a magnitude Mw7.8 earthquake struck in south-central Türkiye, followed by a magnitude Mw 7.7 event about 9 hours later. M7.8 earthquake that ruptured more than 300km fault with fault offsets more than 8m. The death toll from the Türkiye earthquakes has reached 50,783, with more than 107,204 injured and 297 missings. At least 15.73 million people and 4 million buildings were affected, 345,000 buildings were destroyed and more than 2 million residents in the affected provinces were evacuated to nearby provinces. The earthquakes caused about $103.6 billion of direct damage (Erdik et al, 2023a). The Feb. 6 earthquakes affected 10 base isolated hospitals in the region as illustrated in Figure 4.

With the exception of Doğanşehir (#3) and Elbistan (#5) Hospitals, all other hospitals have posed to earthquake ground motion with isolation system displacement demands less than 20% of the available capacities. This percentage was 85% and 50% respectively for the Doğanşehir (#3) and Elbistan (#5) Hospitals (Erdik, 2023b). As reported in TASI (2023), among these hospitals, Battalgazi (#1)\ Elbistan (#5), Hatay (#9), and Adana (#10) hospitals provided continued functionality with some minor non-structural damages. Kahramanmaraş (#4) Adiyaman (#6) Düziçi (#7) Osmaniye (#6) under construction and not open to service. There was extensive Non-Structural damage in Doğanşehir (#3) and Malatya Merkez (#2) hospitals mostly due to improper detailing of the nonstructural elements, constructional problems and blocked seismic gaps (moats) and their cover plates. The damaged non-structural elements included cladding, partition walls, ceilings, mechanical/electrical equipment, utility distribution systems, medical equipment, and other furnishings.

## 5. CHALLENGES IN SEISMIC ISOLATION OF STRUCTURES

The number of seismically isolated structures is increasing yearly in Türkiye. Although the superior earthquake performance of seismically isolated structures over the conventionally built ones is known, the developers still consider the isolation system as a cost-increasing application. This understanding needs to be rectified.

Currently, the seismically isolated building design is more controlled compared to the conventional ones because of the mandatory peer review system. However, apart from the BSc degree in Civil Engineering no further qualification is needed for the designer and the the peer review system is only concerned with code conformity issues. In the absence of a professional engineering system in the country, the training of engineers for the proper and correct utilization of seismic isolation techniques, as well as their licensing, needs to be considered for the healthy development of applications. It is further believed that a thorough peer reviewing system is essential and eventually, the design process needs to be transformed into a professional engineering undertaking.

In general, it should be kept in mind that the appropriate use of seismic isolation technology requires adherence to the following points. Otherwise, the seismic safety of the isolated structure may possibly be lower than that of the conventional one.
1- A rational and functional architectural design.
2- A reliable assessment of the design basis ground motion, particularly in near-fault conditions (e.g. Erdik et al, 2023a)
3- A dependable, robust, and resilient design to ensure post-earthquake functionality.
4- A careful selection, design, manufacturing, testing, installation and maintenance of the seismic isolation units,
5- A good construction implementation for both structural and non-structural elements, with proper quality assurance and control.

As evidenced by the inadequate earthquake performance of some of the isolated hospitals to provide continued functionality in the February 6 earthquakes, there exists ample room for the further development of these points in Türkiye.

The logistical challenges for the seismic isolation applications encompass the following issues.
1- Although the isolator production in the country is developing, their generally inadequate production capacity leaves room for the import of isolators from foreign manufacturers with associated timing and cost problems.
2- Lack of knowledge, in developers, contractors, and engineers, on the selection, procurement, testing, and installation stages of the seismic isolation process results in delays in the construction schedule.
3- The highly limited number of in-country testing facilities, with the capability to provide real-time testing to large-scale isolators, necessitate resting in other countries with inherent scheduling and cost issues. Furthermore, the testing process requires the preparation of official regulations concerning the selection and licensing of testing facilities.

## 6. PROSPECTS IN SEISMIC ISOLATION OF BUILDINGS

### 6.1 Base Isolated Modular Construction

Essentially all of the isolated buildings in Türkiye cast-in- place R/C structures. The isolation plane is located above the foundation at the basement and the isolator distribution follows and matches with the distribution of columns and the shear walls, thereby unreasonably increasing the number of isolation units used in the seismic isolation system. Yet, the current trend in the world is the reduce the the number of isolation elements through structural design and also through the use of precast/prefabricated/modular building elements.

It is expected that the use of base isolated modular construction will serve to realize high speed and low cost constructions for mass housing, dormitories, schools, and hospitals. Most conventional modular buildings around the world are built as a system of modules that are eventually connected laterally to a cast in-situ or prefabricated core that serves as the primary lateral load resisting element. To form the building, the prefabricated modules can be stacked strategically to resist the lateral loads, to enable the load transfer between modules in both horizontal and vertical directions, bolted plates can be used. The main benefits and features of modular building units (modules) are:
- The modules can be designed to encompass all essential components of a building (i.e. utility and elevator shafts, stairs, corridors)
- The modules are constructed in a quality controlled production facility and can include piping, cabling, and kitchen and bathroom equipment.
- The modules can easily be removed for reuse.

The seismic behavior of precast buildings depends on the characteristics (i.e., strength, stiffness, ductility, and deformation capacity) of the connections between the precast structural members and the foundation. One of the reasons of the inadequate performance of precast buildings in past earthquakes has been poorly designed and/or poorly built connections.

Using base isolation, the assembly of prefabricated modules alone could be used as a structural system to realize a structurally feasible low-cost construction. As a result, the structure would not require a structural core and can behave as a purely modular system. The isolators can be placed under the mat foundation in an optimum number and distribution. Seismic base isolation, utilized in precast or modular buildings, will have the potential to reduce the ductility demand under seismic loading, thus making it possible to design and build them with better seismic performance. Furthermore, the low period of vibration associated with modular structures allows for a wide separation of fixed base and isolated periods thereby ensuring the full benefit of seismic isolation. An illustrative application of base isolated modular building construction is provided in Figure 5.

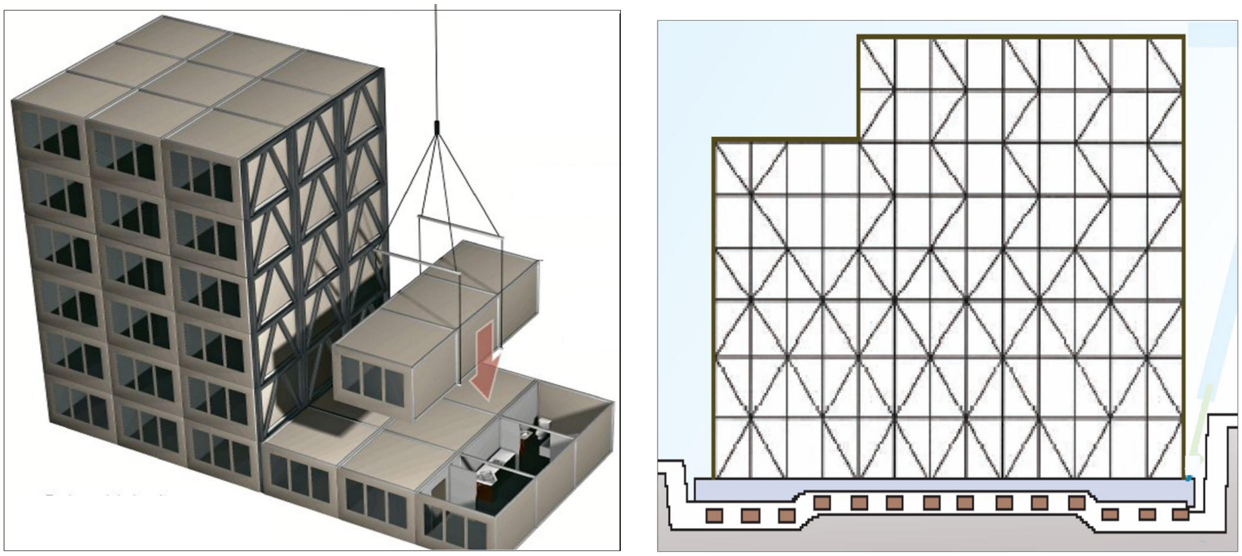


Figure 5. A schematic view of the Base Isolated Modular Construction

### 6.2 Low Cost Isolation Units

The developments in seismic isolation technology have led to several innovative isolation units. In this connection, Fiber reinforced elastomeric isolators (FREIs) were proposed as low-cost isolation devices for widespread utilization, especially for base isolated modular construction described above.

FREI bearings use generally carbon fiber mesh instead of steel plates used in SFRI (Steel Reinforced Elastomeric Isolator). They provide isolation using the same principle of having a low lateral stiffness as SREI bearings; however, the fibers have the advantage of decreased weight and cost, which could potentially broaden the uses of base isolation. Furthermore, due to the increased damping provided by the fiber strands, additional means to add damping to the system are not needed and the cost of production of FREI is much lower than SREI since no vulcanization process is needed. In addition, the performance of the FREI is shown to be superior to that of the SREI in view of the horizontal stiffness and vertical stiffness of the isolator and that it is possible to produce an FREI that matches the behavior of an SREI (Moon et al. 2002)

The concept of FREIs is promising. Since 1999, FREIs have been investigated extensively experimentally, analytically, and numerically, with all studies reporting favorable findings. The primary challenge for practical applications is the lack of a standard and comprehensive design guideline for FREIs. It is believed that increased application of FREIs will encourage manufacturers to enter the market (Van Engelen, 2019).

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# EXPERIENCE OF USING SEISMIC ISOLATION SYSTEMS IN RUSSIA

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## ABSTRACT

The main direction of seismic isolation systems and other dynamic seismic protection systems design are the adaptive systems and non-stationary systems (systems with switchable elements and dynamic parameters which could be changing during an earthquake), nonlinear systems and some combination of those and other systems. The article outlines practical methods for calculating and designing of seismic isolation of multi-story buildings for areas with 7-9 points seismicity. The systems presented in the article developed in and currently used in Russia are economically and socially efficient. They allow, compared with traditional designs, to increase the seismic reliability of structures, reduce the cost of anti-seismic measures, reduce damage from earthquakes, and clarify assessments of investment and insurance risks.

**KEYWORDS:** Base isolation system, Base isolated buildings, Response control, Isolator, Damper

## 1. PPINCIPLE and BRIEF HISTORY of SEISMIC ISOLATION DEVELOPMENT

Seismic isolation refers to structural mechanisms for reducing seismic impact on the part of the structure located above the foundation by installing any systems or elements between the part of the structure and the foundation. In contrast to traditional methods of seismic protection, which consist in increasing the strength of materials and cross-sections of structural elements and connections, seismic isolation is aimed at significantly reducing dynamic loads on structures.

The first attempts to seismically isolate buildings date back to around the third century AD. At the base of Central Asian minarets and a number of other buildings, ancient architects laid soft layers made of reed pillows and plastic clay as pliable elements.

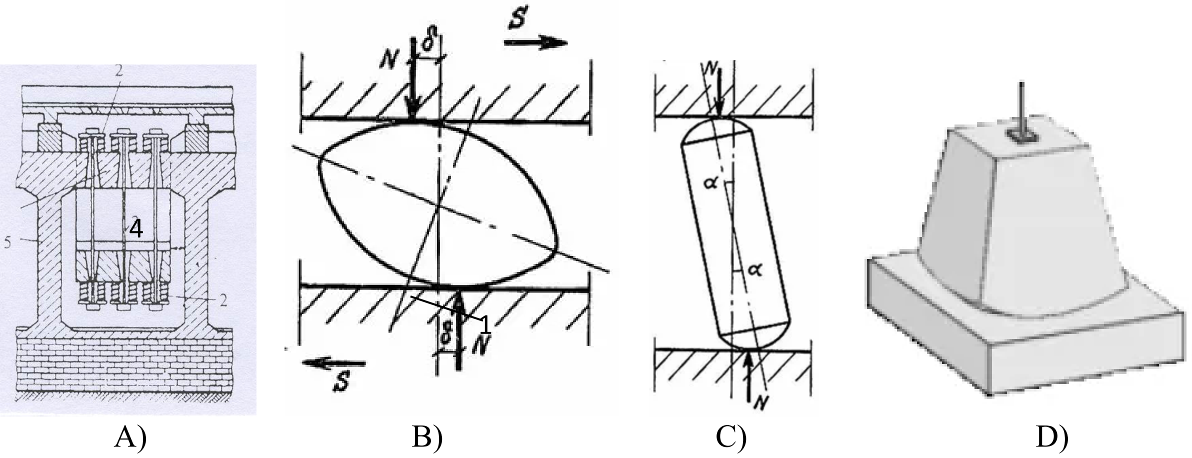
With the emergence and development of the theory of seismic resistance (1900–1925), considerable attention was paid to the problem of seismic isolation of structures. For example, in 1925 M. Viscordini described the designs of roller seismic isolation supports and support columns with spherical upper and lower ends. However, despite the clarity and simplicity of the idea of seismic isolation, it did not become widespread at that time, since the static method used at that time to assess the seismic resistance of structures made it difficult to assess the dynamic properties of the structure and did not allow to quantify the effect of seismic isolation.

Since the mid-1950s, there has been a widespread transition from the static to the spectral method of calculating structures for seismic impacts. When using this method, the seismic loads on the structure are first estimated, taking into account the dynamic properties of the structure, and then, within the framework of the d'Alembert principle, a static calculation of the structure for the effect of these loads is performed.

The dependence $\beta(T_j)$ ($\beta$ is the coefficient of dynamism that depends on the period of oscillations of the structure $T_J$ according to the j-th form) is called a “spectral curve” in the literature. This curve is constructed using data on the behavior of mass construction structures (residential and industrial buildings of medium rise with a relatively rigid structural scheme) during destructive earthquakes and has a clearly expressed monotonically decreasing character. Such a decreasing dependence was the basis for the construction of seismically isolated structures.

Attempts to seismically isolate individual buildings have been made since ancient times. The mass introduction of seismic stress reduction systems into practice should be attributed to the 70s of the twentieth century. One of the pioneers in the field of seismic isolation in construction was Russia and the USSR.

In 1959, in Ashgabat (Turkmenistan, USSR), a house with an earthquake-insulated foundation was built for the first time according to the project of engineer F.D. Zelenkov. The house had a strong frame foundation, to which a system of beams was suspended on metal rods, which were supporting elements for a 4-storey building (Fig. 1).



A) B) C) D)

Figure 1 A)Cross-section of a reinforced concrete frame-seismic shock absorber of a building in Ashgabat: B,C,D) Different type of Kinematic supports types

The regular systems of the Russian domestic seismic insulation were developed at the V.A. Kucherenko Central Research Institute starting from the late 50s. In the 1980s and 1990s, seismic isolation systems began to be used in the United States, Japan, and New Zealand; in the first years on single objects, and after the earthquakes in Kobe (Japan) in 1995 – on a massive scale in the above-mentioned countries, as well as in Italy, China, and other countries.

Over the past 30 years, seismic isolation has become quite widespread in our country and abroad in the construction of not only buildings, but also such critical structures as reservoirs, bridges, dams, airports, stadiums.

In Russian practice, there are more than a dozen implemented types of seismic isolation devices. However, the introduction of seismic isolation systems into the practice of earthquake-resistant construction did not have an appropriate theoretical basis. As a result, buildings with flexible (seismic-isolated) lower floors collapsed during the earthquakes in Scopla, Bucharest and Mexico City. To a certain extent, this limited the spread of seismic isolation and prompted the start of serious research in this area. As a result of the research carried out in recent decades, the concept of earthquake-resistant construction of seismically isolated buildings has been formed, the main provisions of which are as follows.

1) Seismic isolation provides a significant reduction in inertial loads on the structure, but at the same time there are significant mutual displacements of the seismically isolated parts of the structure. These displacements can reach 0.5 m or more. Such displacements can lead to the destruction of the supporting elements or the fall of the structure from them, and eventually to its complete collapse. As a result, when assessing the seismic resistance of seismically isolated structures, their kinematic calculation, i.e. the determination of mutual displacements of seismically isolated parts of the structure, becomes decisive.

2) Evaluation of the kinematic characteristics of seismic isolation requires the correct setting of the design impact, in particular, distortions of the calculated accelerograms in the long-period region must be excluded. Such distortions are present in most known records, and their use makes the calculation results random and gives an erroneous impression of the seismic resistance of the structure.

3) In order to limit the mutual displacements of the seismically isolated parts of the structure, it is necessary to install damping devices between them.

This concept is the basis for the design and use of effective seismic isolation systems in earthquake-resistant construction.

## 2. BRIEF OVERVIEW of SEISMIC INSULATION SYSTEMS of BUILDINGS and STRUCTURES

At present, dozens of monographs of scientists and hundreds of articles on seismic isolation of buildings and structures have been published in Russia. A detailed classification of seismic isolation devices is given in the works of Y.M. Eisenberg, I.G. Horowitz, T.Zh. Zhunusov, L.Sh. Kilimnik, G. Mtsverri, V. Robinson, O.A. Savinov, T.A. Sandovich, R. Skinner, V.I. Smirnov, A.M. Uzdin, Y.D. Cherepinsky, V.G. Yaremenko. The analysis of seismic insulation systems of bridges is also available in the reviews of I.O. Kuznetsova and Z.G. Khuchbarov. Therefore, this review provides only a brief classification of seismic isolation systems according to the principle of their operation during an earthquake and, accordingly, according to the type of equations describing the behavior.

All seismic isolation systems are divided into stationary and adaptive. Stationary systems retain their elastic-damping characteristics in the process of oscillations, while adaptive systems change their parameters, adapting to the loading regime (seismic action). For adaptive systems, there are no nonlinear steady-state modes of motion and it is impossible to construct an amplitude-frequency response (AFR). In contrast to adaptive systems, steady-state modes of oscillation are possible for stationary systems and the corresponding methods for analyzing the equations of motion, in particular, the construction of frequency responses, are applicable.

Stationary seismic isolation systems can be divided into systems with and without restoring force. The last type of seismic isolation is carried out by the arrangement of a seismic isolation sliding belt (seismic belt). In these systems, a load exceeding the friction force in the seismic belt cannot be transmitted to the seismically isolated part of the structure. Systems with a seismic isolation sliding belt have two features from the point of view of their design. Firstly, significant residual displacements are possible between the seismically isolated parts of such systems, and their assessment is one of the tasks of the structure calculation. Secondly, the system of differential equations describing the behavior of the structure is special because the determinant of the stiffness matrix of the system is zero. This circumstance must be taken into account when decomposing the equations of motion into forms of vibrations.

The structures of the seismic isolation belt have been proposed by many specialists, but they have been studied in the most detail in the works of L.Sh. Kilimnik, L.A. Soldatova and V.P. Chudnetsov. According to their proposals in the 1980s-1990s. Several seismically isolated buildings were built in Bishkek (Kyrgyzstan) and Petropavlovsk-Kamchatsky. On the basis of these research and developments, the V.A. Kucherenko Central Research Institute prepared recommendations for the construction of a seismic isolation sliding belt in civil engineering.In turn, seismic isolation systems with restoring force are divided into elastic and gravitational. In the former, the restorative force is the elastic force, and in the latter, the force of gravity.

Seismic insulation foundations on elastic supports are widely used in construction practice. These include buildings with flexible underfloors that have been massively damaged by earthquakes, as well as buildings with rubber supports. Rubber supports are currently the main seismic isolation elements used in Russia and in the world. Seismic isolation with the use of elastic seismic isolation supports is the simplest and most developed, and its use with the correct selection of system parameters is quite effective.

Seismic isolaton foundations based on kinematic supports of the gravity type (KS) are proposed by a number of authors. The use of such foundations is typical for Russia and the CIS countries. The most famous in this field are the kinematic supports of V.V. Nazin, A.M. Kurzanov, Y.D. Cherepinsky (Fig. 1 B,C,D). Buildings on such supports were built in Petropavlovsk-Kamchatsky, Navoi, Yuzhno-Sakhalinsk, Sochi and other seismically dangerous regions of the CIS countries, but the most significant disadvantage of the operation of such foundations is the uneven loading of supports. In the patent literature there are more than a hundred proposals for the construction of gravitational kinematic foundations. Such an abundance of proposals is explained by the fact that a change in the rolling surface of the supports of such a foundation can lead to a change in the dynamic characteristics of the system as a whole, and, accordingly, to a new technical solution. This review provides a detailed classification of gravity-isolating seismic foundations (Fig. 2) and their general characteristics.

At the suggestion of V.T. Yaremenko, gravitational seismic isolation foundations are divided into suspended and supporting. In suspended foundations, the building is installed on the upper foundation slab, which is suspended on rods from the frame structure, rigidly connected to the lower foundation slab. This type of foundation includes the above-mentioned seismic isolation foundation by F.D. Zelenkov (Fig. 1 A). In support foundations, the upper foundation slab rests on kinematic supports. The general equation of motion of a building on kinematic foundations with an arbitrary skating surface was obtained by A.M. Uzdin, A.A. Dolgoy and A.N. Gunchev. Some special cases of motion of structures on kinematic supports are considered in the articles by B.N. Kvasnikov and S.N. Kouzakh.

From the point of view of the type of equations of motion of the system, the behavior of the structure near the resting position is important. A building on free supports can be described by linear equations with small oscillations, but in the case of jammed supports, such linearization is in principle impossible. All jammed supports can be divided into two types – positive and negative stiffness.

For the first time, the mass construction of buildings with seismic isolation systems in the form of switch-off elements and stops of movement limiters was carried out in the late 70s during the construction of the Baikal-Amur Mainline. An entire city of railroad workers, 82 buildings in total, was built up with earthquake-insulated buildings (Fig. 2).

Figure 2 Earthquake-isolated large-panel houses in Severobaikalsk with metal switchable elements.

Seismic insulation with the use of flexible supports (reinforced concrete or metal posts or frames) in the lower floors, with switchable energy-absorbing elements in the form of reinforced concrete diaphragms, with metal switchable elements, with stops-limiters of excessive displacements were developed by Prof. Y.M. Eisenberg, V.I. Smirnov and other students and collaborators (M.M. Deglina, H.N. Mazhiev, A.M. Melentyev, S.K. Uranova (Fig.2).

Systems with changing (self-adjusting) dynamic characteristics during an earthquake are adapted to seismic impacts through the use of special structural elements that increase the rigidity of the structure in the initial state and are switched off when a certain threshold level of seismic vibration amplitudes of the structure is reached. At the same time, all vertical loads from self-weight and seismic loads must be fully absorbed by the supporting structures of the structure in a state when the redundant rigid connections are switched off.

Seismic isolation with switchable braces contains: a rigid element - a stop, a displacement limiter (a tie panel, buttress or other rigid structure) and switchable elements. The basic idea of systems with switchable connections is that the switchable element is rigidly attached to the coupling element and to the main load-bearing structure (transom, floor, etc.), providing a rigid connection between the overlying floors and the foundation up to certain threshold values of seismic load and displacement. After these thresholds are exceeded, the switchable element is destroyed, and in the breaking limit, the connecting element plays the role of a damper.

The design embodiment of redundant switch-off elements can be different and is accepted depending on the required scheme of operation in the building and the fracture deformation diagrams. In the case of buildings with frame lower floors and with rigid upper floors, the role of switching links can be performed by:

- Weakly reinforced stiffening diaphragms with slots. Under horizontal seismic impact, cracks and inelastic deformations develop in the diaphragm piers;

- Metal plates with electric rivets welded to the stops of the movement limiters. In case of seismic impact, there is a step-by-step destruction of welded rivets (multiple changes in the periods of natural vibrations of the building in the process of seismic action);
- Metal plates with variable cross-section. The cross-section change is calculated for the appearance and accumulation of plastic deformations from cycle to cycle under seismic action with subsequent destruction;
- Metal rods that work only in tension. In this case, significant plastic deformations can develop in the switch-off elements, and the switch-off can occur repeatedly. It depends on the number of rods to be installed.

Depending on the design scheme and the height of the building, the switchable connections can be placed either horizontally or at the height of the building. After an earthquake, the backup elements of seismic isolation are restored to their original state.

## 3. SEISMIC INSULATION of BUILDINGS with the USE of KINEMATIC SUPPORTS

In Russia, the use of seismic insulation of buildings on kinematic supports is most widespread in two seismic regions of Siberia. In the Irkutsk region, 77 residential buildings were built for the period from 1984 to 2003, in the Kemerovo region - 15 houses were built for the period from 1997 to 2003. A diagram of seismic isolation in these buildings is shown in Fig. 3.

The Kinematic Support Element (KSE) is a truncated tetrahedral pyramid with a spherical lower part. At the bottom, the KSE rests freely on the support part, and at the top it is hinged to the overhead part. The hinged connection with the superstructure provides mobility in the horizontal plane in all directions. The swivel joint is made in the form of a binding anchor and a small square steel plate. The swivel joint is also a displacement limiter, as the binder creates an increasing resistance to the rotation of the KSE. The gravitational force that keeps the KSE in a state of stable equilibrium determines its horizontal stiffness and depends on the weight of the superfoundation structure, the height of the KSE, and the radius of curvature of the heel. The size of the KSE depends on the magnitude of the vertical load, the strength of the material and the intensity of seismic impact.

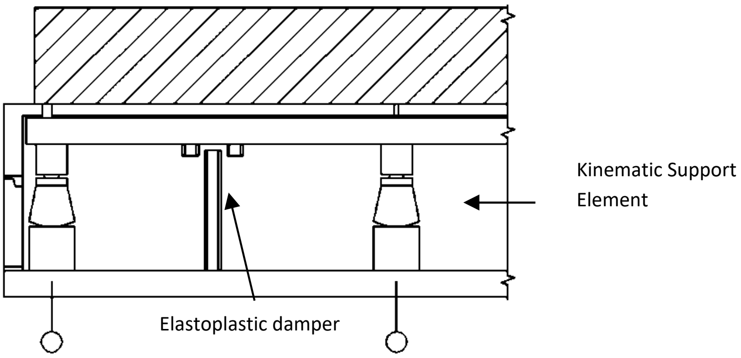


Figure 3 Diagram of the building on kinematic support elements

Most of the houses built in Russia on the KSE belong to multi-storey housing construction. For example, residential buildings in Irkutsk and Novokuznetsk (Fig. 4-5). Reducing seismic loads makes it possible to increase the number of storeys, improve planning solutions, and reduce the consumption of materials in structures. The installation of KSE in the basement allows you to create an open layout and place car parking.

Figure 4  Buildings on kinematic supports in Irkutsk

Figure 5  Building on kinematic supports in Novokuznetsk

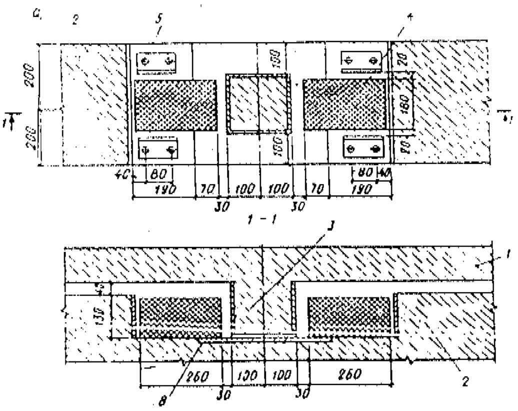


Figure 6  Design of Combined Sliding Supports

In the 1970s, other types of kinematic supports were proposed and applied. In Sevastopol, V.V. Nazin used supports in the form of columns with spherical ends. Later, these columns were improved in Kamchatka by Y.I. Bezrukov. A.M. Kurzanov proposed columns with flat ends and specific inclined displacement limiters.

Prof. S.V. Polyakov, Ph.D. L.SH. Kilimnik (TsNIISK) and Ph.D. L.A. Soldatova were engaged in the study and implementation of seismoinsulation systems - sliding supports using Teflon-stainless steel pairs.

An earthquake-insulating sliding belt is made in the form of a series of supports located between the foundation of the building and the above-ground structures, usually at the intersection of longitudinal and transverse walls (Fig. 6). Each support has two plates made of stainless steel and fluoroplastic-4. Due to the low coefficient of friction in the supports (f=0.05-0.1), when the inertial loads exceed a certain level, the building begins to slip relative to the foundation. From this moment on, the forces from seismic loads in the load-bearing structural elements practically do not change. To ensure the reliability of buildings, the system provides elastic and rigid limiters for horizontal and vertical movements.

Sliding supports, such as the one shown in Fig. 6, were used for buildings up to five storeys high.

## 4. APPLICATION of SEISMIC INSULATION in the FORM of RUBBER-METAL SUPPORTS in the REINFORCEMENT of BUILDINGS

The use of seismic insulation in the form of rubber-metal supports was carried out during the reconstruction of the building of the Central Bank of the Russian Federation, a historical and architectural monument built in 1934 in Irkutsk (Fig. 7).

Figure 7  The Central Bank of the Russian Federation in the Irkutsk Region

The structural solution refers to the so-called buildings with an incomplete frame. The load-bearing structures of the western and northern parts of the building are the exterior brick walls, the internal transverse walls and two longitudinal rows of brick pillars. In the central part of the building, the internal frame is made of monolithic reinforced concrete with circular columns (Fig. 8).

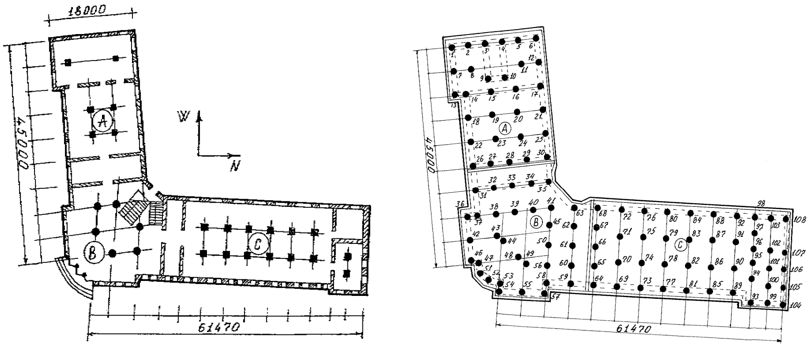


Figure 8  Plan of the first floor of the bank building. Location of seismic isolation supports in the building plan

In terms of its space-planning and structural solutions, the building materials used, the building did not comply with the current anti-seismic regulatory requirements. Taking into account the fact that the building is a historical monument and traditional methods of seismic reinforcement are not applicable, TsNIISK together with the specialists of Irkutsk Promstroyproekt developed and implemented a project to increase the seismic resistance of the bank. A total of 110 seismic poles were installed. Each pole is designed for a load of 2500 kN. All supports have the same dimensions: diameter 510 mm, height 216 mm.

It should be noted that this was the first and very successful experience in the installation of seismic insulation in the form of rubber-metal supports in a non-earthquake-resistant existing building.

Prior to the 1995 Kobe earthquake in Japan, more earthquake-insulated buildings had been built in Russia and the CIS than in any foreign country. Moreover, the seismic isolation systems developed by our specialists are inexpensive and easy to implement.

Statistics shows that the dynamics of the implementation of seismic protection in construction in Russia has slowed down, and the crisis phenomena of the 1990s and 2000s have had a negative impact on the use of seismic isolation. It should be noted that designers and builders have recently become interested in seismic insulation of buildings again.

Figure 9  Seismic isolated high rise Hotel (left) and Olympic university (right) in Sochi

Seismic isolation systems are actively introduced into the practice of earthquake-proof construction in Russia (Fig. 9). This is evidenced by many unique objects using seismic isolation systems. Their design and construction is conducted in the Russian Federation with the participation of specialists from the Research Center of Earthquake Engineering, which is the part of the Research Institute of Building Construction and Russian Association of Earthquake Engineering. Among such objects it is necessary to note the high-rise building  Akhmat-Tower in Grozny city (Chechen Republic) (Fig.10), "Kommunar" Cinema in Novokuznetsk (Fig.11) and others.

Figure 10  Seismic isolated hi-rise building in Grozniy city.

Figure 11  Seismic isolated building of Communar Theatre in Novokuznetsk city (left) and in process (middle)

Seismic isolation is used in cases: high-rise construction, historical monuments, unique structures of airports in Gelendzhik (Fig.12), Magadan, Yelizovo (Fig.13). After the publication of a new edition of the Russian codes, seismic protection systems have found application in medical, educational, and residential buildings. Standard solutions were developed for seismic protection of structures whose own seismic resistance is lower than the seismicity of the site.

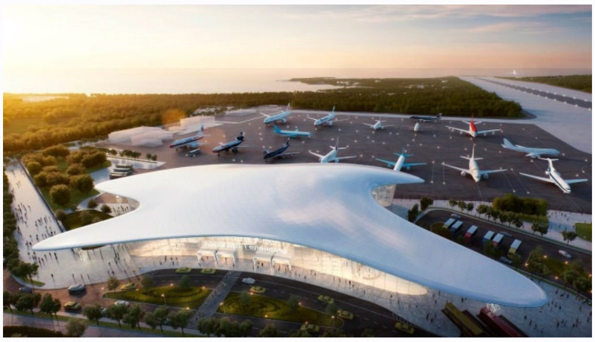


Figure 12  Gelendzhik airport building (LRB, sliders, Hysteretic dampers)

The building of the new city complex of Gelendzhik airport has overall dimensions in terms about 155.0 by 85.0 m. The height of the building is variable, near 25 meters. The structural scheme of the constructed airport complex is a mixed frame-wall with steel-reinforced concrete columns and a spatial structural coating. The structural scheme of the projected airport complex consists from located below the planning mark underground floor, pavilions inside the airport complex, the coating in the spatial structure form, supported by 9 internal columns (located inside the airport complex) and 4 external structural support elements and unique facade structures consisting of a set of inclined vertically oriented trusses.

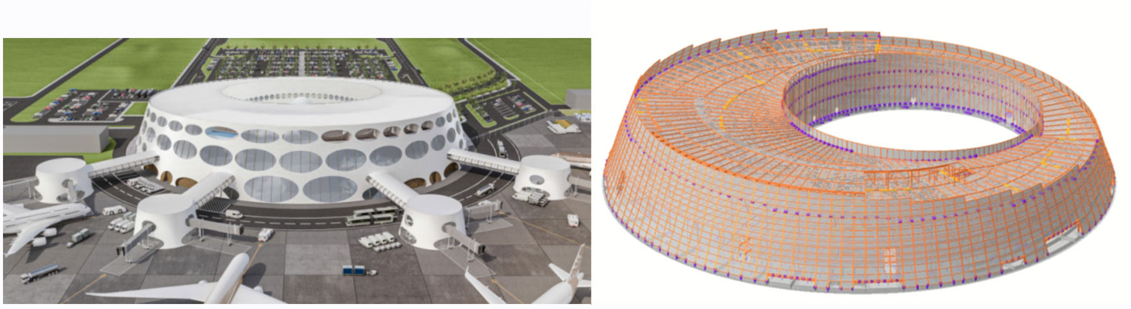


Figure 13  Elizovo airport building (Steel Hysteretic dampers, left)  and calculation model (right)

The building of the airport complex Elizovo in Kamchatka region has a round toroidal plan with a courtyard. The building has 2 3 floors in part floors in part 33-5, 4 floors in buildings part 23-10 (SPA area). The dimensions of the outer diameter of the building is about 173 m, the size of the inner diameter of the building is 88 m. The height of the highest elevation of the roof is 30.05 m. The Roof is covered with decorative lamellas.

The inclusion of damping devices in the structural system makes it possible to reduce the rigidity of the building and thereby reduce the value of the dynamism coefficient, shifting from the area of their increased values on the graph of the dynamism coefficient in the calculation of LSM (Spectral Method) and increasing the damping capacity of the entire system (Fig. 14).

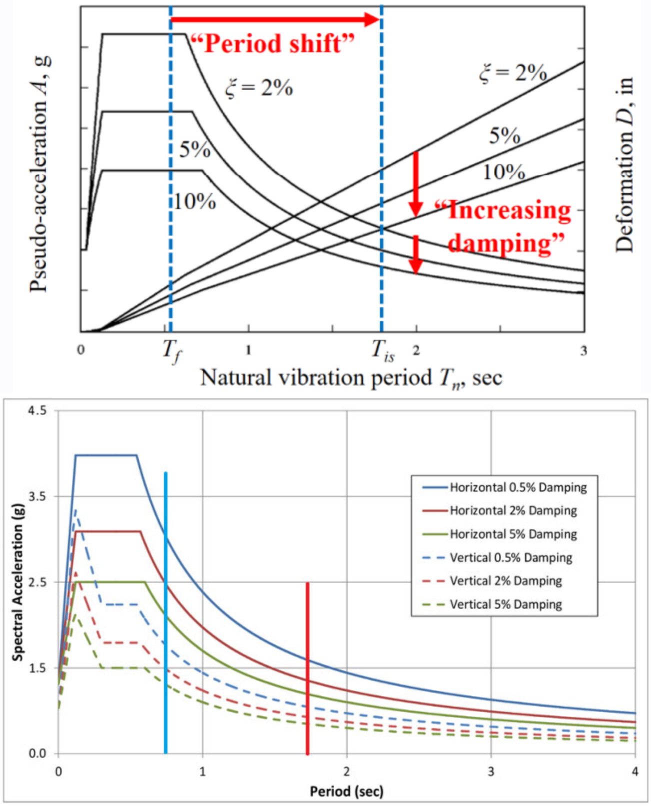


Figure 14 Damping effects in airport building.

Figure 15 School building in Sochi (dampers and sliding supports)

Including buildings designed: hospitals (dampers) and schools (seismic isolation) in Novokuznetsk, hospitals in Simferopol (dampers), Krasnodar, Petropavlovsk-Kamchatsky, Nikolaevsk-on-Amur (seismic isolation), residential buildings in Baikalsk, Tomsk, schools in Sochi (Fig. 15) with dampers, Angarsk (Fig. 16), Alexandrovsk-Sakhalinsky (with seismic isolation).

Figure 16 School building in Angarsk. Re-constructed with LRB.

Figure 17 Bandy Ice stadium in Irkutsk (sliders).

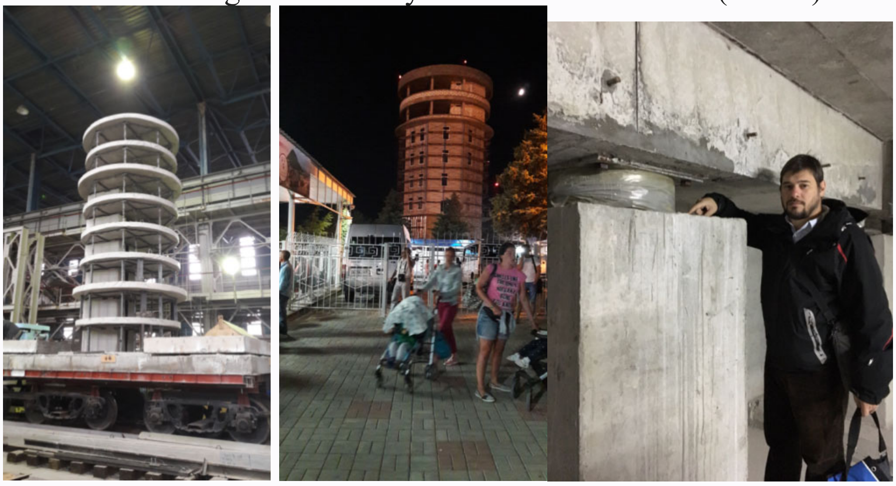


Figure 18 Anapa airport control towers testing model and real building (LRB)

For calculations and optimization of seismic isolation systems, the most important problem is the correct task of seismic impact. At the same time, it is of fundamental importance to take into account the correlation between the amplitude and the prevailing period of seismic impact. When designing seismic isolation systems, it is necessary to take into account that traditional structures of seismic insulation foundations are practically devoid of reserves of bearing capacity. This fact must be taken into account when calculating earthquake-insulated buildings, assigning an increased level of design load compared to conventional buildings, as well as in design, introducing additional redundancy elements into the system. For calculation on 1st stage of Isolated building construction used method of base separation (Fig. 19). The source seismic action is "filtrated" by specially developed software. This method allows design building with installed bearings in the elastic formulation. All inelastic deformations and hi damping involves in software modulation.

The comparative analysis of the results obtained for the three models, representing building with LRB, leads us to the following conclusions:

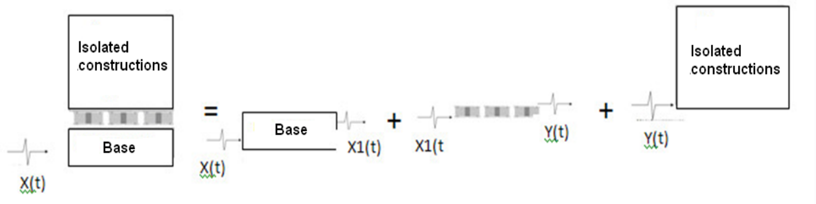


Figure 19  Base separation method of isolated buildings construction design.

In the high-frequency range (frequency range above 0.5-1 Hz) values of response spectra obtained for multi-mass models don't exceed the values of response spectra obtained for the single-mass oscillator. In the low frequency range, on the contrary, the values of response spectra obtained for multi-mass models may have higher values.

The result of solving the system of equations is a set of records of accelerations, velocities and displacements at the level of the top of the seismic insulating layer - a modified dynamic effect that acts on the superstructure. From the modified dynamic action, the spectrum of the acceleration reaction is constructed, which is then used to calculate the superstructure. The discrepancy between the results obtained for dual-mass and multi-mass models is negligible. Response spectra for multi-mass models are well correlated with each other (Fig. 20,21).

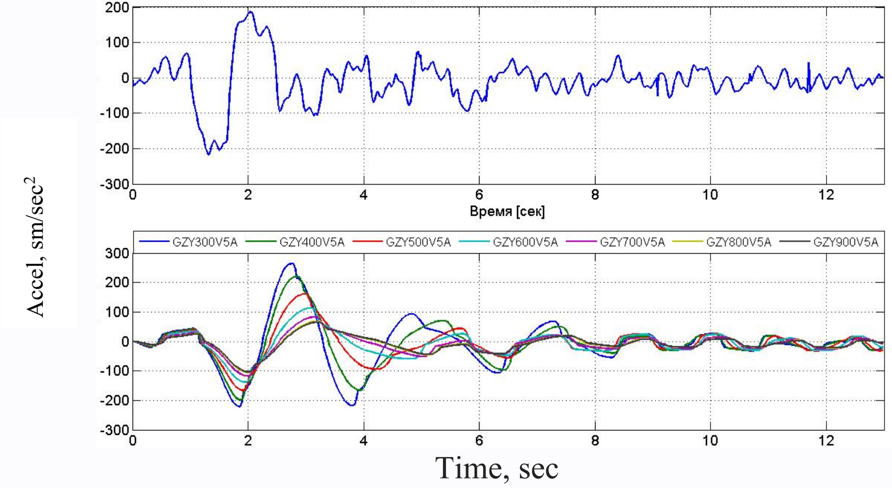


Figure 20  Time history Acceleration Buharest (Up) and filtrated acceleration for different isolation types and sizes.

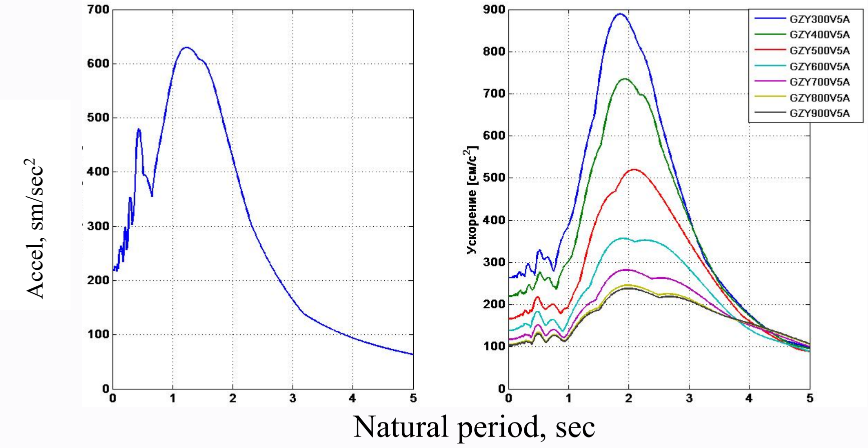


Figure 21  Spectral response Buharest (Up) and response of filtrated acceleration with different LRB isolation sizes.

Seismic isolation is one of the most effective methods of ensuring the seismic resistance of buildings and structures. The use of seismic insulating foundations is most effective for seismic protection of rigid buildings with a pitch period of less than 0.3–0.5 s.

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# CURRENT STATE AND CHALLENGES OF SEISMICALLY ISOLATED STRUCTURES IN ITALY

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## ABSTRACT

This paper summarises the development and application of seismic isolation in Italy, highlighting the importance of a suitable specific technical code. The main criteria on which the current Italian technical code for construction is based are illustrated, and the results of an extensive investigation about the economic aspects and some optimization criteria are reported. The problem of applying base isolation for the seismic retrofit of existing buildings is addressed, keeping them operational during the works in order to reduce the inconvenience to the inhabitants as much as possible. In this regard, safety criteria are discussed and practical solutions are proposed. The importance of the correct application of base isolation is finally emphasized, and the results of an extensive study on the behaviour of seismic isolation systems subjected to low energy seismic actions are reported. In particular, a system composed of HDRBs only, one composed of CSSs and one composed of HDRBs and SDs are considered. In the second and third cases, the onset of motion of the system is linked to friction, which must not be too high, while, in the first case, the behaviour depends on the increase of the stiffness of the rubber as the angular deformation decreases.

**KEYWORDS:** Base isolation, Design of seismic isolation systems, Optimization of seismic isolation systems, Seismic behaviour, Structural health monitoring.

## 1. INTRODUCTION

Japan is one of the first countries in the world for the number of applications of seismically isolated structures. But only some people know that seismic isolation started in Europe in the 70s of the twentieth century, and some interesting pioneering applications were realized in Italy [1][2][3].

The very first one referred to a viaduct in northeastern Italy, the Somplago Viaduct. It was under construction when the area was hit by severe seismic events on September 15th, 1976. The very good behaviour of this bridge caused a rapid increase in the application of anti-seismic systems to new bridges and viaducts in Italy.

The first seismically isolated building in Italy was the fire command building in Naples, completed in 1981. Neoprene bearings are at the top of reinforced concrete towers and support a reticular beam from which a steel structure is suspended, while floor dampers and shock transmitter units are inside the building. The seismic isolation, not considered in the first design, was inserted to retrofit the original design after the November 23rd, 1980, Campano-Lucano earthquake (M = 6.9). A few years later, in 1985, a second fire command building, close to the first one, was protected using similar devices. In 1991, the Telecom Italia Centre of the Marche Region at Ancona was completed. It was protected by 297 High Damping Rubber Bearings (HDRBs). A release test was performed on one of the five buildings with an initial displacement of 110 mm.

The absence of a suitable technical code for seismically isolated structures slowed the use of seismic isolation in Italy for several years. In 1998, the guidelines for seismically isolated structures [4] were issued, but they required a very complicated and time-consuming approval process by a special committee of the Ministry of Infrastructures. Finally, a suitable seismic design code was issued in 2003, after the October 31st, 2002, Molise earthquake (M = 5.4) [5]. During this event, the Francesco Jovine School building in San Giuliano di Puglia collapsed, causing the death of 27 children and a teacher. The new Italian seismic code included design rules for seismic isolation and energy dissipation systems, whose use was allowed without any additional approval.

The new code encouraged the implementation of seismic isolation, especially when high level of safety was required, which could not be obtained with traditional techniques. This happens especially for strategic structures, such as buildings for civil protection purposes, and relevant structures, such as schools and hospitals. In these kinds of buildings, the contents can be very valuable, so the construction cost of the structure is only a low percentage of the total value. On the contrary, the safety requirements are lower for ordinary buildings, and the construction cost increase due to base isolation does not encourage its use.

In 2008, all the revised technical codes, issued separately in the past, were included in the new Italian Technical Code [6]. This became the only valid code in July 2009, after the L'Aquila earthquake, and was finally updated in 2018 (NTC-2018) [7].

The most important challenges of seismic isolation in Italy referred the economic evaluations, the application to existing buildings keeping them operational during the works, and the behaviour recorded under real earthquakes in Italy.

## 2. SEISMIC ISOLATION IN ITALY: TECHNICAL AND ECONOMIC EVALUATIONS

According to NTC-2018, when using seismic isolation, Zero Earthquake-Damage Buildings (ZEDB) are realized [8], and no ductility requirements are needed for the structural elements. As a result, the substructure and the superstructure remain in an elastic range and can be modelled as linear elastic systems [9].

A suitable decoupling of motion is obtained if the ratio between the fundamental vibration period of the isolated building ($T_{is}$) and that of the superstructure considered as fixed base ($T_{fb}$) is $T_{is}/T_{fb} \geq 3$. Still, to obtain a suitable reduction of the seismic acceleration in the structure, it should be $T_{is} > 2$ s. The seismic action is evaluated with respect to a reference period, which coincides with the nominal life for ordinary structures (usually 50 years) but can be amplified for relevant and strategic ones by means of a use factor equal to 1.5 and 2.0, respectively. This means that the seismic action is not amplified directly but acting on the return period. For isolated structures, the Italian Code considers two ultimate limit states:

- The life safeguard limit state (SLV), associated with an exceedance probability of 10% in the reference period. This limit state is used to check the substructure and the superstructure using the same material factor $\gamma_M$ of non-isolated buildings. A behaviour factor $q \leq 1.5$ is allowed for seismically isolated buildings, but for the substructure $q = 1.0$ is to be preferred. The design spectra are obtained by putting $\eta = 1/q$ in the relations that define the elastic spectra, where $\eta = \sqrt{10/(5+\xi)}$ is a damping coefficient which reduces the response spectrum amplitudes and $\xi$ the damping factor.

- The collapse limit state (SLC), associated with an exceedance probability of 5% in the reference period, will be used to check the isolation devices.

The total seismic effects on the structure are calculated as a linear combination of the effects of the three components of the seismic action, $E = E_i + 0.3E_j + 0.3E_k$ (with i, j and k, equal to x, y and z, respectively, and permuted). The vertical component $E_z$ must be considered if the ratio between the vertical stiffness ($K_v$) and the equivalent horizontal stiffness of the isolation system ($K_{esi}$) is $K_v/K_{esi} < 800$. The seismic effects are combined at the SLV with those of the structural loads $G_1$, the permanent non-structural loads $G_2$ and the variable loads $Q_{kj}$ ($\psi_{2j} < 1$ is the variable load factor) as follows: $G_1 + G_2 + E + \sum_j \left(\psi_{2j} Q_{Kj}\right)$.

For elastomeric isolators, the checks refer to the angular strains due to shear only ($\gamma_s \leq \gamma_{s,\max} = 2$), the total angular strain ($\gamma_t \leq \gamma_{t,\max} = 5$), the device instability ($V \leq V_{cr}/2$, where $V$ is the vertical load on the device and $V_{cr}$ is its critical vertical load), and the stress in the steel laminates ($\sigma_s \leq f_{yk}$, where $\sigma_s$ and $f_{yk}$ are the stress and the nominal tensile resistance of the steel laminates, respectively). A suitable graphic procedure for the optimum design can be used, in which the four previous design conditions are represented on the ($D_e$, $V_e$) plane where they define an admissible area for the solution (Fig. 1). The minimum point in which the design curve intersects the admissible area represents the optimum solution [10].

In HDRBs+SDs systems, the locations of SDs are chosen to optimize the dynamic behaviour of the structure. The choice can also be influenced by the vertical loads acting on the columns, and SDs can be inserted under the columns with anomalous vertical loads (very high or very low compared to most columns). The values of the vertical loads influence the friction forces and so the onset of motion of the isolation system. Friction is the main parameter also for Curved Surface Sliders (CSS), in which the vertical load varies from device to device and could varies a lot during the quake [11].

The good performance of seismic isolation systems under strong earthquakes has been testified in several cases. Now it is important to guarantee a correct use of seismic isolation to avoid unexpected behaviours and wrong applications [12].

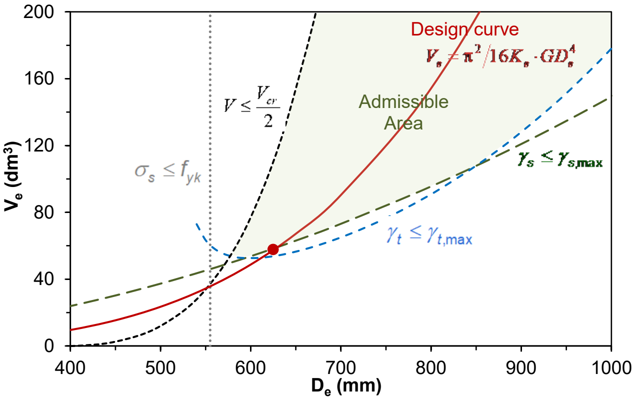


**Figure 1**. Graphic procedure for the optimum design of HDRBs.

The Italian code allows designing the superstructure with the effective seismic action, which is much lower than that to consider for a fixed base building. So, the cost of base isolation can be balanced by savings in the superstructure. The reduction of the spectral amplitudes is related to the change in the fundamental vibration period and the damping ratio. If $\hat{T} = T_{is}/T_{fb}$ and $\hat{\eta} = \eta_{is}/\eta_{fb}$ are the ratios between the values of the vibration period and the damping coefficient for the isolated structure and those for the corresponding fixed base one, then the spectral acceleration reduction when using seismic isolation, for $T_{is} \le T_D$ is ($T_D$ = value of $T$ where the zone of constant velocity ends in the elastic spectrum):

$$\hat{S}_e = \frac{S_{e,is}\left(T_{is}\right)}{S_{e,fb}\left(T_{fb}\right)} = \frac{\hat{\eta}}{\hat{T}}$$

Without losing generality, the value of $T_{fb}$ can be assumed equal to $T_C$, which is the value of $T$ where the zone of constant acceleration ends, if $T_{fb} \le T_C$. The relation $\hat{S}_e/\hat{\eta} = 1/\hat{T}$ is represented in Fig. 2 by the upper curve. If $T_{is} > T_D$, the spectral acceleration reduction is:

$$\hat{S}_e = \frac{\hat{\eta}}{\hat{T}^2} \cdot \frac{T_D}{T_{fb}}$$

In Fig. 2, the corresponding curves are plotted for different values of $T_{fb}/T_D$. They all start from the curve relative to $T_{is} \le T_C$ at the abscissa corresponding to $T_{is} = T_D$.

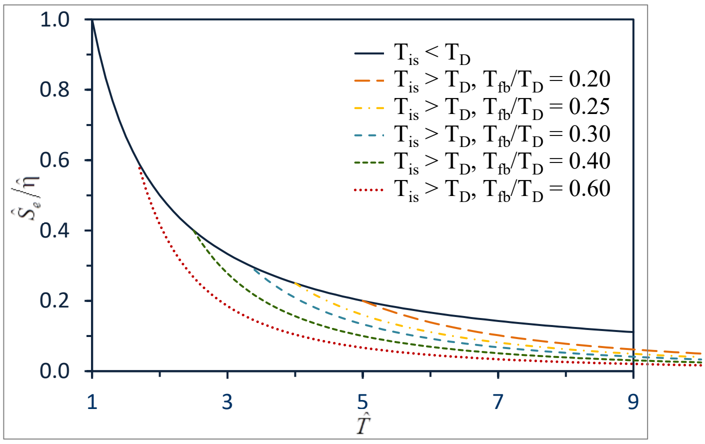


**Figure 2**. Elastic spectra ratios.

The economic suitability of seismic isolation depends on several factors, among which are the earthquake intensity and the soil characteristics, but also the shape and the size of the building. A comprehensive numerical analysis was carried out by Clemente & Buffarini [13] with reference to reinforced concrete buildings. The authors concluded that:

- The difference between the cost of a building designed with a fixed base and the same building designed with base isolation is, in general, very low; furthermore, if well designed, a base isolated building costs less than a fixed base one.
- Differences are certainly negligible for buildings in high seismicity areas (i.e., where $a_g \ge$ 0.20 g on rigid soil with probability of exceedance of 10% in 50 years), where the solution with base isolation could be even less expensive. Base isolation could also be convenient for medium and low seismicity areas, especially for irregular and special buildings.
- One should account for the larger useful area due to the smaller size of columns in the solution with base isolation, which translates into higher value for the building.

A parallel analysis was performed also for masonry buildings, obtaining quite similar results [14]. The use of seismic isolation is certainly suitable if one refers the comparison to the life span of the building. In fact, correctly erected seismically isolated buildings will not need reparation work, even after an earthquake of the same intensity as the design one.

Obviously, a suitable comparison between traditional and base isolated buildings should be made by referring to the same structural target in terms of the degree of safety. In other words, one should design the fixed base building in the elastic range. In this case, the convenience of seismic isolation in terms of construction cost becomes very high.

## 3. SEISMIC ISOLATION OF EXISTING STRUCTURES

Seismic isolation is very suitable for the retrofit of existing structures because it allows the choice of the design spectral amplitude for which the superstructure remains in the elastic range. This is pursued by fixing a suitable period of vibration. Consequently, retrofit interventions in the superstructure can be limited or even avoided [15]. Unfortunately, the application of seismic isolation in the retrofit of existing structures is not always easy and represents one of the challenges of the next future.

Devices can be inserted inside the vertical elements, columns or walls, or between the existing foundations and new sub-foundations, or even between two new sub-foundations [16].

The first technique is to be preferred when the existing foundations are in good conditions or can be easily improved (Fig. 3). It is also the most common technique used in reinforced concrete buildings, where one isolator is put for each column to guarantee a suitable transfer of the gravitational loads in service conditions. The columns could be enlarged to contain the devices and ensure an adequate stiffness of the columns themselves, if necessary.

In masonry buildings, where isolators are usually placed at the wall crossings and at intermediate locations, if necessary, suitable structures must be realized to transfer the actions from the masonry walls to the devices and from these to foundations.

With reference to the elevation, isolators should be placed at the top of the first level, if possible. So, the entire building will be protected, and the displacements during an earthquake will not interfere with the functionality of the floor below. Furthermore, the existing deck just above the isolation interface can be good rigid diaphragm. All the devices must allow the horizontal displacements. They can also be inserted at different levels, but the superstructure must be completely separated from the substructure. Stairwells and the elevator shaft could influence the positioning of the isolators.


(a) (b)

**Figure 3**. Typical insertion of the devices along a column: (a) cutting of the column (courtesy FIP Industriale); (b) temporary structure to unload an entire column (courtesy G&P Intech).

Hydraulic jacks are used to transfer the loads during the retrofitting works between temporary elements connected to the upper and the lower structural element, respectively (Fig. 3b). To adhere again the vertical elements, flat jacks are inserted under each isolator, and injected with resin.

The real challenge is to keep the building operative during the intervention, guaranteeing at least the same safety degree that characterized the structure before the retrofit intervention. This can be pursued by keeping the devices blocked using additional steel profiles, which can be inserted between the upper and the lower plates of the devices (Fig. 4a) or of the columns (Fig. 4b). The increment of the cost with reference to a simple isolation system varies between 2% and 5%. Obviously, all the additional elements can be reused.

The creation of a new sub-foundation is needed when the existing foundations are not in good condition or are insufficient. This situation is typical of old reinforced concrete buildings. Isolators are inserted between the old and the new foundation structures (Fig. 5a).

On the contrary, the creation of two new foundations is to be used when foundations do not exist at all, as usually in old masonry buildings. Usually, continuous concrete beams compose the upper new foundation, while the lower one is made by plinths, which must be connected to each other. The devices are placed between them (Fig. 5b).

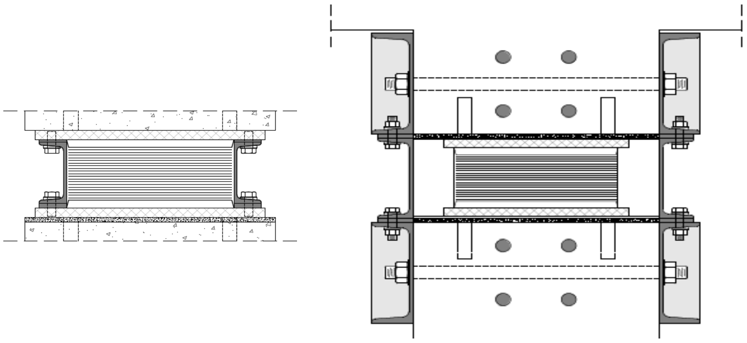

(a) (b)

**Figure 4**. Locking profiles (a) between the device plates with vertical bolts and (b) on the column.


(a) (b)

**Figure 5**. Seismic isolation with (a) a new sub-foundation (courtesy G. Mancinelli) and (b) two new sub-foundations (courtesy FIP Industriale and R. Vetturini).

The isolation interface can also be placed below the existing foundations, without touching them. The Seismic Isolation Structure for Existing Buildings (SISEB) works exactly like this (Fig. 6). A trench is excavated at one side of the building, then horizontal pipes are inserted by means of pipe jacking, creating a discontinuity between the foundations and the soil. The pieces of pipe are composed of a lower and an upper cylindrical sector, respectively, connected by removable elements that are then replaced by isolation devices. Internal and external vertical walls complete the construction [17][18].

Seismic isolation is also a very good system for the retrofit of bridges. Actually, just substituting of the existing bearings with seismic isolators could sometimes be enough to retrofit a bridge. The reduction of the seismic effects on the piers allows avoiding further interventions on them.

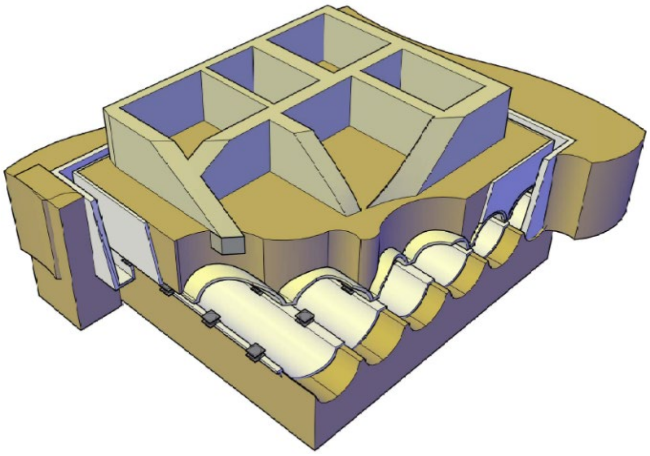


**Figure 6**. Seismic Isolation Structure for Existing Buildings.

## 4. THE CHECK UNDER LOW ENERGY EARTHQUAKES

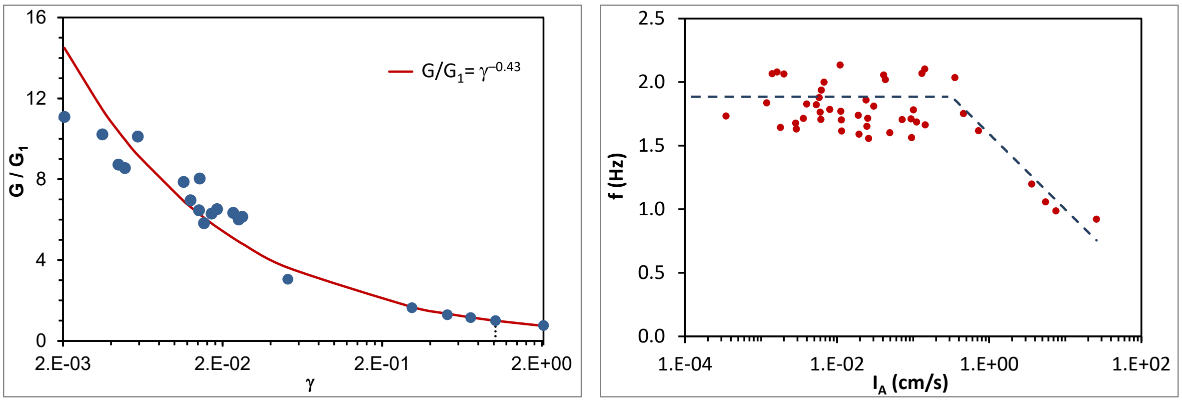
Nowadays, seismic isolation is one of the best techniques to protect structures against earthquakes and, when applicable, should be preferred to other techniques. Anyway, a correct use is to be recommended to avoid failures, which could discourage its use in the future.

One of the topics to consider is the behaviour under low energy earthquakes, such as far fault or just weak events. While seismic isolation systems showed very good performances during several strong events in several countries, the behaviour under low energy excitation has been studied in depth only recently [19] [20]. The seismic sequence that hit Central Italy from August 2016 to January 2017 offered a suitable occasion. Some buildings with different seismic isolation systems were selected for comparison, in particular two seismically isolated buildings of the Civil Protection Centre at Foligno and other base isolated ones at L'Aquila, which were more than 30 km from the epicentral areas. All the events with magnitude equal to or greater than 4.0 were selected and classified based on the energy at the basement of each building, evaluated by means of the Arias intensity [21]. The variation in the resonance frequencies, the peak accelerations and the maximum relative displacements were particularly pointed out.

In the first building of the Civil Protection Centre, the isolation system is composed of HDRBs only [22][23][24][25]. It is well known that the shear modulus of the elastomer increases when the shear deformation $\gamma$ gets lower (Fig. 7a). Consequently, the first resonance frequency gets higher and could become close to those of the superstructure. If this occurs, the decoupling of motion cannot be guaranteed. In the studied building, this did not happen due to the very high stiffness of the superstructure, whose first resonance frequency is 3.4 Hz. It is worth noting that the contribution of the seismic isolation system was also apparent under ambient vibrations only. In Fig. 7b, the first resonance frequency is plotted versus $I_A$: it varies a little around a medium value, equal to that obtained under ambient vibrations (about 1.9 Hz), up to a value of $I_A$ and then decreases when $I_A$ increases. The resonance frequency is always much higher than the design one (0.38 Hz).

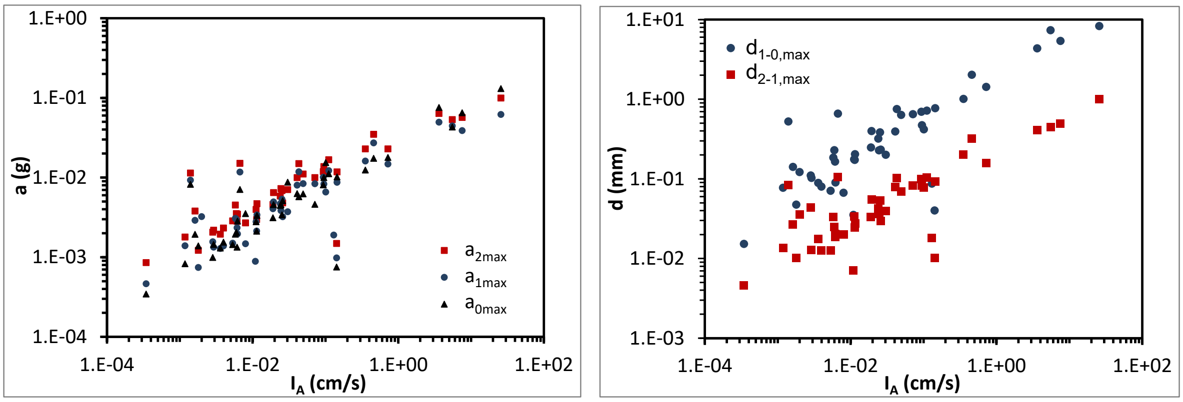
In Fig. 8a, the maximum accelerations at the three levels (L0 = basement, L1 = just above the isolation interface, L2 = top of the building) are plotted versus $I_A$ for all recorded events. For low values of $I_A$, the acceleration at L1 was often greater than that at L0. Just the opposite occurred for higher values of $I_A$. In Fig 8b, the maximum relative displacements between L1 and L0 and between L2 and L1 are plotted versus $I_A$ for the recorded earthquakes. Due to the deformability of the ground floor columns, below the isolation interface, the drift between L1 and L0 is always higher than that between L2 and L1. The difference increases very much with IA.

The observed behaviour can be interpreted as follows. For low energy earthquakes, the isolation system is subject to very low shear strains, for which the shear modulus of the rubber is much higher than that at shear strains greater or equal to one. The first resonance frequencies get higher and could become equal to those of the superstructure.



(a) (b)

**Figure 7**. Isolation system with HDRBs only: (a) normalised shear modulus vs shear strain and (b) first resonance frequency vs IA.



(a) (b)

**Figure 8**. Isolation system with HDRBs only: (a) maximum accelerations at the three levels and (b) maximum relative displacements be-tween L1 and L0 and between L2 and L1 vs IA.

The second case study refers to residential buildings seismically isolated by means of curved surface sliders (CSS) [26]. It is well known that the friction coefficient decreases when the vertical load gets lower (Fig. 9). For this reason, the friction coefficient in seismic conditions (vertical load NE) could be much lower than that under the vertical loads corresponding to the static limit state (vertical load NULS). Therefore, the static friction could be very high so that the onset of motion could not occur under low energy events [27].

In Fig. 10 the resultant inertial force at each instant is compared with the maximum theoretical friction force (red circles) for two different buildings. In the first case (Fig. 10a), relative to a reinforced concrete building, the inertial force gets higher than the friction force at some instant, so the isolation system is put in action. In the second one (Fig. 10b), relative to a wooden building, the friction force is always greater than the inertial one, and the system is not activated. Actually, if friction is very high, the isolation system could not be put in action, and the structure could behave as a fixed base building.

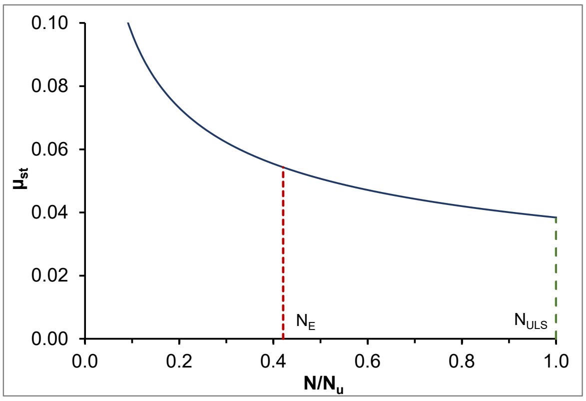
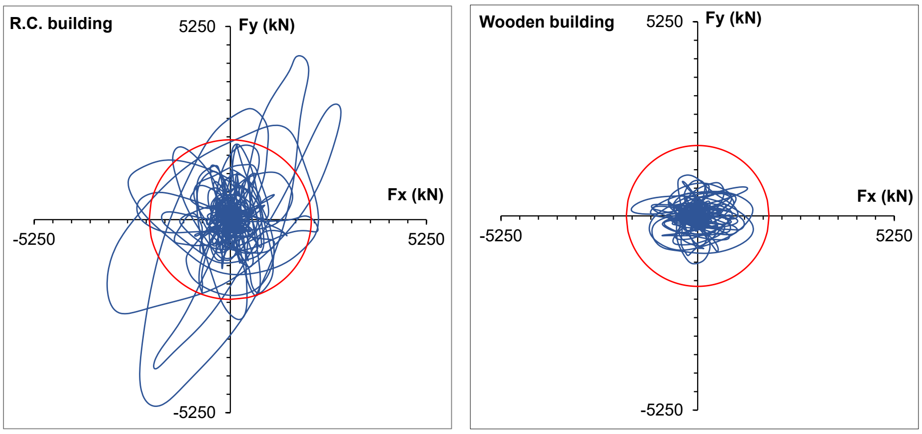


**Figure 9**. CSSs: friction coefficient vs normalized vertical load.



(a) (b)

**Figure 10**. Isolation system with CSSs: maximum theoretical friction force (red circles) and resultant inertial force (blue line) for (a) a r.c. building and (b) a wooden building.

The last case study is represented by a second strategic building of the Civil Protection Centre, seismically isolated by means of HDRBs and SDs [28][29]. In Fig. 11 the first resonance frequency is plotted versus $I_A$. As in the first case of isolation system made of HDRBs only, it varies a little around a medium value up to a value of $I_A$ and then decreases when $I_A$ increases. But this time, the initial value is equal to that of the superstructure (about 3.5 Hz), which is obviously much higher than the design one. In Fig. 12a the accelerations obtained at the three levels (L0 = basement, L1 = just above the isolation interface, L2 = top of the building) are plotted versus $I_A$ for all recorded events. It is apparent that for low values of $I_A$, the acceleration at L1 is almost always greater than that at L0, while the opposite occurred for higher values of $I_A$. In Fig 12b, the maximum relative displacements between L1 and L0 and between L2 and L1 are plotted versus $I_A$ for the recorded earthquakes. The drift between L1 and L0 is always higher that between L2 and L1 and the difference increases very much with $I_A$. One can conclude that for an isolation system composed of HDRBs + SDs, the onset of motion is governed by the static friction of the sliding devices. During the motion, the stiffness of the rubber determines the effective resonance frequency, which could become very high and close to the first resonance frequency of the superstructure.

In all cases, the seismic effects in the superstructure could be higher than those evaluated in the design phase. This occurrence should be accounted for in the design of a seismically isolated structure.

It is worth reminding that the isolation system has a horizontal stiffness low enough to allow the relative displacements required in case of earthquake but high enough to avoid vibrations under very low horizontal actions, such as wind, traffic-induced, or ambient vibrations. In other words, the stiffness should be calibrated accurately to avoid unexpected behaviours.

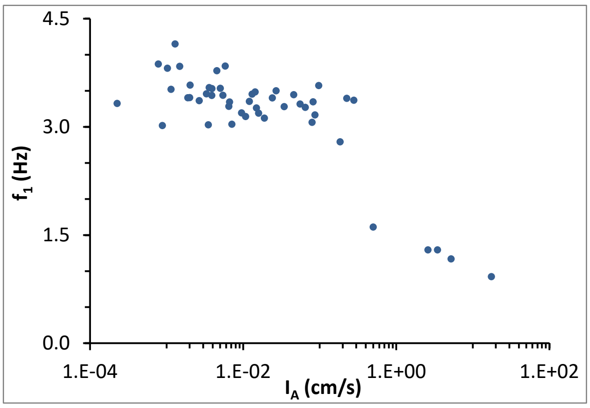
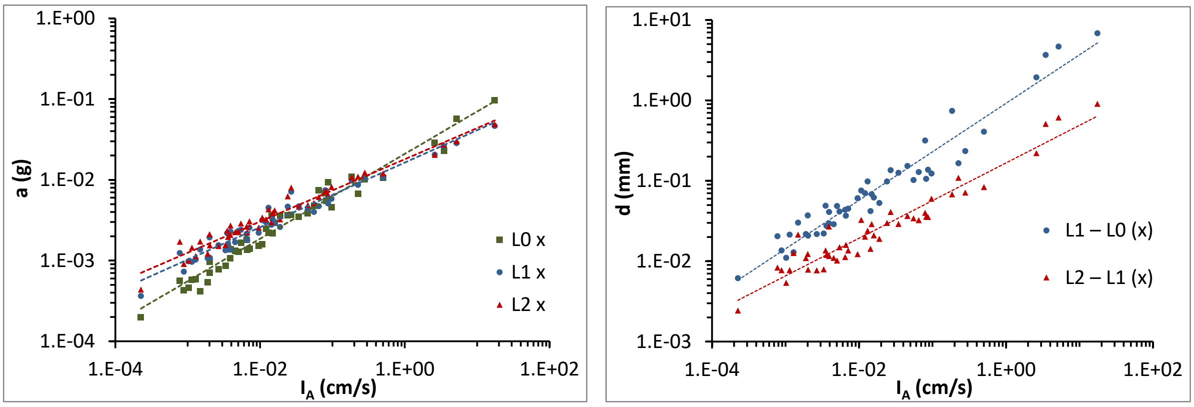


**Figure 11**. Isolation system with HDRBs+SDs: first resonance frequency vs IA.



(a) (b)

**Figure 12**. Isolation system with HDRBs+SDs: (a) accelerations at the three levels and (b) maximum relative displacements between L1 and L0 and between L2 and L1 vs IA.

## 5. CONCLUSIONS

Nowadays, seismic isolation can be considered one of the best protection technique against earthquake, especially for strategic structures for which full integrity and operability after even very strong earthquakes are required, but also for residential buildings. Fortunately, the number of applications is increasing remarkably in several countries.

One of the most important challenges for the future is the wide use of seismic isolation to retrofit existing structures, keeping the structures operational during the works. The most used techniques for new and existing buildings have been shown, as well as new solutions to keep the building operational during the retrofit intervention. These should guarantee at least the same safety level that the structure had before the retrofit intervention.

In order to encourage the application of base isolation in the future, its correct use is to be recommended. The actual behaviour shown during earthquakes is indeed of fundamental importance for future developments. The observed behaviours in Italy pointed out the importance of analyzing the characteristics of the isolation system under low energy earthquakes at the site, such as far fault earthquakes. In fact, the behaviour of isolation devices under low vibrations is quite different from that assumed under the design earthquake at the ultimate limit state.

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# RECENT APPLICATIONS OF SEISMIC ISOLATION IN NORTH AMERICA

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## ABSTRACT

The number of seismically-isolated building projects continues to grow at a steady, albeit slow rate in the U.S., and applications in Canada are starting to appear. Many projects are architecturally notable, and many also involve increasingly large isolation displacements. The use of isolation for sensitive and critical equipment is becoming more common, and in some cases is extending to state-of-the-art three-dimensional protection. The paper gives an overview of a selection of recent notable projects and discusses recent trends in design and applications.

**KEYWORDS:** seismic isolation, buildings, industrial, sensitive equipment, three-dimensional USA, Canada.

## 1. INTRODUCTION

The first seismically-isolated building in the U.S. was completed in 1985. This was a new, four-story building, the Foothill Communities Law & Justice Center in Rancho Cucamonga, California that utilized high-damping rubber bearings. Soon after, the first seismic isolation retrofit in the U.S. and the world was completed, the Salt Lake City & County Building in Salt Lake City, Utah. These and other early projects initially positioned the U.S. at the forefront of the use of the technology. It is now estimated that there are about 200 seismically-isolated buildings in the U.S., and while not nearly the number that have been completed in various other countries, isolation has continued to be used at a steady, albeit slow, pace with many notable applications and distinctive projects.

The use of seismic isolation for buildings in Canada has taken place much more recently with the first building, the retrofit of an historic school building in Vancouver, B.C., being completed in 2017. Isolation is now being used for a number of notable projects currently underway and is being actively considered by engineers and owners for numerous others.

This paper gives an overview of a selection of recent seismic isolation projects in both countries and provides some observations on trends regarding the use of the technology and applications.

## 2. OVERVIEW OF RECENT PROJECTS

The following sections briefly describe a selection of projects that have been completed within the last several years or which are currently under construction, in the categories of architecturally notable new buildings, retrofits, essential facilities, data centers, and several categories of non-building applications: equipment, industrial and artwork.

### 2.1 Architecturally Notable New Buildings

A series of recent building projects in the Los Angeles area have taken advantage of the structural flexibility possible with the use of seismic isolation to achieve dramatic architectural forms. The new home of both the NFL Los Angeles Rams and the Los Angeles Chargers, SoFi Stadium features a sweeping roof structure covering more than 120,000 $m^2$, supported on 53 pendulum isolation bearings atop massive "blade" columns (Figs. 1.a and b). The stadium is within meters of the Newport-Inglewood Fault, and the isolation bearings were designed for a maximum displacement of 2.03 m.

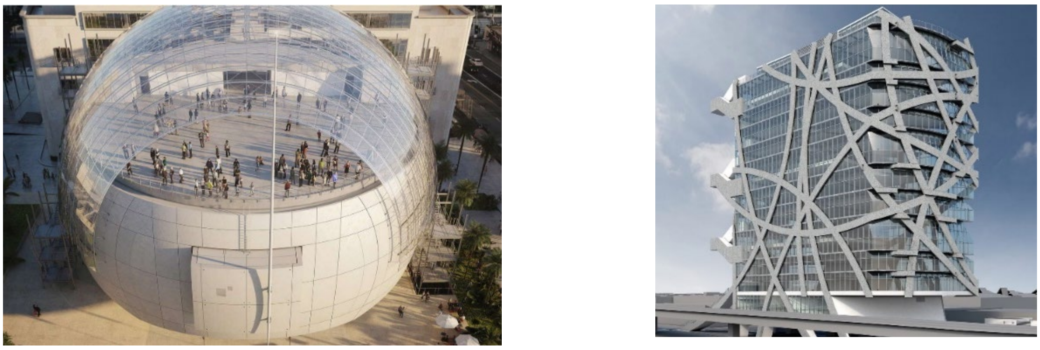
(a) Exterior view of stadium

(b) Roof structure with isolators at top of blade columns

Figure 1 SoFi Stadium, Inglewood, California, USA (photos: SoFi Stadium)

Two other dramatic architectural examples are the Academy Museum of Motion Pictures (Fig. 2.a) and the (W)rapper building (Fig. 2.b). The Academy Museum is a spectacular 45.8 m diameter steel and glass orb supported on just eight isolators with a maximum displacement of 750 mm, while the (W)rapper is a unique, 17-story, 73 m tall steel building with no columns or regular framing, instead a helical band exoskeleton supports the structure and achieves entirely column-free interior spaces. The (W)rapper isolation system comprises 18 triple friction pendulum bearings.

Both the Lucas Museum (Fig. 2.c), and the David Geffen Galleries of the Los Angeles County Museum of Art (LACMA) (Fig. 2.d) feature impressive free-form architectural designs, with isolation not only facilitating the architectural and structural forms, but also providing the highest level of protection to the valuable art and contents to be housed in both complexes. All the projects of Fig. 2 have utilized triple pendulum isolation bearings.



(a) Academy Museum of Motion Pictures
Los Angeles, California, USA
(photo: Renzo Piano Building Workshop)

(b) The (W)rapper
Los Angeles, California, USA
(image: Eric Owen Moss Architects)

(c) Lucas Museum, Los Angeles, California, USA
(image: Lucas Museum of Narrative Art)

(d) David Geffen Galleries, LACMA, Los Angeles, California, USA
(image: Atelier Peter Zumthor & Partner / The Boundary)

Figure 2 New seismically-isolated buildings, Los Angeles, California, USA

## 2.2 Retrofit Projects

The use of isolation for the retrofit and upgrade of historic buildings in the U.S. has always been a significant sector of application, and in recent years that has expanded into Canada. The first Canadian building isolation project was the retrofit of the Lord Strathcona School in Vancouver (Fig. 3.a). This

1,800 m$^2$, three-story timber/masonry/stone building used 30 elastomeric and flat sliding bearings and was completed in 2017. Currently underway is the retrofit of Centre Block, the main building of the Canadian Parliamentary complex (Fig. 3.b). The project includes the addition of a new, underground visitor welcome center, and will see the transfer of the building onto nearly 600 isolators [1].

Construction is currently underway on the seismic upgrade of the Salt Lake Temple of The Church of Jesus Christ of Latter-day Saints (Fig. 4.a). The temple, originally constructed over 40 years and completed in 1893 will be supported on 98 triple pendulum bearings with a maximum displacement of 1.52 m (60 in.). The massive, granite walls of the temple required an innovative underpinning and load transfer approach, with the isolators either side of the axis of the walls (Fig. 4.b).

(a) Lord Strathcona School
Vancouver, British Columbia, Canada

(b) Centre Block, Canadian Parliament
Ottawa, Ontario, Canada (photo: Wikipedia)

Figure 3 Heritage building seismic isolation retrofits, Canada

(a) Temple Building
(image: Wikipedia)

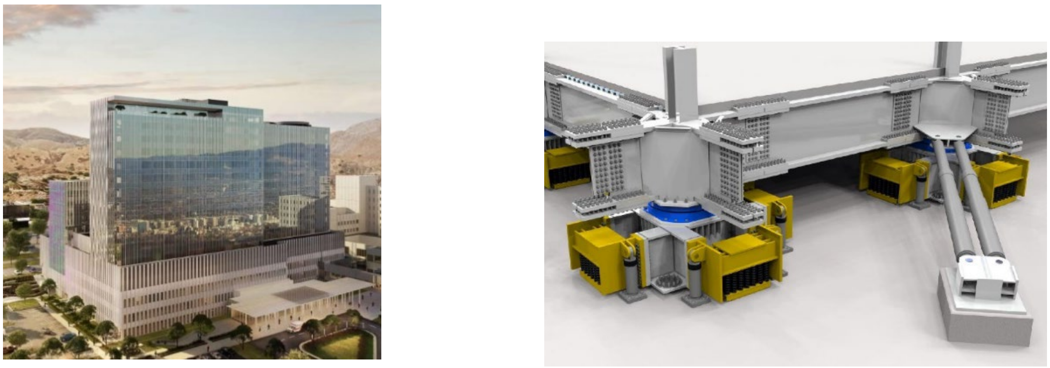
(b) Load transfer and isolator placement
(image: Intellectual Reserve, Inc.)

Figure 4 Salt Lake Temple, The Church of Jesus Christ of Latter-day Saints, Salt Lake City, Utah, USA

### 2.3 Essential Facilities

Along with the retrofit of historic buildings, isolation has also been consistently used in the U.S. for essential facilities. The following examples in Figs. 5, 6, and 7 show some notable recent examples. The Loma Linda University Medical Center in Southern California is a 100,000 m$^2$ new hospital building, comprising two patient towers of 16 and 7 stories (Fig. 5.a). The hospital is located within a few hundred meters of the San Jacinto Fault (see Building “5”, Fig. 10) and is exposed to extremely severe near-field shaking. As a result, the isolation system has been designed to accommodate not only large horizontal displacements (1.07 m) using triple pendulum bearings and fluid viscous dampers, but also to provide isolation in the vertical direction (Fig. 5.b). The hospital construction is complete, with design details included in the basement to allow the implementation of the vertical isolation system in the coming years.

The other essential facility examples of Figs. 6 and 7 are all in the state of Oregon. Figs. 6.a and b. show a new operations center for Oregon's largest energy utility company, and a new headquarters for the Oregon state government Treasury. Both projects have been recently completed and opened in 2021, and both utilize isolation systems with a combination of elastomeric and flat sliding bearings. Along with utility networks, transportation systems are also increasingly regarded as essential facilities, and Fig. 7 shows the currently under-construction main terminal building expansion of Portland International Airport [2]. The roof structure is isolated at the tops of architecturally impressive Y-columns using a total of 68 curved-surface sliding bearings. The use of isolation not only made possible the dramatic architecture but also achieved above-code functionality protection for the facility.



(a) Hospital building general view

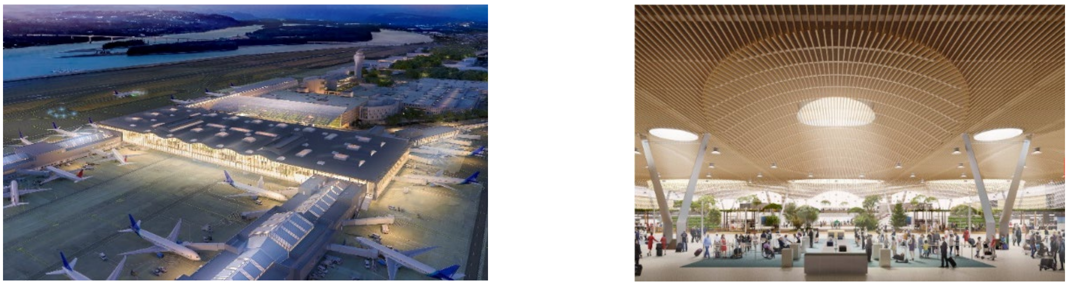
(b) Isolation system components

Figure 5 Loma Linda University Medical Center, Loma Linda, California, USA (images: Ref [5]).

(a) Utility company operations center, Tualatin, Oregon, USA

(b) Treasury Resiliency Building, Salem, Oregon, USA

Figure 6 Essential facilities, Oregon, USA (photos: PGE; GBD Architects)



(a) Exterior view, main terminal building (b) Terminal interior with Y columns

Figure 7 Terminal Roof, Portland International Airport, Portland, Oregon, USA (images: ZGF Architects)

### 2.4 Data Centers

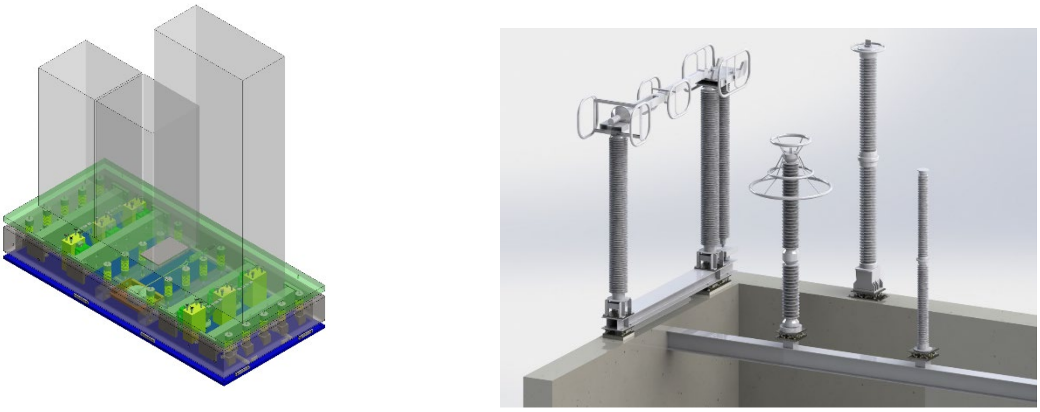
Seismic isolation has been used for a number of data centers in the last several years. Two recent examples are shown in Fig. 8, a 4-story, 16,000 m$^2$, center in Silicon Valley, northern California, and a 2-story, 6,000 m$^2$ project in southern California [3]. Both projects utilize triple pendulum bearings and have been designed for maximum displacements of approximately 800 mm, with the Santa Clara project additionally including fluid viscous dampers to limit the maximum displacement.

(a) Data center, Santa Clara, California (b) Data center, Irvine, California

Figure 8 Seismically-isolated data centers, California, USA (images: (a) NTT/Gensler ; (b) TGS/LPA).

### 2.5 Computer and Electrical Equipment

A major new hydroelectric project in the Canadian province of British Columbia, the Site C Clean Energy Project has made extensive use of state-of-the-art isolation systems to provide enhanced seismic performance of both critical electronic equipment and electrical distribution equipment. Fig. 9.a shows an example of 3-D seismic isolation platforms used to protect spillway gate control equipment critical to dam safety against 1/10,000 year Maximum Earthquake shaking (a total of 39 platforms of varying sizes are used on the project) and Fig. 9.b shows wire rope isolators used to protect high-voltage electrical distribution equipment [4].



(a) 3D seismic isolation platforms for electrical and electronic control equipment

(b) Wire rope isolators for 500 kV electrical equipment

Figure 9 Equipment seismic isolation, Site C Clean energy Project, Peace River, B.C., Canada

## 3. TRENDS

Whilst the total number of seismically-isolated buildings in the U.S. over time has not progressed as significantly as in some other countries, many of the applications that have been completed are structurally or architecturally significant, and among those projects that have been completed in recent years a number of general trends can be observed:

- Design displacements for isolation systems have tended to increase over time. This has been due not only to changes (generally increases) in seismic hazard estimations, but also the greater use by designers of longer-period isolation systems. Fig. 10 is indicative of this change in maximum design displacement over time, showing the inland region of southern California east of Los Angeles that includes a number of isolated buildings. Building "1" is the first isolated building in the U.S., and Building "6" is the Loma Linda University Medical Center (Fig. 5). It can be seen that design displacements, originally in the range of 380-550 mm have increased to as much as 1.07 m over about 25-30 years. These large displacements present significant design challenges and push the performance limits of isolation devices.
- Many recent projects with large displacement requirements have utilized triple pendulum bearings.
- A number of low-rise (2-3 story) steel-framed buildings have used a combination of elastomeric and flat sliding bearings.
- Fluid viscous dampers continue to be used together with pendulum or elastomeric bearings, to moderate large displacement demands.
- The use of isolation for non-building applications, such as computer systems, sensitive and critical equipment and artwork has increased. These systems have recently included high-performance 3-D capabilities.

Interest in seismic isolation in Canada is growing with more engineers now exploring isolation for both new and retrofit construction, and its use even in areas of relatively low seismicity is proving to be both technically and economically viable, particularly for retrofit applications.

## 4. SUMMARY

It is nearing 40 years since the design and completion of the first seismically isolated buildings in the U.S. The rate of adoption of the technology has not matched that of some other countries, nonetheless many notable seismic isolation projects have been completed and continue to be undertaken, with applications pushing the state-of-the-art in terms of seismic protection objectives. The use of seismic isolation for buildings in Canada has started to emerge in the last decade and it is expected that isolation will see increased use in future years, not only in high, but also low-to-moderate seismic regions of the country.

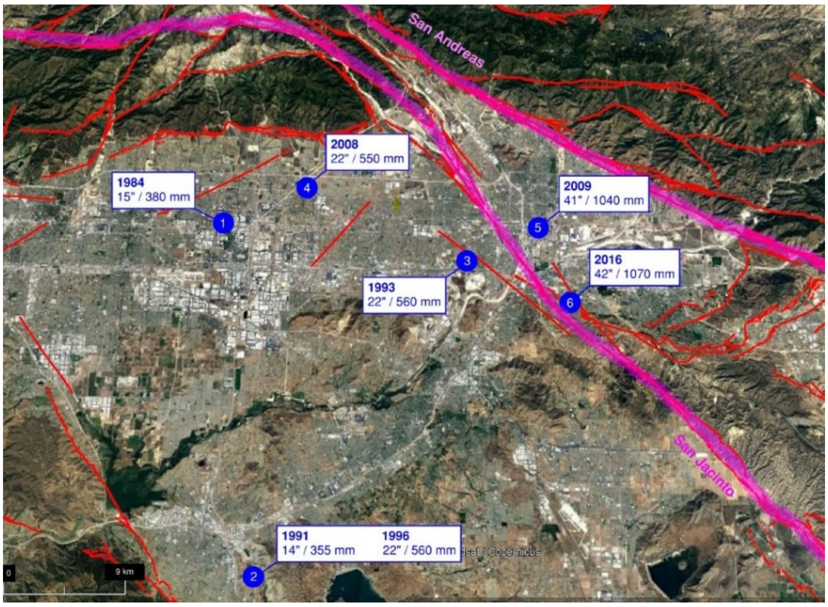


Figure 10 Maximum design displacements for seismically-isolated buildings in inland southern California, 1984-2016. (image: adapted from Google Earth).

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# SEISMIC ISOLATION IN CHILE

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## ABSTRACT

The continental territory of Chile is located on the subduction zone between the Nazca and South American plates. In the last fourteen years, three earthquakes with moment magnitudes $M_w$ larger than 8.2 struck the Chilean territory. Earthquakes with $M_w > 7$ occur every 5 years in average, converting Chile in one of the most seismically active countries in the world. The economical and physical losses, in addition to business interruptions, have motivated authorities, investors, and stakeholders to request the use of seismic protection technologies, such as seismic isolation and energy dissipation in their projects, aiming at improving the seismic performance of structures including hospitals, datacenters, bridges, wharfs, and industrial, office and residential buildings, among many others. Nevertheless, in recent years the protection technologies have been applied mainly in hospitals, datacenters, and educational facilities. This paper summarizes the observations of structural and nonstructural seismic performances of base isolated structures, some of which have been instrumented for more than 30 years. The expected seismic performance of isolated structures designed according to Chilean practices is also discussed and analyzed. The observed and expected seismic performances have been considered for continuous calibration of the Chilean standard for seismic design of isolated structures. The main characteristics of the Chilean standard and professional practice, and its differences with the US and European standards and practices, are also described and analyzed.

**KEYWORDS:** Seismic isolation, Energy dissipation, Code development, seismic performance, seismic monitoring, structural and nonstructural performance

## 1. INTRODUCTION

The continental territory of Chile is located on the subduction zone between the Nazca and South American plates. In the last fourteen years, three earthquakes with moment magnitudes $M_w$ larger than 8.2 struck the Chilean territory. Earthquakes with $M_w > 7$ occur every 5 years in average, converting Chile in one of the most seismically active countries in the world. The economical and physical losses, in addition to business interruptions, have motivated authorities, investors, and stakeholders to request the use of seismic protection technologies such as seismic isolation and energy dissipation in their projects, aiming at improving the seismic performance of structures including hospitals, datacenters, bridges, wharfs, and industrial, office and residential buildings, among many others.

### 1.1 Seismic Activity

Table 1 summarizes the destructive seismic events ($M_w \sim 8$) that have struck Chile in the last 445 years. As observed in Table 1, thirty-one destructive events have been observed in this timespan, resulting in damaging capable events occurring, in average, every 14.5 years within the Chilean territory. In addition, three events with $M_w > 8$ have been observed in the last 14 years. Among the recent earthquakes, the most damaging one was the $M_w$ 8.8 El Maule Earthquake in 2010, with an aftermath of 521 fatalities and 33 billion US dollar in direct losses, equivalent to 15% of 2010 Chilean gross demographic product, GDP. The health system network experienced economical losses close to 3 billion US dollars, and 10 primary health hospitals needed to be evacuated, demolished, and rebuilt. Among the fatalities, 15 occurred in structures with engineered design; 180 approximately were caused by the tsunami following the main shock; and the remaining fatalities occurred in structures without seismic design, mainly adobe self-construction houses in rural areas. With regards to economic losses, 90% of them were associated to nonstructural damage given the strict code that rules structural seismic design [1]. Chile is affected not only by large magnitude events but also frequent and moderate seismic events. Fig. 1 shows the frequency for earthquakes with $M_w$ larger than 5 and 6 per year between 2004 and 2020 [2].

Table 1 Earthquakes with Moment Magnitudes larger than 8 in Chile

| Date | | Magnitude | Approx. Location | Date | | Magnitude | Approx. Location |
|---|---|---|---|---|---|---|---|
| 1570 | Feb. 8 | 8.0 – 8.5 | Concepcion | 1906 | Aug. 16 | 7.9 | Valparaiso |
| 1575 | Dec. 16 | 8.5 | Valdivia | 1922 | Nov. 10 | 8.4 | Vallenar |
| 1604 | Nov. 24 | 8.5 | North Arica | 1928 | Dec. 1 | 8.4 | Talca |
| 1647 | May. 13 | 8.5 | Valparaiso | 1939 | Jan. 24 | 8.0 – 8.3 | Chillan |
| 1657 | Mar. 15 | 8.0 | Concepcion | 1943 | Apr. 6 | 8.3 | Illapel |
| 1730 | Jul. 8 | 8.8 | Valparaiso | 1950 | Dec. 9 | 8.0 | Calama |
| 1737 | Dec. 24 | 7.5 – 8.0 | Valdivia | 1960 | May. 22 | 9.5 | South Chile |
| 1751 | May. 25 | 8.5 | Concepcion | 1966 | Dec. 28 | 8.1 | Taltal |
| 1796 | Mar. 30 | 7.5 – 8.0 | Copiapo | 1985 | Mar. 3 | 7.8 | Central Zone |
| 1819 | Apr. 3-11 | 8.3 | Copiapo | 1995 | Jul. 30 | 8.0 | Antofagasta |
| 1822 | Nov. 19 | 8.5 | Valparaiso | 2001 | Jun. 23 | 8.4 | South Peru |
| 1835 | Feb. 20 | 8.0 – 8.5 | Concepcion | 2005 | Jun. 13 | 7.8 | Tarapaca |
| 1837 | Nov. 7 | 8.0 | Valdivia | 2010 | Feb. 27 | 8.8 | Center-South |
| 1868 | Aug. 13 | 8.5 | Arica | 2014 | Apr. 1 | 8.2 | Iquique |
| 1877 | May. 9 | 8.0 | lquique | 2015 | Sep. 16 | 8.3 | Canela Baja |
| 1880 | Aug. 15 | 7.5 – 8.0 | Illapel | | | | |

From the data shown in Fig. 1, it can be inferred that, in average, and removing aftershocks, 45 and 5 seismic events with $M_w$ greater than 5 and 6 are observed every year in the territory, respectively. Aware of this situation, authorities, stakeholders, investors, and owners are demanding the use of seismic protection technologies in their projects. The high number of moderate events imposes requirements on the selection and design of the seismic protection technologies, which are not only designed for accommodating MCE demands as in ASCE/SEI 7-22 [3] but also for service level earthquakes. Another important characteristic of Chilean earthquakes is related to their durations. Fig. 2 shows the horizontal accelerations recorded in Concepcion City during the $M_w$ 8.8, 2010 El Maule earthquake. In Fig. 2 it can be observed that during approximately 120 sec the acceleration threshold of 0.05g is exceeded. Similarly, the acceleration of 0.1g is approximately exceeded during 90 sec, and the 0.2g acceleration threshold is approximately exceeded during 20 sec.

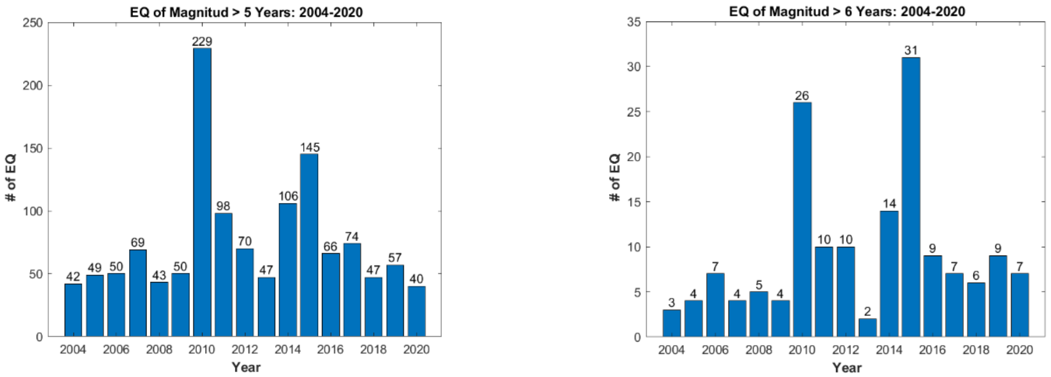


Figure 1 Frequency for seismic events with $M_w$ larger than 5 (left) and 6 (right).

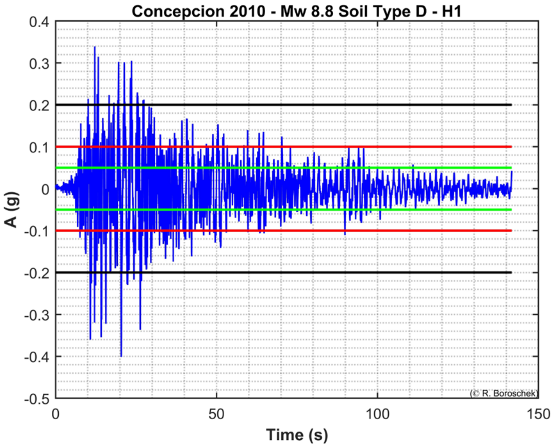
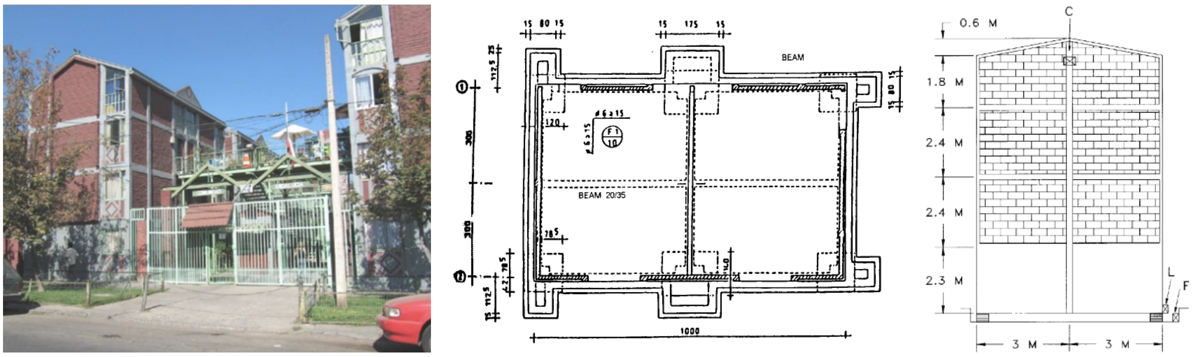


Figure 2 Exceedances of acceleration thresholds

## 1.2 First Applications of Seismic Protection Technologies in Chile

Seismic isolation in Chile began in 1992, when one structure in the Andalucia Condominium (Fig. 3), was seismically isolated by University of Chile Professors Sarrazin and Moroni [4] to introduce this technology in developing countries. The isolated building, shown in Fig. 3, is a 4-story confined masonry structure mounted on 8 high damping rubber bearings. The first level considers reinforced concrete shear walls. The building has a 10x6 m floor footprint. The weight of the structure is 1,630 kN. The typical slab thickness is 10 cm. The structure's roof is a wooden truss. The isolators are 315 mm in diameter and 320 mm in height. The thickness of the rubber layers is 6.7 mm. Four isolators were located in the corners of the building and two at the middle of each long side. The isolators have a vertical load capacity of 350 kN at 200 mm lateral displacement (100% strain). An extensive test series was carried out at the University of California, Berkeley [4]. The design period of the isolated building was 2 sec. The base isolated and one of the fixed base buildings were instrumented. The response of the building during the 2010, $M_w$ 8.8 El Maule earthquake was successfully recorded [5].



a) Isolated (left) and fixed base instrumented structure (right)

b) Plan view isolated structure

c) Elevation isolated structure

Figure 3 Andalucia Condominium: first isolated structure in Chile

The second structure that incorporated seismic isolation in Chile was the Marga-Marga bridge, shown in Fig. 4 [6]. This bridge, that spans 368 m, consists of 4 steel girders mounted on 36 high damping rubber bearings. The height of the tallest reinforced concrete pier is 32 m. Rubber bearing sizes vary among 850x500, 700x500, and 500x500 mm$^2$. All isolators are 302 mm in height, with 204 mm of rubber, 16 steel shims 3 mm in thickness, and two 25 mm thick mounting plates. The design displacement was 156 mm. Two prototypes of each type and all production bearings were tested at the University of Chile. This bridge was fully instrumented by the University of Chile since its construction, using an array of 24 accelerometers.

The first application of seismic isolation in a large structure was the La Reina Military Hospital, developed in 2001 (Fig. 5). The total cost of the structure was 112 million US dollars, the number of beds 330, and the total constructed area was 88,000 m$^2$ approx. The clinical and emergency services were located in a base isolated structure in order to protect the investment and the functionality of their services. The structural system of this building consists of a moment-resistant frame system with an approximate built area of 50,000 m$^2$ distributed in 5 levels, including a basement level for parking. The highest level of the structure corresponds to a mechanical floor. The dimensions in plan are 126x115 m. The column spacing is 9 m in both directions. The floor height is 5.75 m at the basement level and 4.5 m at the upper levels. The building's columns have a typical section of 800x800 mm, except in the basement level, where the typical column section is 1100x1100 mm. The beams have a typical section of 600x900 mm, except in the ceiling of the basement level, where the beams have a 600x1100 mm section. The stronger system at the basement level was requested for an elastic design and to control the story drift at this level. The structure is mounted on 164 seismic isolators located at the ceiling of the basement level, 114 of these isolators were manufactured using high damping rubber. The isolators are 700 and 900 mm in diameter and were made of 20 rubber layers of 8 mm of thickness and 4 mm thick steel shim plates. The remaining isolators have a 150 mm in diameter lead core to increase its energy-dissipation capacity. These isolators are 900 mm in diameter and are located in the perimeter of the structure, in order to control torsional effects. The design displacement was 240 mm. The damping provided by the isolation system was nearly 12%. The period of the isolated structure was nearly 2.5 sec.

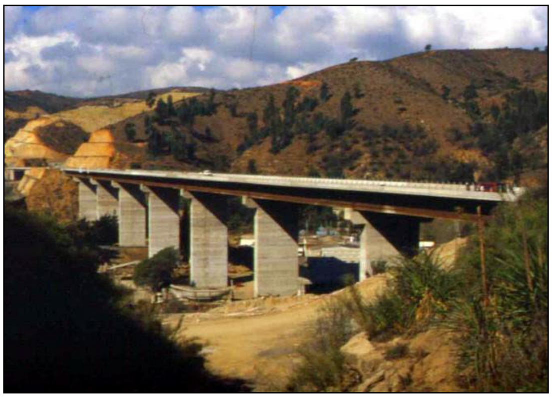


Figure 4 Marga-Marga bridge: first seismically isolated bridge in Chile

Figure 5 La Reina Military Hospital

### 1.3 Current Applications of Seismic Protection Technologies in Chile

Between 1992 and 2010 approximately 10 isolated structures were built in Chile. The 2010 earthquake triggered the demand for using seismic isolation technologies. Currently, approximately 200 isolated structures are built. Fig. 6 summarizes the types of structures incorporating isolation technologies and their proportion to the total. It is observed that most isolated structures correspond to health facilities and residential buildings. Fig. 7 shows the type of technology used for seismically isolating structures. Although most existing applications consider high damping rubber systems (HDRB), the trend is drastically changing, given that all new hospitals (with built area larger than 40,000 m$^2$, approximately) consider natural rubber (RB) and lead rubber bearings (LRB) by government specifications, and the irruption in the market of comparatively lower cost friction pendulums (FP) technologies, that are also applicable to relatively low mass structures such as data centers and control rooms. In addition, it is expected to increase the demand for using this type of technology given the recent evidence of continued functionality of hospitals isolated with friction pendulums, that were struck by the $M_w$ 7.8 and 7.5, 2023 Kahramanmaraş earthquakes in Türkiye. In consequence, the percentages shown in Fig. 7 are expected to change quickly in the upcoming years.

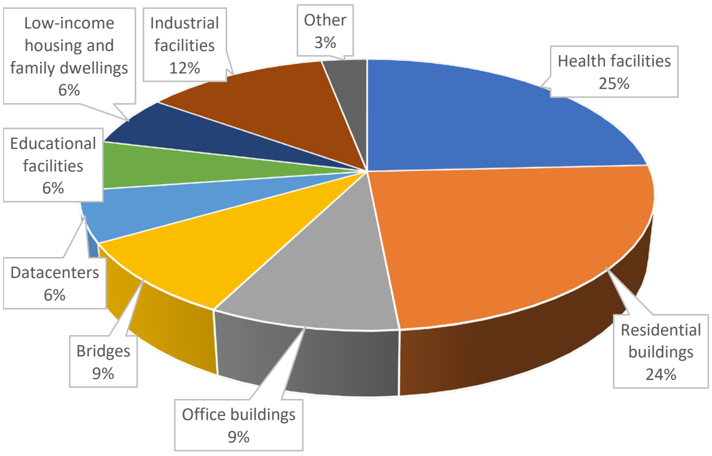


Figure 6 Isolated structures in Chile

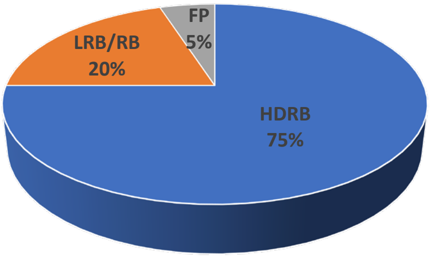


Figure 7 Type of isolation technology

By year 2010 most existing seismically isolated structures in Chile were buildings of relatively low height, mainly health care facilities. In the last decade the application of protection devices rapidly expanded to other types of structures such as datacenters, museums, laboratories, educational facilities, industrial facilities (such as LNG tanks, control rooms, and telescopes), and more importantly, to office and residential buildings. Current trends consider the transition from high damping rubber bearings to lead rubber bearings and frictional pendulum systems, to protect relatively tall buildings, massive structures in isolated blocks, low mass critical tech infrastructure, and bridges. The incorporation of isolation devices manufactured worldwide into the Chilean market has resulted in a reduction of 30% in the cost of the isolators, contributed significantly to increase testing capabilities, and helped with the technology transfer. Fig. 8 shows the Torre del Sol condominium, the first of many relatively tall buildings isolated in Chile. The building, structured using shear bearing walls, was built in Copiapo City, in a 100 years seismic gap zone. The structure, which spans 19,000 m$^2$ approx. and 19 stories, was at its time the tallest residential building with seismic isolation in the Americas. A typical floor covers 53x12.9 m. The total height of the building, including the undergrounds, is 49.6 m. The total seismic weight of the structure supported by the isolation system is 155,000 kN. The foundation soil corresponds to a stiff soil with average shear wave velocity in the first 30 m beneath the surface of 598 m/s. For this project, lead rubber bearings were considered. In order to provide stability to the structure and to prevent tension forces on the isolators, 60x197 cm beams were considered underneath the parking area, on the second underground level. Seismic isolators were arranged at the ends of beams and, generally, at the ends of bearing walls. To reduce costs, the 45 seismic isolators used in the structure were all identical. The maximum compressive force on the isolators (considered for design and for testing) was 8,200 kN, while the tensile force (or minimum compression load) was 0 kN. Prototypes and all production isolators were subjected to an exhaustive test series combining compression and shear to validate the properties assumed for the design and to verify the stability of the isolators during extreme seismic loads. In the design of the isolation system, a series of nonlinear dynamic analyses were carried out taking into consideration 7 seismic records compatible with the demands associated with the maximum considered earthquake defined in the Chilean standard for the seismic zone and ground conditions at the building site. A wide variety of seed records were selected to allow for analysis of the different seismic events to which the structure could be exposed during its lifetime. The analysis showed that the use of isolation allows for achieving a reduction close to 90% in the average base shear, story drifts, and floor accelerations of the structure. The good performance of the structure is related to the high stiffness and redundancy of bearing walls, which allows for concentrating nonlinear deformations in the seismic isolation system. Fig. 8 also shows other similar condominium buildings incorporating isolation systems.

Fig. 9 shows examples of health facilities, office buildings, datacenters, bridges, and viaducts incorporating seismic isolation technologies. Most hospitals are structured considering reinforced concrete intermediate moment resistant frames, with typical story heights of 4.0-4.5 m and distance between columns in the range 7.8-8.5 m. Office buildings are typically structured considering a combined system of shear walls in the core and columns in the perimeter. Datacenters may be structured using a variety of structural systems, including reinforced concrete moment resistant frames, shear walls, steel moment resistant frames, and special concentrically braced frames.

Bridges and viaducts, as shown in Fig. 9d, are typically structured considering simple supported spans, with expansion joints every 4 spans. Girders are typically steel or posttensioned concrete. Bridges and viaducts are designed to fulfill both AASHTO LRFD and AASHTO GSSID requirements.

Figure 8 Examples of seismically isolated tall residential buildings in Chile: Torre del Sol (left); Nunoa Capital (center); and Via Poniente (right)

## 2. CHILEAN CODE FOR SEISMIC ISOLATION DESIGN

### 2.1 First Code for Seismic Isolated Structures Design (2003)

The first Chilean code for seismic design of isolated structures, NCh2745, was released in 2003 [7]. The code, mainly based on the requirements of the UBC-97 standard, collected the experience gained in Chile from the first isolated projects. The seismic demands were determined by the committee based on data recorded by the national network of accelerometers of the University of Chile. The code considered Newmark type design spectra. The Peak Ground Accelerations (PGA's) for the Design Basis Earthquake (DBE) and for the Maximum Considered Earthquake (MCE) were determined probabilistically considering probabilities of exceedance of 10% in 50 years, and 10% in 100 years, respectively. The ratio between MCE and DBE PGA's was estimated equal to 1.2. The displacement branch in the DBE spectra was defined deterministically as the envelope of all historically recorded data (until 2003), multiplied by a factor equal to 2. Fig. 10 shows a comparison between the DBE code spectrum and the 5% damping response spectra obtained from earthquakes $M_w \geq 7$ affecting coastal high seismicity zones between 1985 and 2010. The response and design spectra correspond to soil Type B, characterized by shear wave velocities $v_s$ in the range 500 to 900 m/sec. In a similar way, the Chilean code considered reduction factors due to damping (B) that differed from the values in UBC 97 and ASCE/SEI standards. Fig. 11 shows the reduction factors as a function of SDOF effective damping and period, and a comparison between the reduction factors in UBC and Chilean standards.

The Chilean code limited the super-structure story drifts, computed for DBE level and considering, as a maximum, a response modification factor R ranging between 1 and 2, to a value equal to 0.0025 of the story heigh when modal spectral analysis was performed. This value can be increased to 0.003 if nonlinear response history analysis is carried out. The displacements and design forces shall be linearly scaled whenever the shear at the seismic isolation level results below $0.067W_s$, where $W_s$ corresponds to the reactive seismic weight of the isolated structure, for structures located in coastal zones; and $0.05W_s$ for structures located in Central zones between the Pacific Ocean and the Andes Mountains. In addition, the Chilean code mandates that the vertical frequency of the isolation system shall be at least 10 Hz.

a) Health care facilities

b) Office buildings

c) Datacenters

d) Bridges

Figure 9 Isolated structures examples

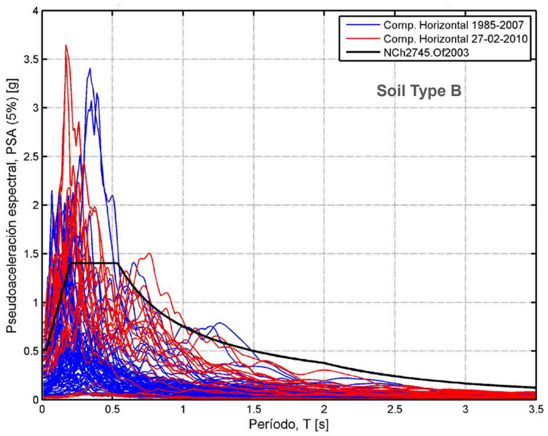


Figure 10 Comparison response and Code DBE spectrum

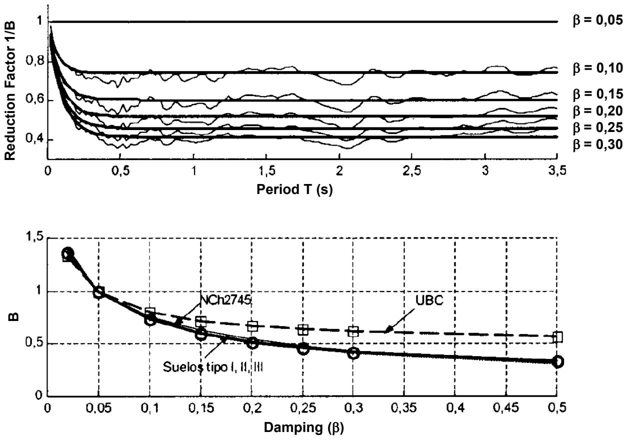


Figure 11 Damping reduction factors in Chilean code

## 2.2 First Review of Code for Seismically Isolated Structures Design (2013)

Ten years after releasing the first version of the code, the standard was reviewed in 2013 to include the experience accumulated during one decade of professional practice and the lessons learnt from the El Maule 2010 earthquake. In addition, the code revision had the objective of promoting the use of the technology and correcting the issues that made difficult applying the code. Among the measures made, the requirements of gap between isolated structures were clarified.

Given the response spectra of the records obtained during the 2010 El Maule earthquake ratified that the design spectra considered by the Chilean standard (Fig. 10) were conservative for periods close to 3.5 sec, the $T_M$ period for which specific site spectra development is not required was increased from 3.0 to 3.5 sec.

The 2013 standard permits that structural elements located above the isolation system in buildings structured using reinforced concrete moment resistant frames can be designed and detailed in conformity with the requirements of ACI-318 standard for intermediate moment frames instead of special moment frames, whenever the criteria for the strong column – weak beam is fulfilled. Similarly, it removes the need for boundary elements in bearing walls in isolated structures. The structural elements located under the isolation interface in reinforced concrete isolated structures must meet the requirements of ACI-318 for special moment frames, while 80% of the seismic load is not transferred to structural walls. The code allows for an increase in the response modification factor for designing the sub-structure elements from 1.0 to 1.5, in consideration of the intrinsic over-resistance of current design procedures. The standard establishes that the response modification factor to be considered for designing the isolated structure does not need to be less than 1.0, so the design demands will not need to be greater than the elastic seismic demands. Fig. 12 shows the fragility curves used to support the decision to use intermediate frames instead of special moment resistant frames [8]. Fig. 12 shows the fragility curves for ultimate rotation capacity of structural elements in isolated (ISO) and fixed base (BF) structures. The curves for the first (Max), 16th (P16) and 50th (P50) percentile ultimate rotation capacity exceedances are shown. In the figure is observed that the PGA triggering the first ultimate rotation capacity in a fixed base special moment frame structure is 35% lower than the PGA triggering the first ultimate rotation capacity in the isolated intermediate moment resistant frame.

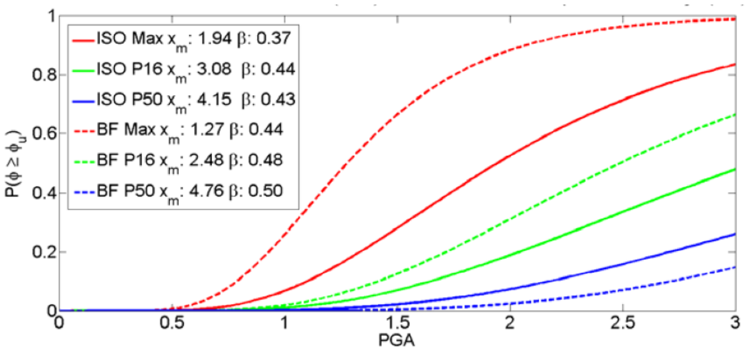


Figure 12 Fragility curves for intermediate and special moment resistant frames.

In the case of structures with seismic isolation systems based on frictional pendulums, the 2013 standard establishes mandatory consideration of response history analysis for designing the isolation system. This measure is based on the difficulties in predicting the behavior of isolators that base their response on a friction that depends on the vertical load and displacement rate, varying at each second on the isolators. Consequently, the code requires that response history analyses include the vertical components of earthquakes. Complementarily, the code clarifies the procedures for determining the total displacement of structures with this type of isolation system, given that torsion effects are controlled given the centers of mass and stiffness coincide at any moment in time.

The 2013 version of the code includes explicit quality control test requirements for rubber and frictional pendulum isolators, an aspect which previously was left to the discretion of the structural engineer of record. In particular, and in the case of natural rubber or high damping isolators, 100% of the isolators in a project require testing. For frictional pendulum isolators, testing is required, as a minimum, for 15% of the isolators in the project, but no less than 4 units.

The code is further complemented with clarifications regarding the requirements for P-Delta analysis, load combinations to be considered for the design of isolation systems and structural components, inspection and maintenance requirements for isolated structures, gap requirements between isolated and fixed structures and between isolated structures, and requirements for the design of nonstructural components in isolated buildings, among other clarifications.

### 2.3 Second Review of Code for Seismically Isolated Structures Design (2023)

The code is currently under review to further introduce improvements and clarifications oriented to ease the implementation of seismic isolation technologies. In consequence, what is described in this section is still under discussion and it may not be adopted. The first topic in discussion is the seismic demand considered for designing isolation systems. The committee concluded the need to increase the ratio between MCE and DBE from 1.2 to 1.4, without consideration of reducing DBE, which will result in an increase in design displacements. In addition, the committee agreed to consider the vertical ground motion component for the analysis and design of all types of seismic isolation systems. The incorporation of lambda factors in the code is still under discussion, but probably the factors in ASCE/SEI 7 will be adopted. Procedures and equations to compute load capacity of elastomeric bearings will be explicitly included, with instructions for their correct application. Minimum safety factors for load and deformation capacities will be explicitly included to uniformize the criteria among designers. Finally, the committee agreed on the need and convenience to clarify that nonstructural components in isolated structures do not need to be designed considering component importance factors $I_p$ greater than 1, even in critical infrastructures. This initiative is expected to result in savings making attractive the use of seismic isolation.

## 3. OTHER DESIGN CONSIDERATIONS AND PROFESSIONAL PRACTICE

### 3.1 Design considerations for health facilities

In addition to the requirements of the Chilean standard, authorities and practitioners consider their own criteria. In particular, the Ministry of Public Health and the Ministry of Public Works elaborated in 2020 a guideline [9] with specific requirements for designing health infrastructure. The guideline mandates the use of natural rubber and lead rubber bearings, prohibiting the use of high damping rubber bearings. The prohibition of HDRB is due to its well know and documented scragging, ageing and reliability issues, and the observed manufacturers' difficulties to fulfill technical specifications testing tolerances. The use of lubricated sliders is also prohibited. The use of flat dry sliders is allowed, as far as the service load on individual sliders does not exceed 1,500 kN. The total service load on sliders shall not exceed 0.25 times $W_s$, where $W_s$ corresponds to the seismic reactive weight of the isolated structure. The first requirement results in the use of sliders in zones of stairs, accesses, patios, and low service loads in general. The second requirement has the objective to define an upper limit to the activation of the isolation system.

Given that current Chilean code does not include procedures to consider variation in bearing properties due to scragging, ageing, temperature, velocity, and travel, among others, the guideline recommends using the lambda factors procedure available in ASCE/SEI 7 for modeling the isolation system. Similarly, the guideline stablishes that the safety factors for bearing load capacities shall be greater than 3 and 1 for static and seismic load combinations, respectively. The minimum safety factor for total shear strain of elastomeric bearings is defined equal to 1.5, including shear strains caused by direct shear and vertical maximum loads, but excluding shear strains due to rotation. This safety factor shall be computed considering a shear strain capacity of the rubber equal to $0.85\varepsilon_u$, where $\varepsilon_u$, the ultimate strain of rubber, shall not be considered greater than 600%. This requirement uniformizes the criteria considered by designers. While tensile stress up to $2G_r$ are permitted by certain design codes, where $G_r$ is the shear modulus of the elastomer, the design criteria for health facilities does not allow tension forces on bearings, given the difficulties for performing laboratory tests for bearings in tension.

Concrete shrinkage effects shall be considered by adding an initial bearing deformation $D_o$ equal to 50 mm to the maximum total displacement $D_{TM}$ of the isolation system. This initial deformation shall be considered independent of the construction joints considered in the project. The initial deformation shall be also considered for determining the static bearing load capacity. This requirement has the objective to consider shrinkage observed in Chilean cements, which is typically in the range 0.8-1.0 mm/m.

The guideline requests performing probabilistic seismic hazard analysis to determine the seismic demands to consider for designing the structure (DBE) and the isolation system (MCE). The considered spectra shall not fall below the NCh2745 spectra.

The guideline requests that the capitals below and above the isolators shall be at least 90 cm larger than the diameter of the bearing, to accommodate the jacks required to jack the structure, if needed, and to have enough room to distribute capital's reinforcement. This requirement does not apply in the building perimeter, around elevators or other singularities. According to the guideline, all building utilities shall be placed at least 1.5 m away from the bearings, to ease routine and post-earthquake inspections.

Elastomeric bearings shall be protected with a F-120/180 passive fire protection system tested according to ASTM E119/ISO 834. The maximum temperature measured by the thermocouples placed at the bearing surface shall not exceed 140 ºC. Before fire testing, the fire barrier shall be mechanically tested to accommodate at least 10 cycles under a displacement equal to $\pm D_{TM}$ without exhibiting any damage. Testing materials only is not allowed. The full constructive solutions shall be mechanically, and fire tested. The fire barrier shall permit the inspection of the bearings every 5 years (maximum) or after earthquakes with $M_w \geq 6$.

Another important requirement raised by the guideline for hospitals is related to the minimum gap required around the isolated structure. The document requires to control the probability of pounding between the isolated structure and surrounding structures to be less than 5% for the DBE, and less than 10% for the MCE level.

### 3.2 Additional Requirements from Professional Practice

In addition to the requirements described in previous sections, practitioners have further considerations to make safer designs. Among these considerations, limits to maximum pressures on isolators and seismic isolation activation requirements are found. Practitioners typically limit the maximum pressure on elastomeric bearings to 17-18 MPa for isolators with diameters in the range 70-115 cm. The activation of the seismic isolation is controlled by limiting the total characteristic strength ($Q_{Tot}$) of the isolation system to be, typically, in the range 0.01-0.03 times $W_s$, to get an isolation system activated by the moderate earthquakes that frequently affect the territory. Controlling $Q_{Tot}$ also allows for controlling permanent deformations.

Fig. 13 [10] shows the effects of varying the yield force $F_y \sim 1.1 Q_{Tot}$ and the post yield period (T) on the normalized base shear ($V/W_s$) and maximum displacement of a SDOF system subject to a set of Chilean ground motions scaled to the NCh2745 spectrum. Typical post yield periods for hospitals and large structures are in the range 4-5 sec. In consequence, for typical $F_y$ and T values, the base shears and displacements are close to $0.1W_s$ and 300 mm, respectively.

Fig. 14 [11] shows the residual displacements ($D_{res}$) as a function of the total characteristic strength of a model structure. The blue, orange, green and brown dots correspond to soil Types A ($v_s \geq 900$ m/s), B (500 m/s $\leq v_s <$ 900 m/s), C (350 m/s $\leq v_s <$ 500 m/s), and D (180 m/s $\leq v_s <$ 350 m/s), respectively. In Fig. 14 it can be observed that for typical characteristic strengths values the residual displacements do not exceed 14 mm.

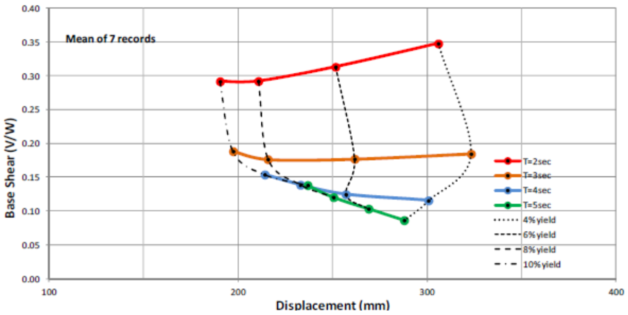


Figure 13 Effect of yield force and post yield period on base shear and maximum displacement

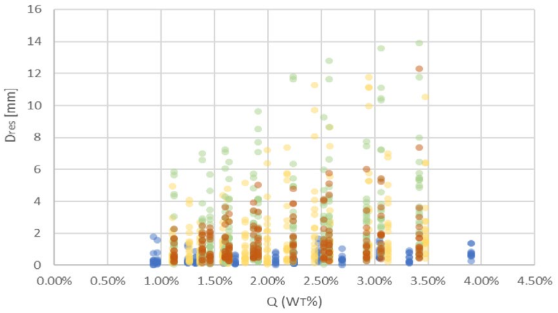


Figure 14 Residual displacements ($D_{res}$) as a function of characteristic strength

## 4. CONCLUSIONS

The application of seismic isolation technologies is rapidly growing in Chile. Currently, by January 2024, the number of structures incorporating protection devices is close to 200. The good performance of the protected structures during the $M_w$ 8.8, 2010 El Maule earthquake, demonstrated throughout the recorded response of instrumented structures, triggered an increased demand for the use of protection devices. The use of protection systems has expanded from demonstration and health facilities projects to datacenters, viaducts, bridges, and office and tall residential buildings. The observation of international experiences and the execution of technology transfer projects have been fundamental for these developments. Among the future challenges is the continuous improvement of the codes to make even more attractive to investors the use of seismic protection technologies.

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# CURRENT STATE AND CHALLENGES OF IMPLEMENTING SEISMIC ISOLATION IN NEW ZEALAND (2023)

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## ABSTRACT

This paper describes the current state of practice and challenges in the application of seismic isolation (base isolation) of structures in New Zealand. The widely used lead-rubber bearing technology was invented by New Zealand scientists. Since 2010 New Zealand has experienced significant earthquake events causing loss of life, serious damage leading to demolition of a large number of buildings, as well as large economic impacts. These events have resulted in a move away from designing conventional structures and relying on high levels of ductility, which often result in irreparable damage. Performance-based design approaches set objectives for achieving resilient seismic behaviour, including specific objectives for acceptable life safety, damage occurrence and repairability, as well as functional recovery of structures. Owners and engineers in New Zealand are now more often adopting earthquake protection technologies including seismic isolation and supplemental damping (energy dissipation) systems such as dissipative braces, viscous dampers and friction sliding devices. The paper provides examples of recent new and retrofit projects that have incorporated seismic isolation and performance-based design objectives that exceed minimum code requirements. Challenges to the ongoing implementation of seismic isolation and other related technologies in New Zealand are discussed.

**KEYWORDS:** seismic, isolation, New Zealand, current state, challenges

## 1 INTRODUCTION

New Zealand is a seismically active country located adjacent to the active Hikurangi subduction zone [ref. Geonet]. The country has been a leader in development of earthquake resistant structural design methods such as capacity design, ductile design of reinforced concrete and the development of seismic isolation and other earthquake protective technologies.

This paper summarises recent progress and developments in the application of seismic isolation (base isolation) for seismic protection of structures in New Zealand. Although New Zealand engineers were instrumental in developing seismic isolation technology, including inventing lead-rubber bearings, use of isolation has been until recently predominantly only for significant public and high importance buildings. Following severe earthquakes in Christchurch in 2010/11 and Kaikoura in 2016, there has been an increase in the application of isolation and other energy dissipation technologies for earthquake protection of new and existing buildings, not just for high importance buildings. Recent examples of new and retrofit structures using isolation and other energy dissipation technologies are summarised. A New Zealand guideline for design of isolation systems for buildings has been published to assist designers of isolation systems.

## 2 APPLICATIONS OF SEISMIC ISOLATION IN NEW ZEALAND

### 2.1 Growth of number of isolated structures

Based on the author's personal enquiries, as at late 2023, there are now approximately 110 isolated structures in New Zealand. Fig. 1 shows the growth in numbers of isolated structures over time including the types of structures and isolation technology. Around half of the total number of structures are bridges and there has been a steady increase in the overall number of isolated structures from 2010, since the Canterbury earthquakes.

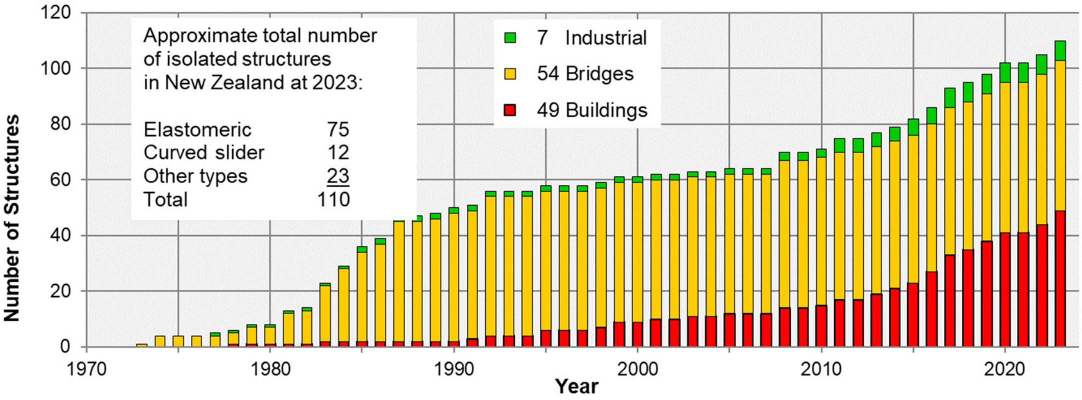

Figure 1. Growth in numbers of structures with seismic isolation in New Zealand.

### 2.2 Examples of Building Projects with Seismic Isolation

Fig. 2 shows the new 50-bed Children's hospital recently built in Wellington [ref. McKee Fehl]. The hospital is a three-level 8,000 m$^2$ floor area building supported on 45 Triple Pendulum™ isolators, providing seismic protection to withstand a 1-in-2500-year event in a high seismicity zone. This required the isolators to accommodate substantial horizontal isolator displacements of 1500 mm, which is the largest displacement provided in an isolation system in New Zealand to date.

Fig. 3 shows the Christ Church Cathedral located in the centre of Christchurch which was extensively damaged by the Canterbury earthquake sequence of 2010/2011. Damage to the largely unreinforced masonry building included collapse of the bell tower and significant dislocation of walls in the building. Previous localised strengthening work likely helped the building survive the earthquakes without more extensive collapse. Repair and strengthening of the cathedral [ref. Christ Church Cathedral] is currently in progress and has included a carefully managed sequence of external stabilization, insertion of a new ground floor slab and raft sub-foundation, new structural walls and tie elements, and extensive re-construction and grouting of the masonry walls. The final stage of the restoration includes retrofit of seismic isolation under the building to protect the repaired and strengthened building against future earthquakes.

**Figure 2. Left: New isolated Wellington Children's Hospital. Right: Triple Pendulum™ isolator diagrammatic.**

**Figure 3. Earthquake repair including base-isolation of historic Christ Church Cathedral. Left: building under repair. Right: graphic of digital model used for engineering analysis.**

## 3 NEW ZEALAND GUIDELINE FOR DESIGN OF SEISMIC ISOLATION SYSTEMS FOR BUILDINGS

A guideline [ref. Isolation Guideline, 2019 and Whittaker 2020] for the design of seismic isolation systems for buildings in New Zealand was recently published for trial use by designers. The Guideline sets a framework and recommendations for designing buildings with seismic isolation, in accordance with the New Zealand Building Code [ref. Building Performance] and the Structural Loading Standard NZS 1170.5 [ref. Loading Standard]. It provides displacement-based analysis and design recommendations that supplement the requirements for normal buildings to account for period elongation and additional damping available in building structures with isolation systems.

The Guideline covers four prescribed isolated building types from simple to complex. The chapters include: performance objectives for isolated buildings, design limit states and design philosophies, design spectra for acceleration and displacement demands, analysis methods, design approaches to be used for the various components of an isolated building; ie superstructure, isolation system and substructure, detailing of the isolation plane, guidance on preparing technical specifications for procurement of the isolation system and isolator devices, recommendations for inspection and maintenance of the isolation system and components. The content of each Chapter is presented as recommendations (normative) and associated commentary (informative).

This project was led by technical societies and funded largely by government agencies. The Guideline was prepared by national specialists and reviewed by several international experts.

The Isolation Guideline provides both acceleration and displacement spectra for design of isolated structures. The design spectra are based on NZS 1170.5 [ref. Standards NZ] elastic acceleration design spectra and derived displacement spectra, including adjustment for the overall equivalent level of viscous damping in the isolated building system. Once the global design actions are established, the methodology then determines the required actions for design of the isolation system, substructure and superstructure, in accordance with appropriate materials design standards (eg for concrete and steel structures).

Although the Isolation Guideline currently has no formal or legal status, is generally regarded as being the authoritative and accepted guidance for designing isolated buildings in New Zealand. The Guideline content is relevant for design of structures with other earthquake protective technologies such as supplemental damping that are also not within the scope of current New Zealand design codes. Each technology and system type requires specific design to reflect relevant performance characteristics.

Whittaker [reference 2020] presented examples of acceleration and displacement demands on isolated structures using the Isolation Guideline document. The behaviour of the typical isolation system is based on a yielding bilinear hysteretic system, which can be represented by the generalised expression for an equivalent curved surface slider system given in Equation 1. The system behaviour for an elastomeric system using lead rubber bearings, can be expressed in a similar equation form representing overall system yield force and elastic restoring force terms.

$$V_b = W(f + \frac{\Delta}{R}) \quad (1)$$

where $V_b$ is the base shear force at the isolation plane

$W$ is the isolated superstructure weight

$f$ is the friction coefficient (and $Wf$ is the effective yield force of the system)

$\Delta$ is the horizontal displacement of the isolation system

$R$ is the radius of curvature for the equivalent curved surface slider system.

The isolation system base shear versus displacement behaviour can be depicted on an acceleration versus displacement response graph, together with the earthquake acceleration versus displacement demand spectrum (the so-called “ADRS” spectrum). This ADRS format plot conveniently allows capacity-demand diagrams, such as the example shown in Fig. 4 (left), to estimate acceleration and displacement response demands on the isolation system. Also shown in Fig. 4 (right), is an example parametric design chart (nomogram) that was derived from the Isolation Guideline by considering a range of typical isolation system parameters at a Christchurch location, where the ground conditions are typically deep soft soils. The nomogram considers a practical range of key isolation system parameters including yield level ranging from 6% to 12% of the isolated weight and post-elastic slope corresponding to a range of equivalent curved surface isolator radii from 2 m to 6 m. The reference to "CALS" in the diagram is to an explicit "Collapse Avoidance Limit State" used in the Isolation Guideline, being a limit state considering survival of a maximum considered rare earthquake. Parametric nomograms for other locations and site conditions were also reported in Whittaker [2020].

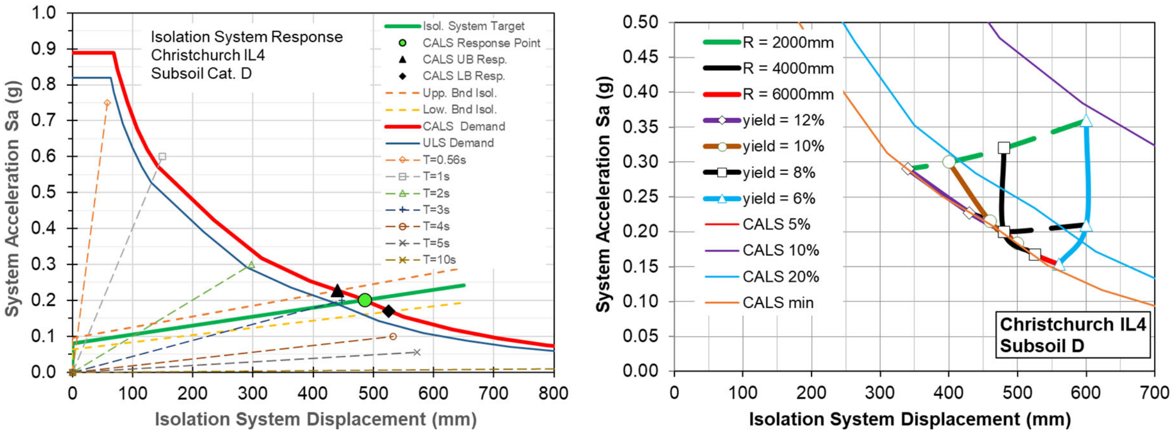

**Figure 4. System response graphs in acceleration-displacement format, showing demands for isolated buildings in Christchurch according to the NZ Isolation Guideline. Left graph shows an example isolation system response against design earthquake demands. Right graph shows parametric demands for various levels of system yield and effective radius of curvature for an equivalent curved surface slider system.**

## 4 CHALLENGES FOR IMPLEMENTATION OF SEISMIC ISOLATION

The following subsections discuss a number of challenges that designers in New Zealand face when conceiving and implementing seismic isolation for structures.

### 4.1 Isolation Versus Other Protective Technologies

It is not easy for designers to compare and quantify the performance benefits and costs of other competing technologies such as dissipative braces and supplemental damping systems including Buckling Restrained Braces (BRBs), friction devices and fluid viscous dampers (FVDs). These systems do not have the beneficial feature of an isolation plane where large seismic movements can be directed and accommodated. On the other hand, these systems avoid the cost and complexity that an isolation plane brings.

Table 1 provides a qualitative comparison of some characteristics of different seismic protection systems, including conventional fixed-base construction, based on the author's experience.

Table 1. Comparison of seismic protection systems.

| Protective System | Benefits | Potential Disadvantages |
|---|---|---|
| Conventional Fixed base (eg moment frame, cross-braced frame or wall) | Code compliance requirements clear.<br>Cost savings with high ductility.<br>Optional performance in excess of code.<br>Can select ductility and repairability. | Ductility brings damage which can be difficult or uneconomic to repair.<br>Large structure sizes in high seismic zones with low ductility. |
| Seismic Isolation | Generally best protection possible.<br>Reduced superstructure sizes and cost.<br>Protection of structure, building fabric & contents from damage and disruption.<br>Large reduction of drifts & accelerations.<br>Concentrates deformation in isolators.<br>Excellent functional recovery.<br>Extensive global use and experience.<br>Design codes / guidelines available. | Alternative code compliance (in NZ).<br>Cost premium over conventional.<br>Requires space for isolation plane / gap.<br>Cost of isolators and additional suspended structure over isolation plane. |
| Fluid Viscous Dampers | Can reduce response significantly.<br>Maximum damping forces out of phase with elastic forces.<br>Can be optimised to limit number. | Must be used with elastic primary structure to provide re-centering.<br>No easy path to code compliance.<br>Typically used in braced configurations which impacts usable floor area.<br>Normal application needs many devices. |
| Friction system (part of frame or braced or rocking system) | Inelastic deformation & damping in devices.<br>Can also provide re-centering if required.<br>Proprietary products available. | No easy path to code compliance.<br>Flag-shaped hysteresis gives limited additional damping. |
| Rocking system | "Partial" isolation solution | Special study for NZ code compliance.<br>Drifts in superstructure large to achieve period shift and force reduction. |
| Buckling Restrained Braces (BRB) | Direct and efficient bracing system.<br>Well-established international supply. | Alternative path to code compliance.<br>Attracts large forces and floor accelerations. Large brace members impact usable area. |

### 4.2 Which Isolation Technology to Use

Most practicing engineers in New Zealand have limited experience to assess the performance characteristics, costs and benefits of each isolation technology and which is best suited to their project. Engineers are reliant on published case studies and advice from specialists and suppliers. The two common systems used in New Zealand recently are laminated rubber bearings (including lead) in combination with flat slider bearings and curved surface slider (pendulum) bearings. Although not common in New Zealand to date, there may be advantages in using laminated rubber or lead rubber bearings in conjunction with viscous dampers to achieve greater reduction of superstructure response.

### 4.3 Knowledge of Structural Engineers

Application of new earthquake protective technologies such as seismic isolation requires practitioners to develop new knowledge and skills to reliably design building systems containing them. Design of these systems requires knowledge and consideration of the following:

- Using displacement-based design methods and utilising supplemental damping.
- Selecting performance-based design strategies to achieve performance outcomes, possibly in excess of code minimum requirements.
- considering damage control and repairability, and reducing functional recovery times.
- Meeting sustainability targets including measuring and reducing embodied carbon.

### 4.4 Building Code Compliance

Many of the available protective technologies are not explicitly covered by design codes and require alternative compliance pathways, as well as specialist peer review. The New Zealand Building Code is performance-based, but compliance is normally achieved following cited design Standards, known as *Verification Methods*. The Building Code also permits compliance using *Alternative Solutions* using guidelines or methods that are not cited but may be accepted, normally with appropriate peer review. These approaches can bring increased risk of non-compliance and unintended outcomes, so care is needed.

### 4.5 Specification Supply and Testing of Devices

Seismic protection devices are usually proprietary, meaning they are designed and manufactured by the supplier to meet performance requirements specified by the building designer. In New Zealand almost all isolation devices are imported from international suppliers and most prototype and production testing is also carried out overseas by the supplier or approved test agency, with independent oversight and verification. Designers and specifiers need to be familiar with these procurement processes to ensure reliable outcomes are achieved. The New Zealand Isolation Guideline provided guidance for specifying isolation systems and devices including sample technical specifications for typical isolation devices following international standards such as EN 15129 or ASCE 7-17 Chapter 17.

### 4.6 Revised New Zealand National Seismic Hazard Model

The seismic hazard in New Zealand has recently been updated [ref. GNS Science 2022]. For some parts of the country the seismic hazard appears to have increased significantly, perhaps up to 2 times, compared with the current code hazard maps. These increases in hazard, if reflected fully in the design standard, will lead to substantial increases in seismic design actions and displacement demands, as well as costs, in all structures, including those with isolation.

### 4.7 Earthquake Insurance Availability

The availability of earthquake insurance is relatively high in New Zealand. It is understood that more than 80 percent of property damage from recent major earthquakes in New Zealand was insured. New Zealand has a government-led Earthquake Commission (EQC) fund which provides first-cover for residential properties, including land damage from earthquakes. As at 2023, this scheme provides first-cover up to around US$200,000 per residential property for natural disaster events. Most residential property owners purchase additional top-up earthquake insurance cover, up to an agreed insured value. Commercial properties are generally insured for earthquake damage, under material damage insurance policies. Insurance premiums are likely to increase under the influence of sporadic seismic activity and anticipated more extreme weather events. Hopefully, increases in natural and seismic hazards will lead to greater interest in seismic risk mitigation, such as use of seismic isolation, rather than passing risk to insurers. Global sustainability pressures will likely also encourage further development and uptake of seismic resilient and protective technologies such as seismic isolation.

## 5 CONCLUSION

Seismic isolation remains the premier earthquake protection technology in New Zealand. Use of seismic isolation and other supplemental damping technologies has increased steadily following recent severe and damaging earthquakes. Owners and engineers are increasingly recognising the significant performance and life-cycle benefits that these technologies bring to reducing disruption and improving functional recovery of buildings and their contents. The benefits include increases in safety, as well as reductions in the frequency and severity of damage and downtime to repair any damage that does occur. These trends are likely to continue with the increased focus on sustainability and increasing earthquake insurance premiums.

A recently published New Zealand guideline for design of buildings with seismic isolation helps designers of these systems meet the requirements of the national building code. Peer review is a key step in ensuring designs meet national standards and stated performance objectives.

In addition to seismic isolation, other energy dissipation and supplemental device technologies are now being routinely used in New Zealand, including dissipative braces, fluid viscous dampers, friction slip devices and design using rocking foundations.

Seismic isolation and other supplemental energy dissipation technologies are essential for protecting buildings and their occupants from future earthquakes in New Zealand.

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