SEISMIC RESPONSE CHARACTERISTICS Of BASE-ISOLATED FRAMES SUPPORTED BY STEPPED FOUNDATIONS IN MOUNTAINOUS AREAS

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ABSTRACT

Building structures may undergo different degrees of damage or even collapse under the action of earthquakes, especially in mountainous areas, and in order to reduce the risk of seismic hazards, seismic mitigation measures should be taken for building structures in mountainous areas. In this paper, seismic isolation bearings are introduced into mountainous terrace foundation frame structures and their seismic performance is thoroughly studied. We compare the effects of structures with and without seismic isolation bearings on seismic performance, analyze the seismic performance of several structures with seismic isolation bearings arranged at different locations. And combined with the construction cost of building structures, an analysis was conducted on different structures. It is found that, after the seismic isolation bearings are arranged at different elevations to form unequal isolation layers, the isolation layer can enter the yielding state under seismic action, but still does not exceed the horizontal ultimate deformation of the lead-core rubber seismic isolation bearing, which shows a good effect of seismic isolation and energy dissipation.

In order to improve the comprehensive disaster prevention capability of urban and rural areas, this paper proposes a method to rapidly predict the seismic response of stepped seismic isolation frame structures in mountainous areas using artificial intelligence (AI). We designed 7-story typical RC frame structures using the structural design software Midas Gen, and used the control variable method for dynamic time course analysis. We obtained five factors that have a strong influence on the seismic performance of stepped seismically isolated frame structures in mountainous areas, including the seismic isolation bearing arrangement, the degree of structural regularity, the intensity of defense, the type of site, and the seismic intensity. Based on the results of the dynamic time history analysis and combining these influencing factors, we established a sample library containing 384 seismic samples. Suitable domains and affiliation functions were assigned to each influencing factor, and fuzzy rules were established based on the seismic sample library, and a fuzzy inference model was built using the fuzzy logic toolbox in Matlab, and the accuracy and stability of the model were verified. The experimental results show that the seismic influencing factors selected in this paper can accurately map the seismic damage prediction results of the frame structure, and the method is accurate, fast, efficient, and can be applied to the rapid seismic damage prediction of step-isolated frame structures in mountainous areas.

Keywords: Base-isolated frames supported by stepped foundations in mountainous areas, seismic response, earthquake prediction, fuzzy inference modelling, dynamic time history analysis .

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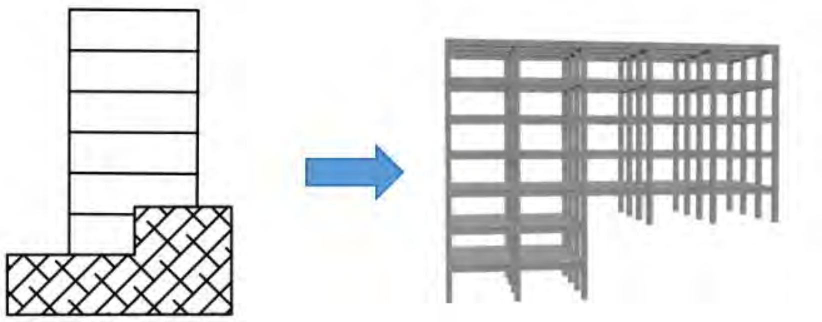
CHAPTER 1
INTRODUCTION

1.1 PROBLEM STATEMENT

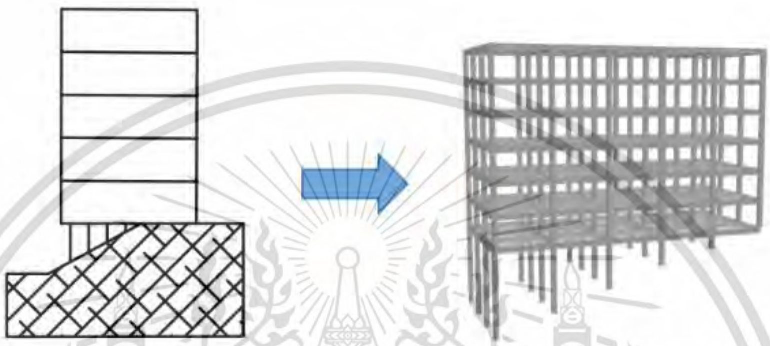
Earthquakes are a common natural disaster, posing a great threat to the safety of people's lives and property. In recent years, earthquakes have occurred frequently in China, with larger earthquakes reaching a magnitude of 8.0 in the 2008 Wenchuan earthquake, a magnitude of 7.0 in the 2013 Ya'an earthquake, and a magnitude of 7.0 in the 2017 Jiuzhaigou earthquake[1]. Especially in mountainous areas with complex terrain and frequent seismic activity, buildings are more vulnerable to earthquakes. China's mountainous region accounts for 33%, in order to alleviate the shortage of flat land resources, effectively protect the ecological environment, and adapt to the mountainous terrain, in recent years, a new type of building structure has appeared---base-isolated frames supported by stepped foundations in mountainous areas, and the common mountainous terraced foundation building is shown in Figure 1.1. Mountain ladder type foundation frame structure means that the embedded end of the foundation is not on the same horizontal plane, and the common mountain ladder type foundation seismic isolation frame structure has two forms of dropping layers and hanging feet, as shown in Fig. 1.2, and this paper will focus on the study of this structure type in Fig. 1.2-a.

(a) Hongyadong scenic spot **(b) A scenic spot in China**

Fig 1.1 Architectural diagram of a stepped foundation in a mountainous area



(a) Dropping layers



(b) Hanging feet

Fig 1.2 Common stepped foundation isolation frame in mountainous areas

The force characteristics and seismic performance of the mountainous terraced foundation frame structure and the ordinary flat ground frame structure are significantly different. Southwest China is in the Mediterranean-Himalayan seismic zone, and earthquakes have occurred frequently in recent years, and many buildings in mountainous areas have suffered different degrees of damage in earthquakes. At present, the domestic traditional seismic anti-seismic technology still occupies the mainstream position, with the continuous progress of science and technology, people's defence against earthquakes in the form of continuous optimization, from the previous traditional seismic transition to seismic isolation, and seismic isolation technology as a reduction of seismic isolation of the mainstream technology in the field of space for the promotion of a larger. Isolating buildings from the ground is a technique employed to minimize the effects of earthquakes on structures, known as building isolation.Not only is the seismic effect good, but also can achieve the economic purpose.The seismic isolation of a residential building structure involves installing a seismic isolation layer that facilitates a comprehensive reset between the foundation, base, or substructure of the house and the superstructure. This elongates the self-vibration period of the entire structural system, diminishes the impact of horizontal seismic forces on the superstructure, and meets the desired seismic protection standards. Figure 1.3 is a schematic diagram of foundation isolation.

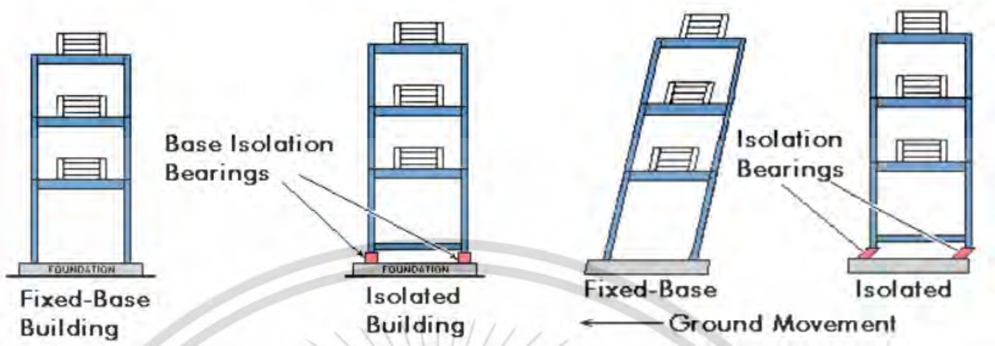


Fig 1.3 Schematic diagram of foundation seismic isolation principle

Foundation isolation structure system is the most widely used and mature seismic isolation structure in the world, the foundation isolation device has stacked rubber bearing, friction slip device, rolling isolation device and hybrid foundation isolation device and other types. Among seismic isolation devices, laminated rubber bearings are extensively utilized and represent the most mature technology. This technology is commonly employed both domestically and internationally in seismic isolation projects involving building structures, bridges, and equipment. The majority of applications in China, Japan, the United States, and other countries involve the successful implementation of laminated rubber bearing seismic isolation technology, with these buildings and bridges having successfully passed earthquake tests. The main use of stacked rubber seismic isolation bearing to absorb seismic energy, reduce the role of the earthquake on the superstructure[2]. Stacked rubber seismic isolation bearing in the project application as shown in Figure 1.4.

(a) During construction

(b) After construction

Fig 1.4 Application of seismic isolation bearings in the project

Due to the vertical irregularity of mountainous terraced foundation frame structure, the force characteristics and damage modes of the structure under seismic action are different from those of ordinary flat ground frame structure, and the forces of mountainous terraced foundation frame structure are more complicated[3]. In the case of conventional flat frame structures, the utilization of stacked rubber isolation bearing technology proves effective in diminishing the dynamic response of the structure during seismic activity, thereby enhancing structural safety. So far, only a few people have conducted research on stepped foundation frame structures combined with seismic isolation bearings in mountainous areas, so this paper will be the foundation seismic isolation technology applied to the mountainous terraced frame structure - mountainous terraced foundation seismic isolation frame structure, mountainous terraced foundation seismic isolation frame structure schematic diagram as shown in Figure 1.5.

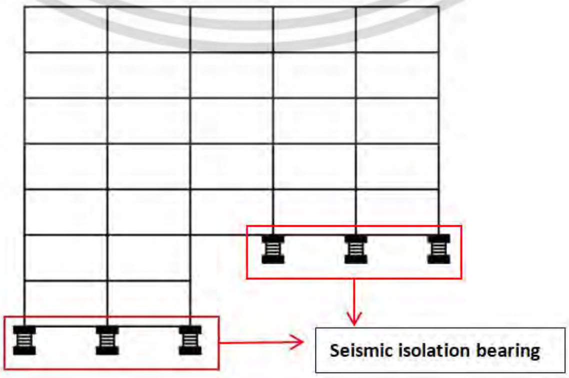


Fig 1.5 Mountain stepped foundation isolation frame structure

By analyzing the seismic response characteristics of a structure, one can ascertain the structural damage state resulting from seismic forces. This enables the identification of seismic hazard factors that significantly influence the structure's seismic performance. Subsequently, a seismic hazard sample library is established, encompassing multiple seismic hazard factors. An artificial intelligence model is then created to swiftly predict the structure's damage state, allowing for proactive seismic hazard predictions. Based on these predictions, appropriate reinforcement measures can be implemented for the structure. Moreover, practical recommendations for the design of mountainous stepped-foundation isolated frame structures are formulated through a comprehensive analysis. These suggestions aim to enhance the seismic performance of such structures in mountainous regions, mitigate structural damage during earthquakes, and safeguard the lives and properties of individuals.

1.2 OBJECTIVES OF THE RESEARCH WORK

This study is centered on investigating the seismic response characteristics of mountainous stepped base seismically isolated frame structures. Its objectives include providing design recommendations for such structures, assessing structural damage states based on seismic response characteristics, predicting earthquake-induced damage, and developing a model for the rapid prediction of structural damage. The ultimate aim is to enhance the seismic performance of stepped base seismically isolated frame structures in mountainous areas, thereby reducing earthquake-related losses and ensuring the safety of individuals. Summary Objective:

1. The first objective is to compare the seismic performance of an ordinary mountainous stepped frame structure with that of a mountainous stepped base-isolated frame structure, which will visually show that the structure containing base-isolated bearings is seismically effective.

2. The second objective is to change the arrangement of seismic isolation bearings and to compare the seismic performance of mountainous stepped-foundation seismically isolated frame structures with different arrangements of seismic isolation bearings, which can be used as a reference for structural design and optimisation. Comprehensive analysis of each structure based on construction cost and construction period.

3. The third objective is to study the influencing factors that have a significant impact on the seismic performance of stepped base isolated frame structures in mountainous areas and to analyse the seismic response of these influencing factors on the structure.

4. The fourth objective is to assess the structural damage level resulting from seismic forces, utilizing the seismic response of the structure. Additionally, a model will be developed that incorporates artificial intelligence technology for swift prediction of the structural damage degree caused by earthquakes.

The ultimate goal is to guide the design of such structures as stepped base seismic isolation frames in mountainous areas, and to design structures that can achieve the goal of "not being damaged by small earthquakes, being repairable by medium earthquakes, and not collapsing by large earthquakes"[4]. Reducing the effects of earthquakes on mountainous terraced base isolation frame structures enables the use of relevant parameters to predict seismic hazards, thereby protecting people's lives and property.

1.3 HYPOTHESES OF THIS STUDY

As earthquakes pose a significant threat to human safety and can result in varying degrees of damage to different types of buildings, this study focuses on analyzing the seismic response of a stepped base isolated frame structure in mountainous areas. The force dynamics in such regions are complex, and seismic performance is influenced by the vertical irregularity of the structure during earthquakes.The conventional seismic-resistant approach of reinforcing building structural elements with increased materials like reinforcing steel, concrete, and steel structures, while common, may lead to house collapse, severe casualties, and economic losses during earthquakes exceeding fortification intensity. The inability to accurately predict the magnitude of future earthquakes further complicates this method. In high-intensity zones, larger building components increase construction costs, impacting space utilization and building functions. In contrast, structures equipped with a foundation isolation system demonstrate superior seismic resistance. A seismic isolation device is incorporated into the foundation to create an isolation layer, preventing the transmission of seismic energy to the superstructure.

This results in reduced seismic energy input to the superstructure and an extended self-vibration period, lowering seismic response and meeting seismic requirements for enhanced building safety. Seismic isolation technology not only ensures the overall integrity of the building structure and protects non-structural components but also prevents internal structural damage and associated secondary disasters. It is anticipated that mountainous terraced frame structures employing seismic isolation techniques can reduce seismic action on the superstructure of a building by over 50%. This study identifies factors significantly impacting the structure's seismic performance through dynamic characteristics analysis. A model combining artificial intelligence technology for seismic damage prediction is established to swiftly predict the degree of damage. Design suggestions for a seismic isolation frame structure with a stepped foundation in mountainous areas are proposed based on the structure's force and seismic performance. In summary, the mountainous stepped frame structure with seismic isolation technology proves to be more seismic-resistant, safer, and economical compared to the ordinary mountainous stepped frame structure. The accuracy of the developed rapid prediction model for the degree of structural damage is closely tied to the selection of seismic factors, the seismic sample database's capacity, and other influencing factors.

1.4 MAIN LINES OF RESEARCH

This study primarily concentrates on the structural design of mountainous stepped base seismically isolated frame structures using the structural design software Midas Gen. Subsequently, finite element analysis is conducted to examine the seismic performance of such structures. The seismic response of the structure is analyzed to identify influential factors that significantly impact its seismic performance. Based on these factors, a multi-influence factor seismic damage sample database is established, and the seismic damage prediction model is developed using the fuzzy toolbox in Matlab. The specific research route is illustrated in Figure 1.6.

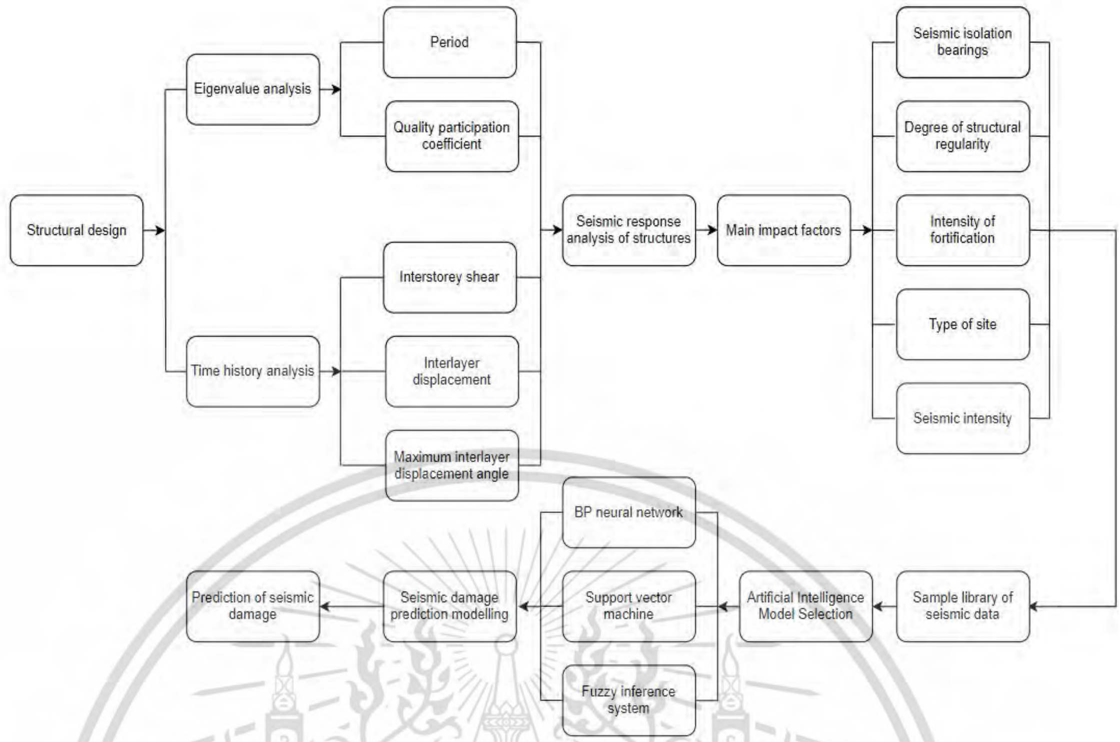


Fig 1.6 Main research lines

1.5 SCOPE OF THIS PAPER

Presently, there is a limited theoretical foundation guiding the design and research of seismically isolated buildings in mountainous areas globally, indicating that existing theories do not fully align with practical engineering needs. Many engineering designers rely on their past experiences when designing seismically isolated buildings in mountainous regions. To address this gap, this paper employs numerical simulation with the finite element software Midas Gen as a research tool, focusing on the seismically isolated frame structure with a stepped foundation in mountainous areas. Midas Gen is utilized to simulate the seismic isolation bearing, comparing various calculation models under the influence of multiple earthquakes. The study identifies factors with a significant impact on the seismic performance of mountain buildings, establishing a multi-factor seismic database. Using Matlab, a rapid prediction model for the degree of structural damage to mountain structures under seismic action is developed, enabling seismic damage predictions. Building upon existing research findings, the study delves into the force characteristics and seismic damage prediction of mountainous stepped-foundation seismically isolated frame structures.

The scope of this paper covers the following areas:

1. All of the mountainous stepped foundation frame structures in this study are of the dropped floor type in Figure 1.2-a. It is carried out based on Southwest China, and the relevant building codes as well as engineering profiles need to be in accordance with Chinese standards.

2. The buildings studied in this paper are all medium-rise buildings, none of which has more than seven floors.

3. The seismic performance findings from this study should enable the assessment of the structural damage degree and the identification of influential factors that significantly impact the seismic performance of the structure.

4.This study is based on a model developed by fuzzy tools in Matlab to quickly predict the degree of structural damage.

1.6 STRUCTURE OF THE PAPER

The thesis is structured into five chapters, each focusing on a specific aspect of the research. A brief overview of each chapter is provided below:

Chapter 1: Introduction

This chapter outlines the background to the study of stepped-foundation seismically isolated frame structures in mountainous areas and the significance of making earthquake predictions, defines the objectives and scope of the study, and the problems to be addressed.

Chapter 2: Literature review

This chapter provides a thorough review of articles concerning seismically isolated frame structures with stepped foundations in mountainous areas. The review encompasses the history of seismic isolation technology, applications of seismic isolation rubber bearings, the suitability of existing seismic isolation methods, the present state of research on seismically isolated frame structures with stepped foundations in mountainous regions, and the current status of research on seismic damage prediction.

Chapter 3: Methodology

This chapter centers on the mechanical characteristics of laminated rubber bearings, their integration into Midas Gen, and the choices related to seismic waves, finite element analysis methods, and approaches pertinent to seismic damage prediction. The goal is to lay the groundwork for the subsequent phases of the study.

Chapter 4: Results and discussion

In this chapter, the primary focus is on utilizing the finite element software Midas Gen for structural design, modeling, dynamic characteristic analysis, and time course response analysis of the structure. The results of the study are comprehensively compared and analyzed to identify factors with a significant impact on the seismic performance of the structure. Building upon these influential factors, a seismic damage sample database is established, and a model based on artificial intelligence technology is developed for the rapid prediction of the structure's damage degree. This chapter also involves earthquake damage prediction, and based on the analysis outcomes, presents rational suggestions for the structural design of mountainous stepped-foundation seismically isolated frame structures.

Chapter 5: Conclusions and outlook

The final section summarises the main findings and conclusions of the study. The benefits of studying the seismic performance of stepped-foundation isolated frame structures in mountainous areas and the feasibility of seismic damage prediction through artificial intelligence techniques are summarised, in addition to looking at areas for future research, reflecting the fact that the whole research process is relevant. Overall, the structure of the thesis follows a logical progression, starting with an introduction to the problem, followed by a literature review, detailed analysis and evaluation, and finally a summary of the findings and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter aims to offer a comprehensive overview of seismic isolation technology for building structures, encompassing its concepts, principles, and development. It includes a detailed examination of the classification and operational principles of the rubber seismic isolation bearings employed in this study. Additionally, the chapter provides a survey of the current state of research and practical applications in engineering, delves into existing design methods for general seismic isolation of framed structures, and evaluates the applicability of current seismic isolation methods. This review serves as a foundational background for the thesis and furnishes crucial information for the analyses undertaken in this study.

2.1 OVERVIEW OF THE FOUNDATION ISOLATION SYSTEM

2.1.1 Foundation isolation concept

Seismic isolation for building structures involves placing a seismic isolation layer between the foundation, base, or substructure and the superstructure of a house. This layer typically comprises stacked rubber seismic isolation bearings with an overall reset function. The primary objective is to extend the self-vibration period of the entire structural system through the implementation of the seismic isolation layer. This extension helps diminish the horizontal seismic impact on the superstructure, thereby meeting seismic design requirements and enhancing the overall seismic performance of the structure.

2.1.2 Principle of base isolation

The base isolation system is designed to reduce the effect of earthquake on the structure, which can be known according to Fig. 2.1 (seismic influence coefficient curve). According to the seismic response spectrum curve, it can be known that the structural self-oscillation period is inversely proportional to the acceleration response spectrum. The seismic isolation structural system uses its own characteristics to adjust the damping and regulate the relationship between the period of the superstructure and the characteristic period of the site, Figure 2.2 shows the structural self-oscillation period and the acceleration response spectrum; Figure 2.3

shows the self-oscillation period and the displacement response spectrum. This can be done by increasing the structural damping ratio or increasing the period of the structure. Figure 2.4 shows the schematic diagram of the principle of foundation seismic isolation device.

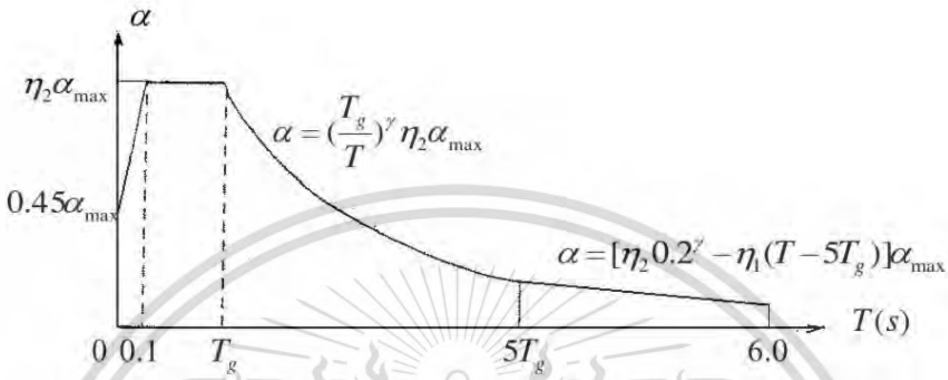


Fig 2.1 Seismic impact factor curve

Among them: α is the seismic influence coefficient; γ is the attenuation index; T is the structural self-oscillation period; α_{max} is the maximum value of the seismic influence coefficient; T_g is the characteristic period; η_1 is the descent slope adjustment factor for the straight-line descent section; η_2 is the damping adjustment factor.

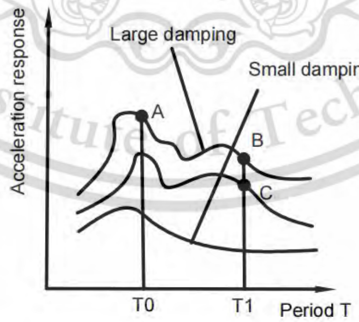


Fig 2.2 Structural natural vibration period and acceleration response spectrum

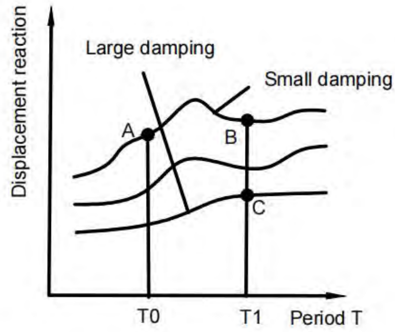


Fig 2.3 Structural natural vibration period and displacement response spectrum

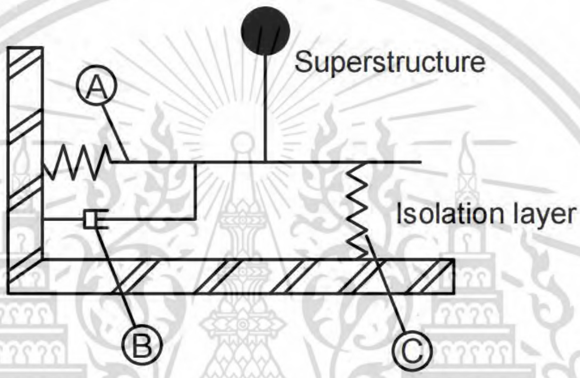


Fig 2.4 Schematic diagram of vibration isolation device

Among them, A is the device supporting the upper structure in the horizontal direction, which can extend the self-oscillation cycle of the structure, provide resilience and achieve the effect of seismic isolation; B is the horizontal energy-consuming device between the upper structure and the lower structure, which reduces the amplitude of the upper structure and the role of energy consumption; C is the device supporting the upper structure in the vertical direction, which ensures that the upper structure has the normal use of the function.

2.1.3 Advantages of base isolation systems

1. The structure using the foundation seismic isolation system can significantly reduce the seismic response of the structure, so that the superstructure is in an elastic working state, the damping of the seismic isolation layer is greater than that of other layers, consuming the main energy of the earthquake.

2. Greatly simplify the complex nodes and seismic construction measures of the structure in the high intensity area, making the structure more economical and applicable.

3. The base seismic isolation bearing will be reset and easily replaced after damage, which is very conducive to the rapid repair and restoration of the building structure after the earthquake.

2.1.4 Development and application of base isolation

In 1881, Kawai Kozo, a Japanese scholar, first proposed the concept of foundation seismic isolation, which suggests that several layers of logs should first be placed vertically and horizontally on the foundation, a concrete foundation should be made on the logs, and then a house should be built on the concrete foundation in order to weaken the energy transmitted by the earthquakes[5].

1909. United States J.A. Kalantrenz of the United States proposed another seismic isolation scheme, which is to lay a layer of talc or mica between the foundation and the upper building so that the building will slide during an earthquake to isolate it.

In 1921, the American engineer F. L. Wright in the design of the Imperial Hotel in Tokyo, Japan, intended to use dense short piles through the surface of the hard soil, directly inserted into the bottom of the soft soil layer, the use of soft soil layer as a seismic isolation layer.

In 1924, Kenzaburo Oniguchi of Japan proposed a seismic isolation method of inserting bearings between the column footings and the foundation of a building.

In 1927, Taro Nakamura of Japan discussed the addition of a damper-absorbing device, which was a useful exploration in the theory of seismic isolation.

In 1984, New Zealand constructed the world's first four-storey building with lead-core laminated rubber mats as the seismic isolation element.

In 1985, the first four-storey, stacked rubber mat seismic isolation building in the United States was completed at the Judicial Affairs Centre in San Dinh, California.

In 1986, another 5-storey technology centre building was built in Japan with lead-core rubber mats.

Research in this area is being carried out in about 30 countries around the world, and the technology has been applied to bridges, buildings and even nuclear facilities. Some 3,100 basic seismic isolation buildings have been constructed in the world, more than 80 per cent of which use stacked rubber mat isolation systems.

In the late 1980s, Chinese scholars began to focus on rubber vibration isolation bearing technology. Zhou Fulin from Guangzhou University and other scholars as academic leaders, carried out the development of rubber seismic isolation bearing, seismic isolation structure analysis and design methods, rubber bearing product performance inspection, testing technology, construction technology and other all-round systematic research work, put forward the rubber bearing seismic isolation of the building of a complete set of technology. At present, the construction of seismic isolation technology in most provinces and autonomous regions have been applied, has built more than 4,000 seismic isolation building.

2.2 CURRENT STATUS OF RUBBER ISOLATION BEARING RESEARCH

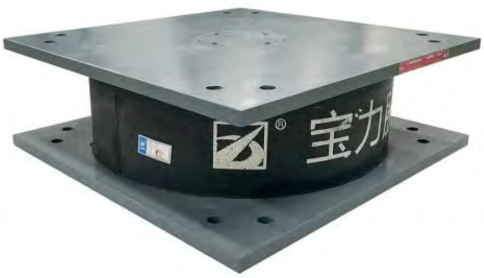
Since the 1960s, people have carried out relatively systematic research and experiments on seismic isolation bearings, and tested them in actual engineering, and made a lot of tracking observations. About the research on seismic isolation members, there are two main aspects: on the one hand, actively exploring new materials, new techniques and new methods to develop various kinds of seismic isolation members, and on the other hand, studying how to apply seismic isolation bearings in engineering practice and considering their seismic isolation performance and engineering cost issues. A review of some scholars' research on rubber seismic isolation bearings is shown in Table 1.

Table1.Overview table of the current state of research

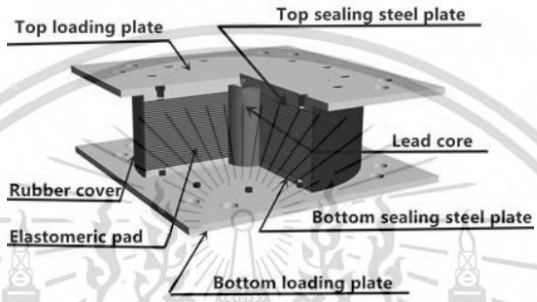
Author	Years	Analysis conclusion
Ahmet Hilmi Deringöl	2019	The seismic response of the base-isolated frame can be accurately estimated by adjusting the structure for the appropriate isolation period, yield strength ratio, and effective damping ratio[6].
Parham Shoaei	2019	A regression equation is proposed to predict the optimal design variables, i.e., initial stiffness and yield force, for a base isolation system[7].

Du Yongfeng	2019	The protective layer of lead core rubber seismic isolation bearings plays an important role in slowing down the decay of their fire resistance[8].
Ahmet Hilmi DERİNGÖL	2020	The use of lead-core rubber isolation bearings can improve the seismic response of regular and irregular frames with some degree of elevation[9].
Ahmet Hilmi Deringöl	2021	The seismic performance of base-isolated structures is significantly influenced by the isolation parameters. The most favorable base isolation model was obtained when higher isolation periods and effective damping ratios were combined with lower yield stiffness ratios[10].
Yang Zhen	2022	The specific mechanical parameters of lead core rubber seismic isolation bearings were analyzed and compared using the control variable method[11].
Haosheng Zhou	2022	The peak vertical force of the seismic isolation bearing can be reduced by decreasing the standardized strength factor, increasing the horizontal period, and the sway-vertical frequency ratio[12].

Nowadays the most widely used bearing is laminated rubber bearing, laminated rubber vibration isolation bearing is divided into ordinary laminated rubber vibration isolation bearing, high damping laminated rubber bearing and lead core laminated rubber bearing[13]. Which ordinary laminated rubber bearing does not have enough energy-consuming capacity, generally need to be used together with other dampers; high damping laminated rubber bearing production cost is high, and is not widely used in the project; lead core laminated rubber bearing can absorb more energy, and construction and installation of convenient, reasonable price, so it is widely used in the project. Lead core laminated rubber isolation bearing consists of Top sealing steel plate, Top loading plate, Rubber cover, Elastomeric pad, Lead core, Bottom sealing steel plate, Bottom loading plate seven parts. Composition, lead core stacked rubber seismic isolation bearing construction details shown in Figure 2.5.



(a) Lead core rubber isolation bearing diagram



(b) Lead core rubber isolation bearing construction details

Fig 2.5 Lead rubber isolation bearing

2.3 APPLICABILITY OF SEISMIC ISOLATION ANALYSIS METHODS

Presently, the two primary seismic isolation analysis methods employed in engineering applications are the mode decomposition response spectrum method and the time-distance analysis method. The mode decomposition response spectrum method relies on structural modal analysis, making it the most commonly used and effective technique for analyzing the seismic effects of linear structural systems. In existing research on seismic isolation structures, the mode decomposition response spectrum method is widely acknowledged and preferred for its fast calculation speed and stability. On the other hand, the time-distance analysis method considers complete damping, vibration mode coupling, elastic-plastic properties of the structure, and numerical analysis. This comprehensive approach makes the time-course analysis method the most accurate among seismic analysis methods.

In 2016, Li Chunyin from Chongqing University used the finite element software SAP2000 to study the applicability of existing foundation isolation design methods in stepped foundation frame structures, designed an eight-story typical stepped foundation isolation frame structure, selected five natural seismic waves and two artificial seismic waves and ground vibration input according to the multi-encounter level, and used the vibration pattern decomposition reaction spectrum method and time-range analysis method to analyse the designed structure by taking the average value of the shear force between each floor under the action of seven seismic waves and the results of the analysis of the vibration pattern decomposition reaction spectrum method with the forced decoupling to make a comparison. The average value of the interstorey shear under the action of seven seismic waves is compared with the results of the forced-decoupled vibration mode decomposition response spectrum method, and the interstorey shear values of the floors calculated by the forced-decoupled vibration mode decomposition response spectrum method and the time-range analysis method are relatively close to those obtained by the time-range analysis method, with a maximum difference of about 10 %[14].

In 2019, Luo Huijun [33] from South China University of Technology studied the applicability of seismic isolation methods using the finite element software SAP2000, designed a 7-story typical stepped-foundation seismic isolation frame structure, selected five natural seismic waves and two artificial seismic waves, and amplitude-modulated the seismic waves by adjusting the value of the maximum ground vibration input acceleration to 200 $\mathrm{cm/s^2}$, and the selected seismic waves were The checking and calculating is done, which meets the specification requirements. The selected seismic waves were input into the finite element software SAP2000, and the interstorey shear force was obtained by the time-distance analysis method and the vibration pattern decomposition reaction spectrum method, and the maximum error of the two methods was 8.2%, and the interstorey shear force value of each floor had a very small error[15].

In accordance with the stipulations outlined in the Code for Seismic Design of Buildings, the discrepancies between different seismic computation methods should be limited to within 20%. Upon analyzing the results obtained from the two computation methods mentioned above, it is evident that the computation results derived from the vibration decomposition response spectrum method not only fulfill engineering requirements but also exhibit accuracy that aligns with the practical needs of engineering applications.

2.4 CURRENT STATUS OF RESEARCH ON SEISMICALLY ISOLATED FRAME STRUCTURES WITH STEPPED FOUNDATIONS IN MOUNTAINOUS AREAS

Mountainous stepped-foundation seismically isolated frame structures are a complex engineering field involving the design and construction of buildings with good seismic performance in mountainous areas, and a number of scholars have done a series of studies in this field, as reviewed in Table 2.

Table2.Overview table of the current state of research

Author	Years	Analysis conclusion
He Ling	2010	If the stiffness ratio of the bottom storey of the stepped contact frame structure is increased, then the plastic energy dissipation capacity of the entire stepped base frame structure will be increased and its seismic performance will be improved[16].
Zhao Wei	2012	The effects brought about by the different ways of structural arrangement on the damage modes of stepped foundation frame structures are analyzed[17].
Tang Green	2012	The seismic performance of stepped foundation frame structure is investigated and it is concluded that the seismic performance of stepped foundation frame structure is better when lead core rubber and sliding bearings are used for the upper grounding section[18].
Yang Botao	2014	Stepped foundation frame structure on the grounded column column bottom and its column top node damage is serious, the upper ground for the deformation of the larger weak parts, the damage mode is mainly beam hinge "beam-column hybrid hinge"[19].
Hu XiaoYi	2014	After the installation of seismic isolation devices, the upper part of the can achieve the purpose of

		vibration damping and isolation, but the effect of the substructure is still to be studied[20].
Yang, Jinliang	2018	A seismic isolation model was strengthened using a BRB and the seismic laws were summarized for the strengthened model[21].
Ayoub Shakouri	2021	The level of ductility and type of connection significantly affect the seismic response of base isolated and fixed base buildings[22].
Yasaman Jalali	2021	Superstructures with special ductility reduce peak floor acceleration by a maximum of about 20% compared to ordinary structures. In addition, the special ductility level increased the peak drift demand by 75% compared to a normal base isolation building[23].
Jae-wook Jung	2022	The nonlinear increments of the response spectrum within the structure with respect to the intensity of the input ground shaking as well as the nonlinear behavior of the vibration isolators are evaluated[24].

2.5 CURRENT STATUS OF RESEARCH ON EARTHQUAKE DAMAGE PREDICTION

At present, the prediction methods of earthquake damage of single building at home and abroad include six kinds of historical earthquake damage statistical method, expert assessment method, fuzzy analogy method, semi-empirical and semi-theoretical method, structural theory calculation method and dynamic analysis method[25]. Freeman in the United States conducted a statistical analysis of building damage caused by worldwide earthquake disasters, which was a more comprehensive summary of earthquake damage experience in the early days.

Algermissen, Steinbrugge et al. obtained the probability curves of ground shaking and structural damage for various types of buildings in the San Francisco area based on seismic data and engineering experience, and in the 1970s, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey

(USGS) organised earthquake damage studies in San Francisco, Los Angeles and other cities. In the 1970s, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS) organised research on earthquake damage in San Francisco, Los Angeles and other cities, and established ground shaking intensity and structural damage probability curves by combining seismic hazard data and engineering experience.In the 1980s, the U.S. Federal Emergency Management Agency (FEMA) carried out a study on the assessment of future earthquake damage in California, and established a damage prediction method based on damage probability matrices by researching seismic hazard and structural vulnerability. Through the study of seismic hazard and structural vulnerability, it established a damage prediction method based on the probability matrix, and relied on this method to develop the seismic risk assessment software HAZUS.

After the Tangshan earthquake, research on seismic capacity analysis and seismic damage prediction of single buildings in China has been carried out one after another. Yang Yucheng et al. (1982) proposed a seismic damage prediction method for multi-storey brick houses using the seismic strength of the wall as the main criterion, and at the same time taking into account the role of structural components and the influence of the site on seismic performance by adopting the historical seismic damage statistics method[26]. Liu Xihui et al. (1984) proposed a fuzzy quantitative earthquake damage prediction model for damage level, site soil category and intensity by establishing a fuzzy set of affiliation functions for the factors influencing the earthquake damage and the degree of damage using a fuzzy analogy method[27]. Yin Zhiqian et al. (1996) proposed the concept of damage probability of susceptibility, and adopted a semi-empirical and semi-theoretical method to give the relationship between the degree of earthquake damage and the resistance index of different types of structures, and obtained the calculation formula of damage probability and the earthquake damage matrix. On the basis of the original vulnerability analysis, the team proposed a dynamic model for seismic hazard prediction by considering the influence of time factor on seismic loss, and obtained the dynamic seismic damage matrix and dynamic loss matrix[28]. Wang Zhitao et al. (2007) proposed an earthquake damage prediction method based on housing census data by adopting an artificial neural network method and selecting previous earthquake damage examples with typical damage characteristics as learning samples[29]. Based on the fuzzy mathematical decision theory, Sun Bertao et al. (2008) proposed a single structure seismic damage prediction method based on a multifactor comprehensive analysis including site category, structure type, construction age, and number of structural floors[30]. The above seismic damage prediction methods generally rely on seismic damage statistical laws, expert experience, theoretical analyses, and experimental studies, and their scope of application and reliability are different according to different theoretical bases.

With the development of artificial intelligence technology, machine learning algorithms are gradually applied to the prediction of earthquake damage in buildings, and these methods usually only need to collect the more easily accessible seismic impact factors of the structural part, and based on a certain number of samples, the results of the earthquake damage prediction can be obtained quickly with the help of computer simulation. The rapid prediction method of earthquake damage for reinforced concrete frame structures based on BP neural network proposed by Zhang Lingxin et al. can obtain high accuracy in the case of sufficient number of samples, but it is difficult to establish a more accurate nonlinear prediction model in the case of small samples[31]. Su Yuan et al. carried out a preliminary study of structural earthquake damage prediction methods using the support vector machine algorithm, but the influencing factors and the number of samples considered are too small, and the prediction results have a certain degree of randomness. In order to better adapt to the society's increasing demand for earthquake prevention and disaster mitigation, the structural damage prediction method for frame structures still needs to be improved continuously[32]. Yan Jiaqi et al. used fuzzy logic to establish a fuzzy comprehensive evaluation model for the seismic performance of RC frame structure teaching buildings to predict the seismic performance of frame structures, and the reliability of the method was verified[33]. Li Na established a numerical analysis model of semi-active vibration damping control of seismic isolation structure with neural network and fuzzy controller, and carried out a research on vibration damping control of seismic isolation frame structure[34].

CHAPTER 3
METHODOLOGY

3.1 SEISMIC ISOLATION STRUCTURE DESIGN PRINCIPLES AND PROCESS

3.1.1 Principles of seismic isolation structure design

1. When designing a base-isolated building, the design ground vibration parameters, such as response spectra and seismic waves, should be chosen to be compatible with the site where the building is located.

2. Stacked rubber mat seismic isolation structures under vertical ground shaking are designed in the same way as conventional basement seismic structures.

3. To meet the required vertical bearing capacity, it is essential to minimize the horizontal stiffness of the seismic isolation device. This reduction aims to decrease the self-oscillation frequency of the seismic isolation structure, placing it significantly below the superior frequency range of ground vibration. This strategy ensures more substantial attenuation of seismic response. Simultaneously, it is crucial to control the maximum displacement of the seismic isolation within permissible limits.

4. Under the action of wind loads, the seismic isolation structure cannot have much horizontal displacement. Therefore, wind stabilisation devices are often required for the base isolation system of a structure, so that the isolation layer hardly deforms under wind forces less than the design wind load, while under seismic forces exceeding the design wind load, the wind stabilisation device is used together with the isolation device to isolate the structure.

5. In all types of houses where rubber mats are used for seismic isolation measures, the total building height and the number of storeys should comply with the requirements shown in Table 3.

Table3. Limits on total height and number of floors of seismically isolated buildings

Structure type	Height/m	Storey
masonry	Adopt traditional masonry earthquake-resistant structure	

Reinforced concrete structure	30	10
Reinforced concrete frames, shear walls,earthquake resistant wall construction	40	12

6. In seismic isolation structures, stacked rubber pads should avoid being subjected to tension. As a precaution, the maximum height-to-width ratio of the structure should adhere to the specified limits outlined in Table 4.

Table4. Maximum aspect ratio of seismically isolated houses

Intensity	6	7	8	9
Maximum Aspect Ratio	2.5	2.5	2.5	2.0

7. Rubber cushion seismic isolation bearings and other elements within the seismic isolation layer should undergo suitable fire protection measures in accordance with the fire resistance level applicable to the location of the seismic isolation layer.

3.1.2 Seismic isolation design steps for general structures

For regular flat structures, seismic isolation design methods are well established and the whole procedure is shown in Figure 3.1.

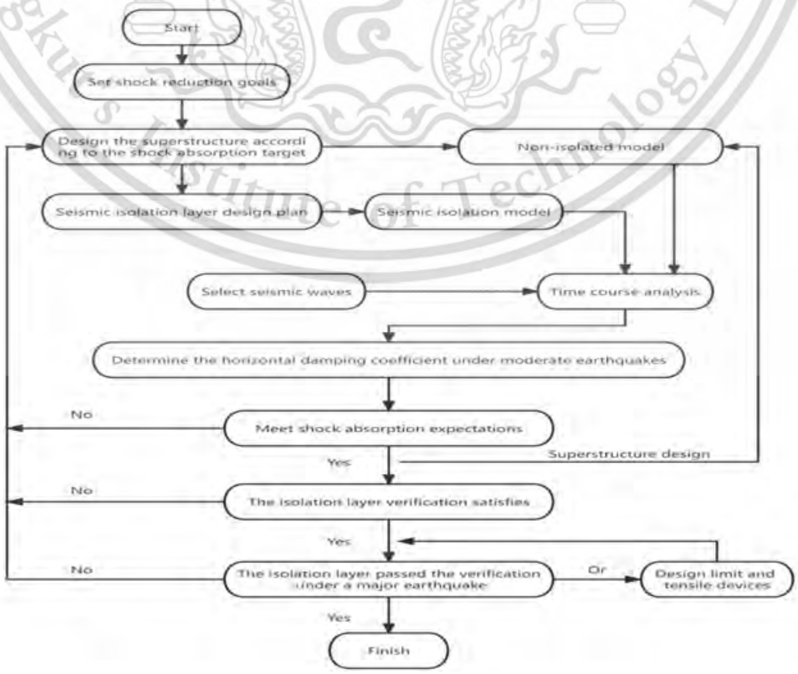


Fig 3.1 Seismic isolation design steps for general structures

3.2 MECHANICAL PROPERTIES OF RUBBER SEISMIC ISOLATION BEARINGS

3.2.1 Several theoretical assumptions for the derivation of mechanical properties

The formulae for calculating the parameters of laminated rubber bearings require the support of the following assumptions, which are varied to have different degrees of influence on stiffness, damping ratio and yield limit.

1. Elastic deformation theory

Bearing stiffness formula is in the bearing in the elastic working state, small deformation of the case of derivation. Once the laminated rubber bearing elastic-plastic or plastic work, resulting in a large nonlinear deformation, then you need to take into account the material in the nonlinear deformation of the laminated rubber bearing stiffness.

2. No deformation assumption of laminated steel plate

When subjected to vertical and horizontal loads, we assume the absence of out-of-plane deformation in the steel plate within the laminated rubber bearing. However, in practical working conditions, the steel plate is bound to experience out-of-plane deformation. Factors such as the thickness of the steel plate and the effects of openings can influence the performance of the laminated rubber bearing.

3. Rubber material without compression assumption

In the derivation of the elastic modulus formula for laminated rubber bearings, it is assumed that the Poisson's ratio of the rubber material is equal to 0.5. The relationship between the modulus of elasticity E_0 and the shear modulus G is E_0=2$G(1+v)$, which is obtained by substituting the Poisson's ratio of the rubber material at E_0=3G. However, the actual rubber material in the larger vertical load, will produce a small compression change, on the text of the elastic modulus formula derivation has a slight effect.

4. Shape factor of rubber seismic isolation bearing

By the geometric parameters of the bearing can be obtained from the laminated rubber seismic isolation bearing of the first shape coefficient S_1 and the second shape coefficient S_2 , the first shape coefficient S_1 is defined as the bearing in the effective pressure-bearing area of a single layer of rubber and its free-side surface area of the ratio of the expression of the formula shown in Equation 3.1. The second shape coefficient S_2 Under the action of the earthquake, the rubber bearing will occur a large horizontal deformation, which requires a large deformation of the rubber bearing in the high-pressure stress does not lose its own stability, in order to control the stability of the rubber bearing, the introduction of the second shape coefficient S_2. Its formula expression is shown in equation 3.2.

$$S_1 = \frac{d - d_0}{4t_R} \tag{3.1}$$

$$S_2 = \frac{d}{nt_R} \tag{3.2}$$

Among them: d is the rubber diameter, d_0 is the diameter of the lead core; t_R is the thickness of a single rubber layer ; $\mathrm{nt_R}$ is the total thickness of the rubber layer .

5. Rubber hardness correction factor k

Because different laminated rubber bearing manufacturers in the actual production and application of the bearing, through a variety of additives to improve the mechanical properties of rubber materials, so that the actual experimental value of the elastic modulus of the rubber bearing and our assumption of the theoretical calculation of the value of the derivation of the deviation of the elasticity of the rubber material modulus of elasticity formula, the introduction of the hardness of the rubber material correction coefficient k.

$$E_{sp} = E_0(1 + 2kS_1^2) \tag{3.3}$$

Among them: E_{sp} is the apparent modulus of elasticity of rubber,MPa ; E_0 is the modulus of elasticity of rubber, MPa; k is the rubber hardness correction factor; S_1 is the first shape factor of the rubber body.

6. Modification of the modulus of elasticity of rubber

When the pure rubber body is compressed vertically, the rubber body will project laterally, and the Poisson's ratio of the rubber material is close to 0.5. Since the rubber layer of the rubber seismic isolation bearing is very thin and is restrained by the steel plate, the lateral deformation produced is very small, and the bearing has a very high vertical stiffness. Considering the compression characteristics of rubber, Cent, Lindley et al. proposed a correction formula for the longitudinal modulus of elasticity that takes into account the uncompressed nature of rubber, i.e.

$$E_c = (\frac{1}{E_{sp}} + \frac{1}{E_\infty})^{-1} \tag{3.4}$$

Among them: E_c is the corrected modulus of elasticity of rubber, MPa; E_∞ is the bulk modulus of elasticity of rubber, MPa.

For the modulus of elasticity correction factor k, which is related to the hardness, there is no measured data. P. Blindley proposed a relationship between the modulus of elasticity correction factor k, the modulus of elasticity E_0, the bulk modulus of elasticity E_∞, the shear modulus of elasticity G, and the hardness of the natural rubber material, as shown in Table 5.

Table5. Rubber material performance parameters table

Rubber international hardness	E_0/MPa	G/MPa	k	E_∞/MPa
30	0.92	0.30	0.93	1.0×10^3
40	1.50	0.45	0.85	1.0×10^3
50	2.20	0.64	0.73	1.03×10^3
60	5.34	1.06	0.57	1.15×10^3
70	7.34	1.72	0.53	1.27×10^3

3.2.2 Vertical stiffness of the support K_V

Vertical load so that the rubber bearing in the direction of the force to produce vertical unit displacement, the ability to resist this vertical load that is the The vertical stiffness of the rubber bearing [41]. It is obtained by Equation 3.7.

$$K_V = \frac{E_{cb}A}{T_r} \tag{3.5}$$

Among them:

$$E_{cb} = \frac{E_c E_b}{E_c + E_b}$$

Among them: T_r is the total thickness of the rubber layer, $T_r = t_r \times n$; A is the cross-sectional area of the rubber inside the bearing, mm^2; E_c is the corrected rubber modulus of elasticity, MPa ; E_b is the bulk modulus of elasticity, MPa .

3.2.3 Horizontal stiffness of the support K_H

Vertical load so that the rubber bearing in the direction of the force to produce vertical unit displacement, the ability to resist this vertical load that is the The vertical stiffness of the rubber bearing . It is obtained by Equation 3.7.

Horizontal load makes the rubber bearing produce unit displacement in the horizontal direction, the ability to resist this horizontal load is the horizontal stiffness of the rubber bearing K_H. According to the theory that the horizontal seismic force and vertical load act together on the laminated rubber bearing to produce buckling of the bearing (Haringx theory), it is solved according to the following equation:

$$K_H = \frac{P^2}{2k_r q \tan(qH/2) - PH} \tag{3.6}$$

$$q = \sqrt{\frac{P}{k_r}(1+\frac{P}{k_r})} \tag{3.7}$$

Among them: P is the vertical pressure; H is the sum of the total thickness of the rubber layer T_g and the total thickness of the laminated steel sheet T_s ; q is the bearing stiffness conversion factor, mm^{-1} ; k_r is the effective bending stiffness of the bearing, $N \cdot mm^2$; $k_r = (EI)_{eff} = E_{rb} I \frac{\mathrm{H}}{\mathrm{T_R}}$, $E_{rb} = \frac{E_r E_b}{E_r + E_b}$, E_r is the flexural modulus of elasticity of rubber, MPa .

$$E_r = 3G(1+\frac{2}{3}kS_1^2) \tag{3.8}$$

Among them: I is the moment of inertia of the support section.

3.3 IMPLEMENTATION OF SEISMIC ISOLATION RUBBER BEARINGS IN MIDAS GEN

Midas Gen software provides several commonly used types of vibration isolator and damper units. These include six types of non-linearly connected units such as lead-core rubber-bearing isolators, viscoelastic dampers, gaps, hooks, hysteresis systems, and friction pendulum isolators.

In these nonlinear connection units, lead core rubber bearings use the property of low strength of lead after yielding to avoid the same or close to the ground vibration frequency by adjusting the intrinsic frequency of the structure for the purpose of seismic isolation and dissipate the ground vibration energy through hysteresis characteristics. The mechanical model of lead core laminated rubber bearing is shown in Figure 3.2.

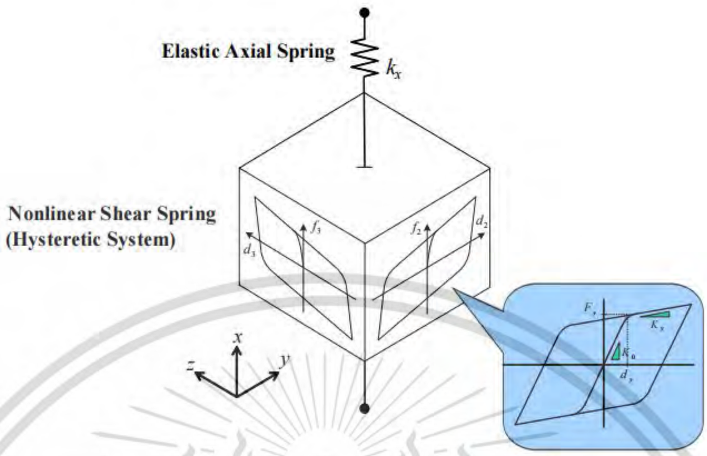


Fig 3.2 Mechanical model of lead core laminated rubber isolation bearing

The lead core rubber bearing comprises six springs, with two shear components exhibiting correlated biaxial elastic-plastic properties. The remaining axial and torsion bending components in other directions are linear and independent of each other. The correlation between force and deformation for the two shear components in the lead-core rubber bearing isolation device is expressed as follows.

$$f_y = r_y k_y \cdot d_y + (1 - r_y) F_{y,y} z_y \tag{3.9}$$

$$f_z = r_z k_z \cdot d_z + (1 - r_z) F_{z,z} z_z \tag{3.10}$$

Among them:

k_y and k_z are the initial stiffness of the shear component in the y and z directions of the unit coordinate coefficient; $F_{y,y}$ and $F_{y,z}$ is the yield stiffness of the shear component in the y and z directions of the unit coordinate coefficient; r_y and r_z are the post-yield strength reduction rate of the shear component in the y and z directions of the unit coordinate coefficient; d_y and d_z are the deformation between two nodes of the unit coordinate coefficients y and z direction shear components; z_y and z_z are the hysteretic characteristic internal parameter of the shear component in the y and z directions of the unit coordinate coefficient.

As an internal parameter reflecting the hysteresis effect, it is defined by the Biaxial Plasticity (Biaxial Plasticity) formula developed by Park, Wen, and Ang (1986) and others on the basis of Wen's (1976) uniaxial plasticity model.

$$\begin{Bmatrix}\dot{z}_y\\ \dot{z}_z\end{Bmatrix}=\begin{bmatrix}1-z_y^2\left\{\alpha_y \operatorname{sgn}\left(\dot{d}_y z_y\right)+\beta_y\right\} & -z_y z_z\left\{\alpha_z \operatorname{sgn}\left(\dot{d}_z z_z\right)+\beta_z\right\}\\ -z_y z_z\left\{\alpha_y \operatorname{sgn}\left(\dot{d}_y d_z\right)+\beta_y\right\} & 1-z_z^2\left\{\alpha_z \operatorname{sgn}\left(\dot{d}_z z_z\right)+\beta_z\right\}\end{bmatrix}\begin{Bmatrix}\dfrac{k_y}{F_{y,y}}\dot{d}_y\\ \dfrac{k_z}{F_{y,z}}\dot{d}_z\end{Bmatrix} \qquad \textbf{(3.1)}$$

In the formula:

α_y 、 β_y 、 α_z and β_z represent the hysteretic curve shape parameter of the shear component in the x and y directions of the unit coordinate system; $\dot{d}_y$ and $\dot{d}_z$ represent the deformation change rate of the shear components in the y and z directions of the unit coordinate system.

The mechanical properties of lead-core laminated rubber seismic isolation bearings should be correctly reflected in the calculation model using the finite element software Midas Gen:

1. When the reaction spectrum analysis method is used, the mechanical properties of this series of bearings can be modelled in terms of horizontal equivalent height and equivalent damping ratio;

2. The mechanical properties of this series of bearings can be simulated by the equivalent bilinear restoring force model when the nonlinear dynamic time course analysis method is used. The bilinear restoring force model model of lead-core laminated rubber seismic isolation bearing is shown in Fig. 3.3.

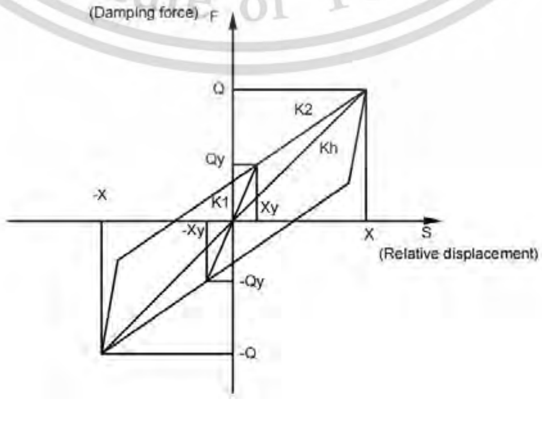


Fig3.3 Bilinear restoring force model for lead core laminated rubber seismic isolation bearing

3.4 FINITE ELEMENT ANALYSIS METHODS

Dynamic problems of structures can usually be divided into two main categories: free vibration problems of structures and dynamic response problems of structures. There are two main approaches to structural dynamic analysis: analytical and numerical. For the analytical method, a sufficient simplification of the structure is the basis of the analytical method. The classical vibration theories of several structures have been studied in depth, so the approximate solution methods have been relatively perfect for the dynamic analysis of some simple structures, such as beams, columns and their simple combination systems. However, for complex structures, analytical methods have some limitations in analysing their dynamic performance, thus promoting the development of numerical methods. In the context of the continuous development of computer technology and structural finite element theory, numerical methods have become more and more perfect. Numerical methods are able to analyse the dynamic response of a structure more effectively by establishing a numerical model that is closer to the actual structure. This approach has advantages in dealing with vibration and dynamic problems of complex structures because it can overcome the limitations of analytical methods in these cases .

Structural dynamics analysis usually consists of three main parts: eigenvalue analysis, response spectrum analysis and time-course analysis, and in this paper, we mainly use dynamic time-course analysis, so we mainly introduce the principle of time-course analysis method.

1. Eigenvalue analysis:

Eigenvalue analysis is used to calculate the self-oscillation period and each vibration mode of a structure. This analysis method focuses on the intrinsic vibration characteristics of the structure and determines the vibration frequency and mode of vibration of the structure by solving the eigenvalue problem. It is often used in engineering to predict the free vibration behaviour of structures.

2. Reaction spectrum analysis:

Response spectrum analysis is the most commonly used method in engineering for calculating the dynamic response of structures under seismic action. This method is based on the theory of vibration mode decomposition reaction spectra and is particularly suitable for analyses in the elastic phase. However, in the elastic-plastic phase, the reaction spectrum method is no longer applicable because it cannot accurately describe the nonlinear behaviour of the material.

3. Time-course analysis:

Time-range analysis methods are based on measured seismic waves or synthetic seismic wave data and are used to simulate the actual dynamic response of a structure under seismic action. Time-range analyses can be divided into two main categories: elastic time-range analyses and elasto-plastic time-range analyses. They take into account the vibration response of the structure at different points in time, and are therefore able to predict the behaviour of the structure more accurately, including non-linear effects.

Time-course analysis is a closely time-dependent method for investigating the response of structures under seismic action. In time-range analysis, actual seismic event records or synthetic seismic wave data are usually used as inputs, and then the seismic response of the structure is calculated by numerical methods based on the equations related to structural dynamics. During an earthquake, the seismic acceleration changes continuously with time, so the time-course analysis method takes into account the seismic acceleration at each moment in time. Time-course analysis can be divided into two main types: elastic time-course analysis and elasto-plastic time-course analysis. The difference between these two is whether or not the elastic and plastic properties of the structural material are considered. In elastic time-course analysis, it is assumed that the structural material deforms only elastically under the action of an earthquake, i.e., it does not deform plastically until the elastic limit is exceeded. This type of analysis is commonly used to study the elastic response of structures and focuses on evaluating the vibration characteristics and elastic performance of structures. In contrast, in elasto-plastic time-course analyses, both elastic and plastic properties of the structural materials are considered. This means that the structure can undergo some degree of plastic deformation under seismic action to more realistically simulate the behaviour of the structure. This type of analysis is suitable for situations where the plastic deformation and energy dissipation of the structure during an earthquake need to be considered, and is commonly used to assess the seismic performance and seismic resistance of structures.

The time course analysis method is based on the dynamical equations, and the analytical solution of the response of the structure under dynamic action is based on the dynamical equilibrium equations of the mass system in the structure. According to Newton's second law, the equilibrium equation for a multiple free system is a function of time:

$$[\mathrm{M}]\{\ddot{\delta}(t)\}+[\mathrm{C}]\{\dot{\delta}(t)\}+[\mathrm{K}]\{\delta(t)\}=\{R(t)\} \tag{3.12}$$

In the formula: $[\mathrm{M}]$ is the mass matrix; $[\mathrm{C}]$ is the damping matrix; $[\mathrm{K}]$ is the stiffness matrix; $\left\{\ddot{\delta}(t)\right\}$ is the absolute ground acceleration vector; $\left\{\dot{\delta}(t)\right\}$ is the absolute ground velocity vector; $\{\delta(t)\}$ is the absolute ground displacement vector.

The ground seismic motion is a rather complex time course process, while there are structural restoring forces, damping forces, etc. acting on the structure, and at the same time these forces change with the time course. For the multi-degree-of-freedom equilibrium system equations caused by seismic action are as follows:

$$[\mathrm{M}]\{\ddot{\delta}(t)\}+[\mathrm{C}]\{\dot{\delta}(t)\}+[\mathrm{K}]\{\delta(t)\}=-[\mathrm{M}][\mathrm{t}]\{\ddot{\delta}_g(t)\} \tag{3.13}$$

In the formula: $[\mathrm{t}]$ is the impact factor; $\left\{\ddot{\delta}_g(t)\right\}$ is the ground motion acceleration.

In contrast to the mode decomposition method, the time-domain analysis method is more precise as it directly accounts for the internal forces and deformations of the structure at each time step. This approach fully captures the actual response of the structure under seismic action. The time-domain analysis method is characterized as a direct dynamic method, and within this analysis, the seismic acceleration time-domain curve plays a pivotal role. Commonly used seismic waves in engineering practice encompass measured strong earthquake records from the intended site, typical strong earthquake records, and artificial seismic waves generated through seismic hazard analysis.

The characteristics of the time-range curves are mainly affected by the following three factors:

1. Peak Ground Acceleration: The maximum acceleration reached by a seismic wave serves as an indicator of earthquake intensity, determining the magnitude of

seismic force exerted on the structure. A higher peak acceleration signifies a more potent seismic action.

2. Spectral Characteristics of Ground Motion: The spectral characteristics of seismic waves describe the energy distribution of seismic waves at different frequencies. The spectral characteristics directly affect the response of the structure at different vibration frequencies and therefore need to be considered in the analysis.

3. Duration of strong earthquakes: The duration of a strong earthquake is the length of time that a seismic wave vibrates. Seismic waves of longer duration may lead to cumulative vibration effects on the structure, and therefore the time course of seismic waves needs to be considered.

Taking these factors into account, the time-range analysis method can more comprehensively simulate the actual response of a structure under seismic action, which helps engineers to more accurately assess the seismic performance of the structure and take necessary design and repair measures.

3.5 SEISMIC HAZARD PREDICTION METHODS BASED ON ARTIFICIAL INTELLIGENCE TECHNIQUES

1.BP neural network-based earthquake damage prediction method

BP (Back Propagation) neural network is by far the most successful neural network learning algorithm, which is widely used in engineering work to solve all kinds of real-world problems.The BP neural network framework contains an input layer, a hidden layer, and an output layer, and the algorithm belongs to supervised learning[35].BP neural network consists of a large number of neurons as the nodes of the network that are connected to each other, and after being processed by the excitation function, each neuron will get the calculation result as the strength connection signal of its network weights. After that, each neuron will get the result of the calculation as the strength connection signal of its network weights, and then by adjusting the size of these connection strength values, the pattern information contained in the input data can be mapped to the output layer, and the essence of the algorithm is to take the sum of network error squares as the objective function and make this function reach the minimum value. The method of fast earthquake damage prediction using BP neural network is as follows:

A number of frame buildings are taken as research objects, and several key data with high correlation, such as the number of floors, floor height, floor height, column area ratio, etc., which are easy to obtain, are taken as the seismic impact factors, and a BP neural network seismic damage prediction model is trained by making full use of the good modelling characteristics of MATLAB visibility. Multiple sets of data tests are used to compare the data of single simulation results, and the accuracy and stability of the model are verified by randomly selecting data samples for several times to build the model. The neural network model framework diagram is shown in Figure 3.4.

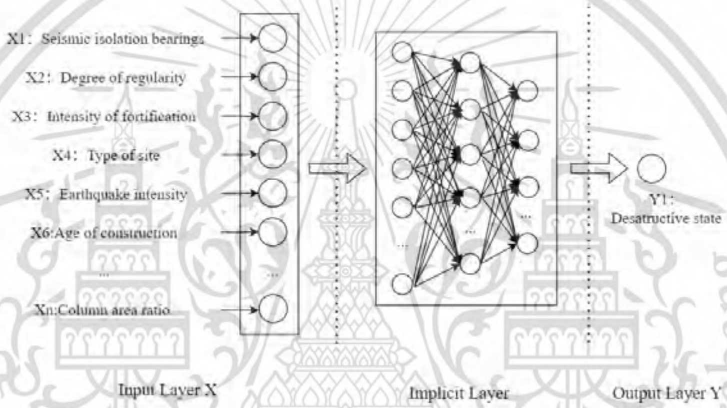


Fig 3.4 Neural network model framework diagram

2. Support vector machine (SVM)-based earthquake damage prediction methods

SVM is a method of machine learning, the basic idea is to build a support vector machine model based on the nonlinear relationship between the feature vectors and the categories in the given training samples, and use the model to classify or regress the unknown samples.Cortes & Vapnik formally proposed the concept of support vector machine in 1995. Its theoretical basis is the statistical learning theory that aims to solve the machine learning problem in the case of small samples.The most basic theory of SVM is the binary classification theory, and its basic idea is to build a classification function according to the principle of structural risk minimisation to distinguish two different types of samples as much as possible. For different samples, the classification function can be roughly divided into two categories: linear classification function and nonlinear classification function. The basic idea of SVM-based seismic damage prediction method for masonry structures is to extract the data from the seismic damage examples and input them into SVM to establish a nonlinear relationship model between various seismic damage influencing factors and the seismic damage level, and then analyse the existing data of the building to be evaluated according to the model, so as to predict the seismic damage level of the building under the effect of earthquakes of different intensities.

3. Fuzzy system based earthquake damage prediction methods

In 1965, L.A. Zadeh, an American expert in automatic control, introduced the concept of fuzzy subsets, marking the inception of fuzzy systems theory. A fuzzy system, which defines input, output, and state variables using fuzzy sets, represents an advancement over deterministic systems. Rooted in a macroscopic approach, fuzzy systems capture the nuanced characteristics of human brain thinking. They excel in articulating high-level knowledge and can simulate comprehensive human inference to address problems in fuzzy information processing that are challenging for conventional mathematical methods. This versatility extends the application of computers to humanities, social sciences, complex systems, and other fields. Fuzzy systems are adept at tackling nonlinear problems and find widespread use in automatic control, pattern recognition, decision analysis, time series signal processing, as well as human-computer dialogue systems, economic information systems, medical diagnostic systems, earthquake prediction systems, weather prediction systems, and more. The earthquake prediction methods based on fuzzy systems are outlined as follows.

This study conducts an analysis of the typical seismic hazards faced by reinforced concrete frame structures. It summarizes the primary factors influencing the seismic performance of frame structures, establishing specific analysis conditions for each factor. Utilizing the finite element analysis method, various models incorporating different influencing factors are examined. The seismic performance index is determined by the maximum interstorey displacement angle parameter of the structure under varying intensities. The study evaluates the impact of each factor on the overall seismic performance of the structure. Additionally, a fuzzy inference model for the damage degree of RC frame structures is formulated, aiming to swiftly predict the structure's damage degree.

3.6 ESTABLISHMENT OF FUZZY INFERENCE EARTHQUAKE PREDICTION MODEL

The basic concept of fuzzy reasoning is the process of using a set of fuzzy sets to reason out fuzzy conclusions through fuzzy rules. The basic concepts involved in the theory of fuzzy reasoning are described below:

1. Theory

Domain refers to the range when discussing a fuzzy concept, e.g., the domain U=[0, 100] indicates that a person's age is in the range of 0 to 100 years.

2. Fuzzy sets

The symbol A is generally used to denote a fuzzy set, while $A(x)$ denotes the element x affiliation degree for the fuzzy set A. Mathematically, the representation of fuzzy set A can be written:

$$A = \{(x, \mu_A(x)) | x \in U\}$$

where U is the thesis domain and$x$ is an element in the thesis, and$\mu_A(x)$ is the element$x$ affiliation degree for the fuzzy set A.

3. Affiliation function

Reasonable choice of affiliation function is the key to achieve fuzzy inference, affiliation function is generally based on the nature of the domain and fuzzy set combined with practical engineering experience to choose, it can make a quantitative description of the concept of fuzzy, commonly used affiliation function including Gaussian, trigonometric function, bell function and trapezoidal function .

4. Fuzzy rules

Fuzzy rules are the preconditions for fuzzy reasoning, which represent the mapping relationship between input and output fuzzy linguistic variables, and usually consist of two parts: premise and conclusion, and the common form is "IF (premise)..., THEN (conclusion)...".

Example:

Rule 1	If x is A_1	Then x is B_1
......	......	......
Rule m	If x is A_m	Then x is B_m
New input	x is A^*	

Output	y is B^*

Among them.x 、 y belongs to the thesis domain U, V;i =1, ...m ;A_i .B_i The set consisting of all fuzzy sets belonging to U, V.

The fuzzy inference modelling process is shown in Figure 3.5.

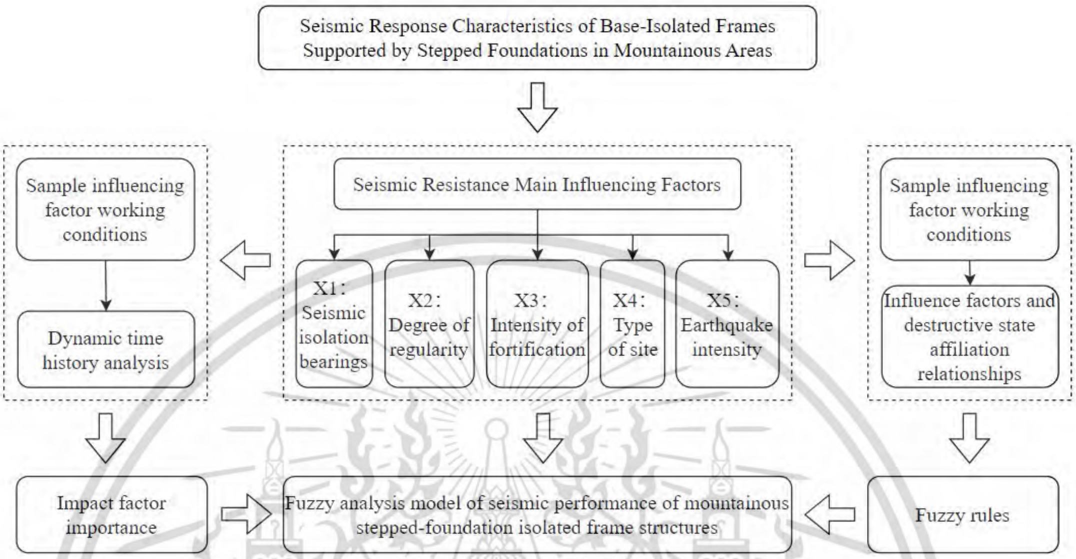


Fig 3.5 Fuzzy inference model building process

CHAPTER 4

RESULT AND DISCUSSION

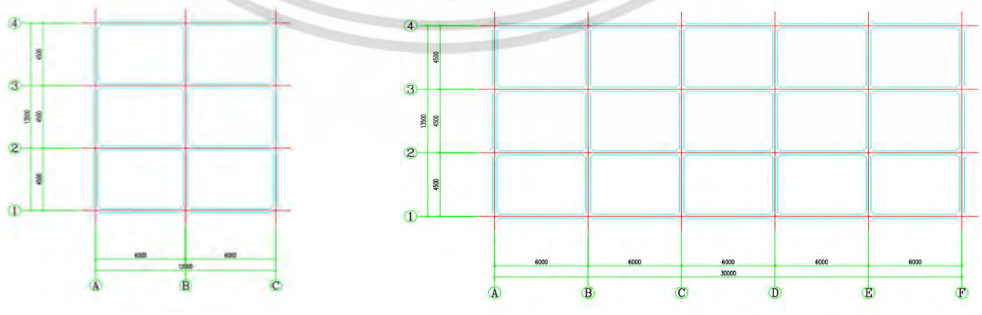
4.1 BUILDING STRUCTURE DESIGN AND ESTABLISHMENT

4.1.1 Overview of the project

As shown in Figure 4.1, the establishment of a typical mountainous terraced foundation frame structure, the number of floors of the building dropped part of the floor is 2 floors, the height of the floor is 3.3m, and the number of spans of the dropped floor is 2 spans. The number of floors in the upper part of the building is 5 floors, the height of the floor is 3.3m, and the structural system is reinforced concrete structure, the structural plan of the office building is shown in Fig. 4.1, and the structural elevation is shown in Fig. 4.2. The column network size is 4.5m×6.0m; the load values of each floor are taken as follows:

1. Seismic and wind loads: the seismic intensity is 8 degrees (0.2g), the building site category is Class II, the seismic grouping is Group II, the characteristic period is 0.4s, the cycle reduction coefficient taking into account the influence of the infill wall is taken as 0.7, and the frame seismic grade is Grade II. The basic wind pressure is $w_0 = 0.4 kN/m^2$, and the ground roughness is B.

2. Constant live load: floor live load is taken as $2.0 kN/m^2$; floor constant load is taken as $4.5 kN/m^2$, roof constant load is taken as $7.0 kN/m^2$; roof live load is taken as $0.5 kN/m^2$.



(a) Partial structural layout of dropped floors

(b) Structural layout of upper floors

Fig 4.1 Structural Layout

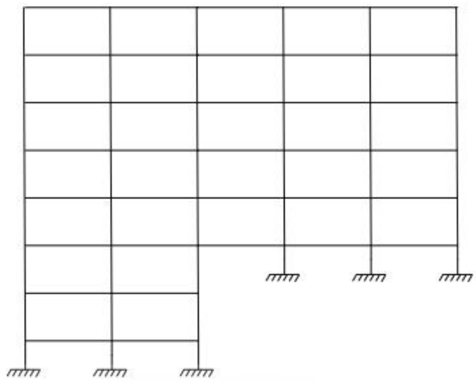


Fig 4.2 Structural elevation layout

4.1.2 Model design and construction

MIDAS Gen uses a spatial rod system model that allows the real constraints of a dropped floor structure to be simulated directly by defining the general constraints of the two levels of supports in the upper grounded portion and the lower grounded portion of the stepped foundation frame structure. MIDAS-Gen 3D frame is used to simulate the beams and columns of the frame structure. Both beam and column units are modelled using beam units that can withstand tension, compression, bending, shear and torsion. The finite element software MIDAS Gen is used to reinforce the structure. After the modelling and checking of the structural design software Midas Gen, the cross-section sizes of the beams, slabs and columns of the example model are determined to meet the code requirements, and the thickness of the floor slabs is 0.12m; the cross-section size of the columns is 0.6m×0.6m, and the cross-section of the floor beams is 0.3m×0.6m; the thickness of the protective layer of the concrete for the beams and columns is 0.04m, and that of the floor slabs on each floor level is 0.02m. The concrete is of C30 grade; the beams and slabs are of C30 grade; the beams and slabs are of C30 grade. C30 grade is adopted; HRB400 grade is adopted for the force tendons and hoop tendons of beams, slabs and columns. Calculated by Midas Gen structural design software, it meets the relevant requirements of the specification. The three-dimensional model established by MIDAS Gen is shown in Figure 4.3.

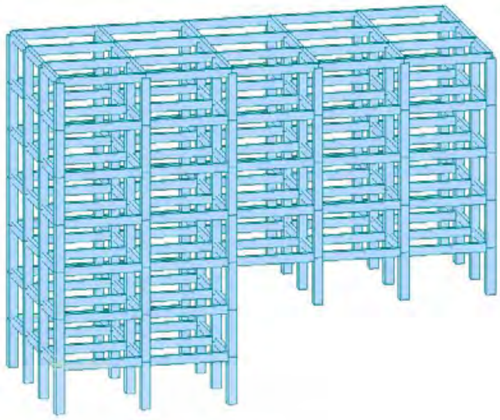


Fig 4.3 3D view of the baseline model

4.1.3 Calculation of seismic isolation bearings

Since most of the relevant provisions of the building seismic design code on the design of seismic isolation structure are guiding, and the stepped base seismic isolation frame structure is a special form of seismic isolation, there is no specific design process to be referred to, not to mention that there is no simplified calculation method to be computed, so in the preliminary arrangement of seismic isolation bearing, the limit value of vertical compressive stress of seismic isolation bearing under the representative value of gravity load can be obtained from the seismic isolation rubber bearing's Minimum diameter, by defining the representative value of gravity load working conditions, the axial force of the non-seismically isolated frame structure with stepped foundation is obtained in the finite element analysis software MIDAS Gen. If the structure is to be seismically isolated, according to the magnitude of the axial force of each column, F, the minimum force area of the bottom seismic isolation bearing, A, can be calculated by using Equation 4.1, and by using Equation 4.2, the bottom seismic isolation bearing's minimum diameter, and the calculated specific results are shown in Table 6.

Minimum force area of seismic isolation bearing:

$$A = \frac{F}{\sigma} \tag{4.1}$$

Minimum diameter of seismic isolation bearing:

$$D = 2\sqrt{\frac{A}{\pi}} \tag{4.2}$$

Table6.Calculation of axial forces and minimum diameters of seismic isolation bearings.

Column number	Axial force (kN)	Minimum area (mm^2)	Minimum diameter (mm)
C1	547.10	36473.33	240.99
C2	909.90	60660.00	310.79
C3	909.90	60660.00	310.79
C4	547.10	36473.33	240.99
C5	981.90	65460.00	322.86
C6	1634.20	108946.67	416.51
C7	1634.20	108946.67	416.51
C8	981.90	65460.00	322.86
C9	851.50	56766.67	300.65
C10	1387.70	92513.33	383.82
C11	1387.70	92513.33	383.82
C12	851.50	56766.67	300.65
C13	740.10	49340.00	280.30
C14	1235.90	82393.33	362.21
C15	1235.90	82393.33	362.21
C16	740.10	49340.00	280.30
C17	719.30	47953.33	276.33
C18	1204.30	80286.67	357.55
C19	1204.30	80286.67	357.55
C20	719.30	47953.33	276.33
C21	392.20	26146.67	204.05
C22	670.30	44686.67	266.75
C23	670.30	44686.67	266.75
C24	393.20	26213.33	204.31

This project adopts foundation bearing isolation, the seismic isolation bearing can be set in the upper grounding layer and the lower grounding layer or two seismic isolation layers are set to form two different elevations of the seismic isolation layer, if the bearing isolation measures are taken, all the columns at the bottom of the proposed selection of the same type of lead-core seismic isolation bearing, according to Table 6 can be seen to meet the area pressure of the smallest seismic isolation bearing for the 416.51mm, the diameter of this project selection of 500mm This project uses 500mm diameter lead core rubber bearing, the symbol is LRB500, and its design parameters are shown in Table 7.

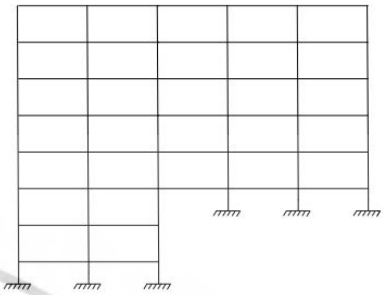
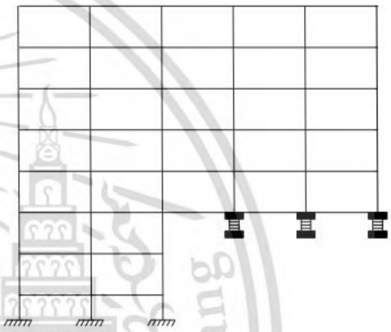
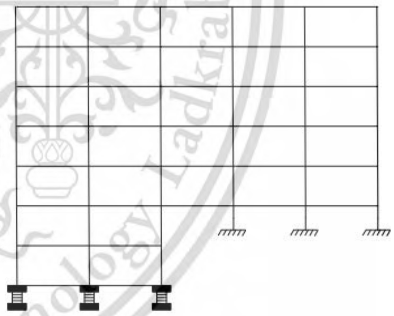
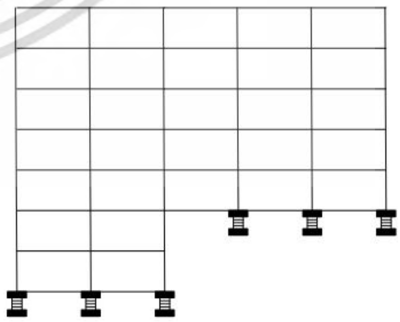
Table7.Main performance parameters of isolation bearings

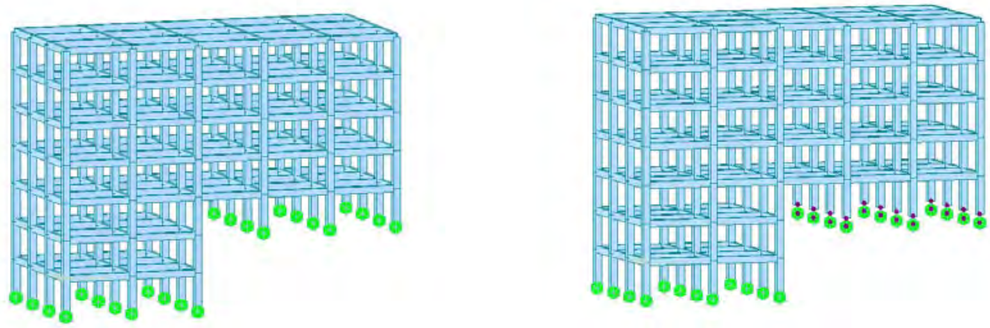
Type	Effective diameter	Total thickness of rubber	Stiffness before yield	Equivalent stiffness	Vertical stiffness	Yield force
	(mm)	(mm)	(kN/m)	(kN/m)	(kN/mm)	(kN)
LRB500	500	92	10910	1270	2400	40

4.1.4 Determination of seismic isolation programme

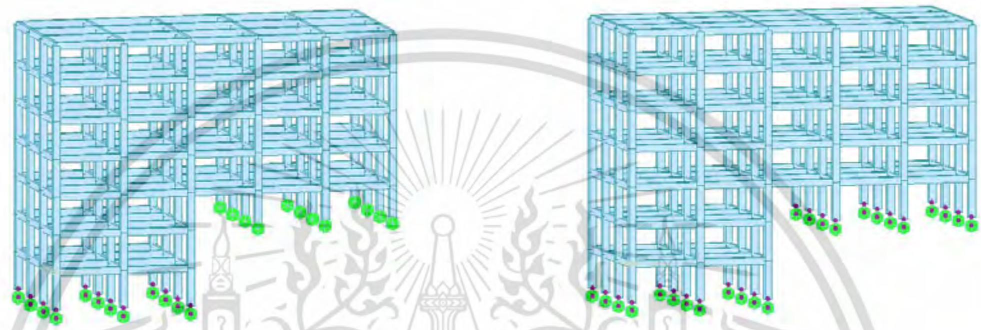
Research on stepped-foundation frame structures indicates that without the use of foundation isolation, the most vulnerable layer in such structures is situated at the upper grounded end — precisely where seismic forces exert the maximum stress. In accordance with conceptual design requirements, three seismic isolation arrangement schemes are considered: the first involves placing the seismic isolation bearing solely at the bottom of the upper grounding column, keeping the lower grounding end fixed; the second places the seismic isolation bearing only at the bottom of the lower grounding column, while both the lower and upper grounding ends remain fixed; and the third scheme positions the seismic isolation bearing at the bottom of both the upper and lower grounding columns, forming two distinct elevation horizontal planes for the seismic isolation layer. The models outlined in Table 8 are derived, with a particular focus on the analysis of the following four models in this paper. The perspective view of the model constructed using Midas Gen is illustrated in Figure 4.4.

Table8.Seismic isolation plan

Serial number	Arrangement of seismic isolation bearings	name (of a thing)	Schematic of the model
1	No seismic isolation bearing	Modle1	
2	Vibration isolation bearings for the upper grounded portion only	Modle2	
3	Seismic isolation bearings in the lower grounded part only	Modle3	
4	Vibration isolation bearings are arranged in both the upper and lower grounded parts.	Modle4	



(a) M1 3D view (b) M2 3D view

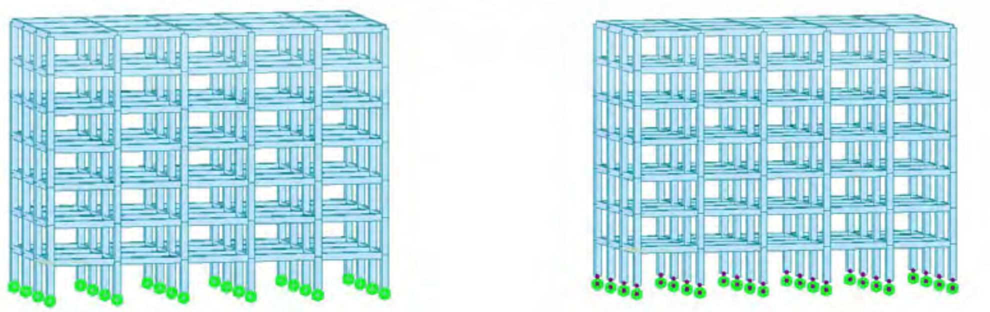


(c) M1 3D view (d) M2 3D view

Fig 4.4 Perspective view of the Midas Gen model

4.1.5 Ordinary flatland modelling

In order to comparatively study the force response of a mountainous stepped-foundation seismically isolated frame structure and an ordinary flat structure without changing the engineering profile and the member dimensions of the structure, an ordinary flat structure with the plan layout of Fig. 4.1-b is built to obtain M5, and seismic isolation bearings are given to the bottom of the columns of M5 to obtain M6, and the specific three-dimensional model is shown in Fig. 4.5.



(a) M5 three-dimensional view (b) M6 three-dimensional view

Fig4.5 Perspective view of the general levelling structure model

4.2 STRUCTURAL MODAL ANALYSIS OF SINGLE BUILDINGS

4.2.1 Self-oscillation period

The structural self-oscillation period refers to the time required for a structure to complete a free vibration according to a specific vibration pattern, in which the time required to complete the first vibration pattern is also called the basic self-oscillation period. The period is an important parameter for determining the size of lateral stiffness of a structure and the existence of local weakly constrained vibration. If the period of the structure is judged to be unreasonable, it is necessary to modify the arrangement of structural components or check the location of the specific local vibration, so as to make the calculation results more accurate. The modal analysis of the six seismic isolation dropped layer structural models established, and the comparative analysis of the period, resulting in the period and frequency of each calculation model are shown in Table 9.

Table9.Seismic isolation plan

	Mode number	Frequency		Period
		(rad/sec)	(cycle/sec)	(sec)
M1	1	3.924	0.625	1.601
	2	5.856	0.932	1.073
	3	7.133	1.135	0.881
	4	20.275	3.227	0.310
	5	20.713	3.297	0.303
	6	23.151	3.685	0.271
M2	1	4.286	0.682	1.466
	2	5.387	0.857	1.167
	3	6.996	1.113	0.898
	4	20.357	3.240	0.309
	5	20.964	3.337	0.300
	6	23.234	3.698	0.270
M3	1	3.219	0.512	1.952
	2	3.227	0.514	1.947

	3	3.668	0.584	1.713
	4	17.699	2.817	0.355
	5	18.055	2.874	0.348
	6	24.933	3.968	0.252
M4	1	2.616	0.416	2.402
	2	2.710	0.431	2.318
	3	3.105	0.494	2.024
	4	14.976	2.384	0.420
	5	15.332	2.440	0.410
	6	20.004	3.184	0.314
M5	1	6.489	1.033	0.968
	2	6.746	1.074	0.931
	3	7.470	1.189	0.841
	4	20.552	3.271	0.306
	5	21.301	3.390	0.295
	6	23.515	3.743	0.267
M6	1	2.430	0.387	2.586
	2	2.447	0.390	2.568
	3	2.678	0.426	2.346
	4	13.413	2.135	0.468
	5	13.769	2.191	0.456
	6	15.342	2.442	0.410

Comparison of the self-oscillation period and frequency of different calculation models is shown in Table 11 above.M1 is an ordinary frame structure with no seismic isolation bearing at the bottom of the upper and lower grounding columns, and the grounding ends are solidly connected, while M4 is a seismic isolation frame structure with seismic isolation bearing at the bottom of the upper and lower grounding columns, which forms two seismic isolation layers with different elevations. From the table, it can be seen that the first self-oscillation period of M1 is 1.601s, the first self-oscillation period of M4 is 2.402s, the first self-oscillation period of M4 is 0.801s more than that of M1; the first self-oscillation period of Model 5 is

0.968s, and the first self-oscillation period of Model 6 is 2.586s, which means that after adopting seismic isolation technology, the self-oscillation period of the structure can be extended. period after adopting the seismic isolation technology. The main reason is that the addition of seismic isolation bearings will make the drop layer structure itself become softer, resulting in the tendency of the period to become longer.

M2 is that the bottom end of the upper grounding column is equipped with seismic isolation bearings, and the bottom end of the lower grounding column is solidly connected to form a seismic isolation layer.M3 is that the bottom end of the lower grounding column is equipped with seismic isolation bearings, and the bottom end of the upper grounding column is solidly connected to form a seismic isolation layer that is different from that of M2.M2's first self-resonance period was 1.466 s, which is higher than that of M1's first self-resonance period. The first self-oscillation period of M2 is 1.466s, which is 0.135s less than that of M1. According to the rules of ordinary structures, the first natural period of M2 should be greater than that of M1, and that of M3 is 1.952s, which is 0.351s more than that of M1. The addition of seismic isolation bearings to the ordinary flat frame structure will make the dropped layer structure itself become softer, which will result in the tendency of the period to become longer, but the object of the research in this paper is the mountainous terrace foundation frame structure, which is different from the ordinary flat frame structure in terms of the seismic isolation bearings. However, in this paper, the object of study is the mountainous stepped foundation frame structure, compared with the ordinary flat ground frame structure, the mountainous stepped foundation structure appears multiple foundations with different elevations, and the structure will have vertical irregularities. In this study, so in this study, the first natural period of M2 is slightly lower than that of M1, the first self-oscillation period of Model 3 and Model 4 is higher than that of M1, and the first self-oscillation period of Model 6 is higher than that of Model 5. In summary, the first self-oscillation period of the mountainous terraced foundation seismically isolated frame structure is still longer than that of a mountainous terraced foundation frame structure with no seismic isolation bearing, but the first self-oscillation period of the structure still has a tendency to become longer. However, the arrangement scheme of seismic isolation bearings has a greater influence on the period of the mountainous stepped foundation frame structure.

4.2.2 Quality participation factor

The participation coefficient of structural mass is an important parameter in structural dynamics, the participation coefficient of structural mass indicates the ratio between the mass distribution and the total mass of the structure when it vibrates in a certain mode, which is usually used for analysing the vibration characteristics and dynamic response of the structure. In this paper, the modal analysis of the four seismic isolation dropped layer structural models established in this paper is carried out for the comparative analysis, which results in the participation coefficients of the mass of each computational model as shown in Table 10 shows.

Table10.Seismic isolation plan

Model number	Mode number	Quality participation coefficient		
		X	Y	Z
M1	1	0.00	51	42.59
	2	91.66	0.00	0.00
	3	0.00	40.04	52.35
M2	1	0.00	51.66	40.11
	2	90.93	0.00	0.00
	3	0.00	38.38	54.13
M3	1	0.00	49.24	46.05
	2	99.87	0.00	0.00
	3	0.00	50.60	46.45
M4	1	0.00	78.45	20.64
	2	99.53	0.00	0.00
	3	0.00	21.22	71.31
M5	1	80.80	0.00	0.00
	2	0.00	80.79	0.00
	3	0.00	0.00	81.06
M6	1	99.60	0.00	0.00

	2	0.00	99.65	0.00
	3	0.00	0.00	99.67

Analyzing the mass participation coefficients of vibration patterns in each model reveals distinctive characteristics. For Model 5 and Model 6, the first vibration pattern is translational in the X-direction, the second vibration pattern is translational in the Y-direction, and the third vibration pattern is rotational. Conversely, for Model 1 to Model 4, the first vibration patterns are translational and torsional in the Y-direction, the second vibration pattern is translational in the X-direction, and the third vibration pattern combines translational in the Y-direction with torsional vibration patterns in the Y-direction. The torsional effect is particularly notable in the first vibration mode of Model 1, Model 2, and Model 3, with mass participation coefficients in the Z-direction surpassing 0.4, closely approaching those in the X-direction. Additionally, the mass participation coefficients in the Y-direction for the first vibration mode of Model 2 and Model 3 are noticeably smaller than that of Model 4. This suggests that when seismic isolation layers are separately arranged at the grounded ends of two different elevations, the overall translational effect of the structure is improved, essentially categorizing it as a "seismic isolation translational type." This highlights the effective reduction of higher-order vibration mode effects on the dynamic characteristics of the isolated structure through the separate placement of isolators.

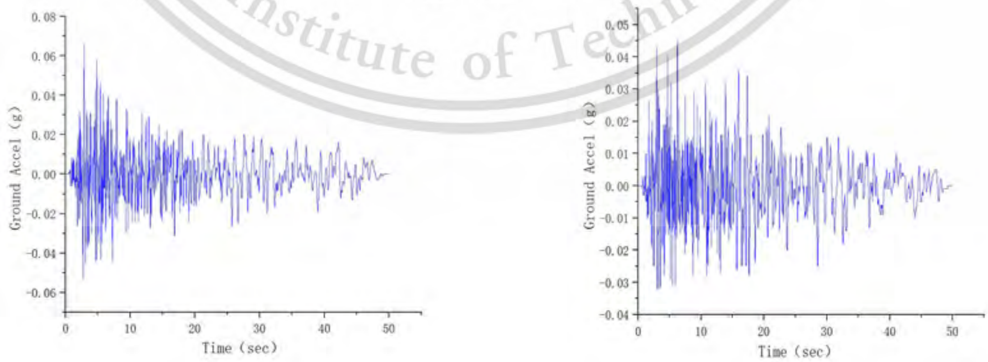
4.3 ANALYSIS OF TIME-DEPENDENT RESPONSE OF SEISMIC ISOLATION STRUCTURES WITH STEPPED FOUNDATIONS IN MOUNTAINOUS AREAS

4.3.1 Selection of seismic waves

In the design and analysis of earthquake engineering, the selection of seismic waves is crucial, because it directly affects the assessment of the seismic performance of the structure and the design results, and only by comprehensively taking into account the dynamic characteristics of the structure, the environment and site type in which it is located, and the prevalence of loaded seismic waves with the selection of a typical seismic record can the conclusions of the time-range analysis be broadly convincing.

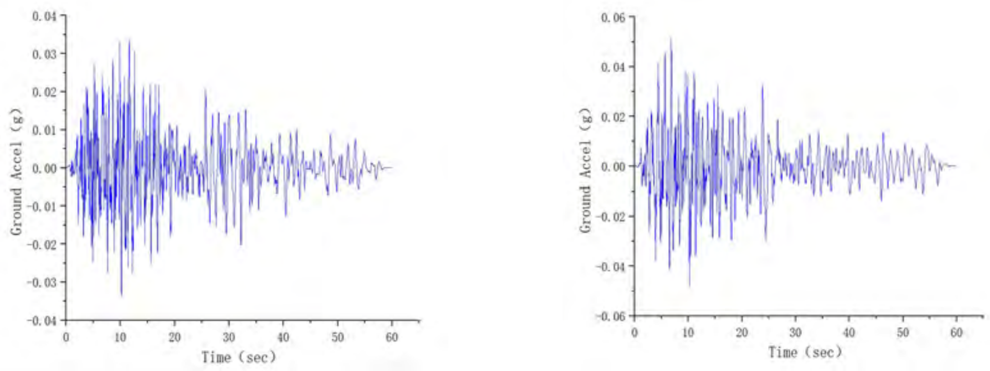
Within MIDAS GEN, the program database offers several common and typical seismic waves. However, it is crucial to note that these seismic waves may not align well with the specific characteristics and site attributes of the structure. Consequently, there is a necessity to manually select the seismic waves. According to code requirements, the average seismic influence coefficient curves derived from the chosen time-range curves should exhibit a statistically significant match with the seismic influence coefficient curves utilized in the vibration mode decomposition response spectrum method. The discrepancy between the average seismic influence coefficient curve of the time-range curve and the seismic influence coefficient curve employed in the vibration mode decomposition response spectrum method should not exceed 20% at the corresponding cycle point. Generally, the average bottom shear of the calculation result should not be less than 80% of the calculation result obtained through the vibration mode decomposition response spectrum method. Additionally, the calculation result for each seismic wave input should not fall below 65%.

Adhering to the principles outlined above, this study employs three natural seismic waves and one synthetic seismic wave sourced from the Pacific Earthquake Engineering Research Centre (PEERC) database for the dynamic elastic-plastic time-history analysis of the stepped-foundation seismically isolated frame structure. The selected natural seismic waves include RSN9 seismic wave, RSN22 seismic wave, and RSN26 seismic wave, with their waveforms displayed below.



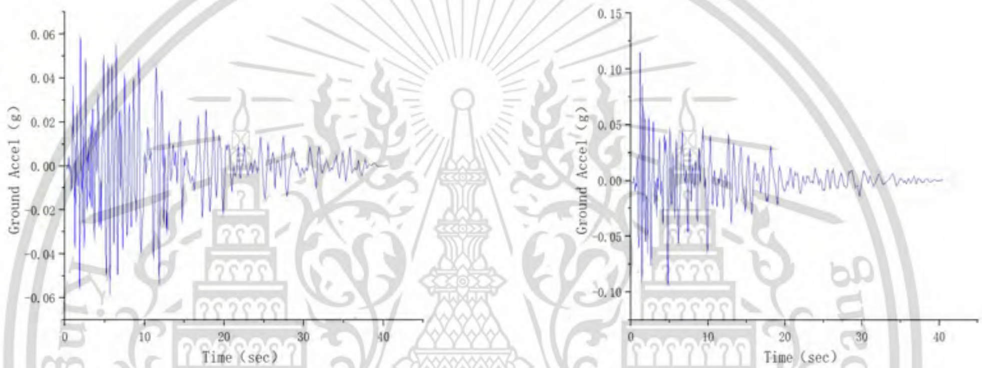
(a) X-direction **(b) Y-direction**

Fig 4.6 RSN9 Seismic Wave Acceleration Time-Course Plot



(a) X-direction (b) Y-direction

Fig 4.7 RSN22 Seismic Wave Acceleration Time-Course Plot



(a) X-direction (b) Y-direction

Fig 4.8 RSN26 Seismic Wave Acceleration Time-Course Plot

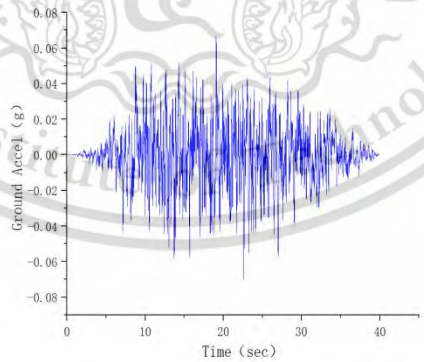


Fig 4.9 Artificial Seismic Wave Acceleration Time-Course Plot

The response spectral curves, average spectral curves, and normative spectral curves of the four selected seismic waves are plotted in the same figure, as shown in Figure 4.10.

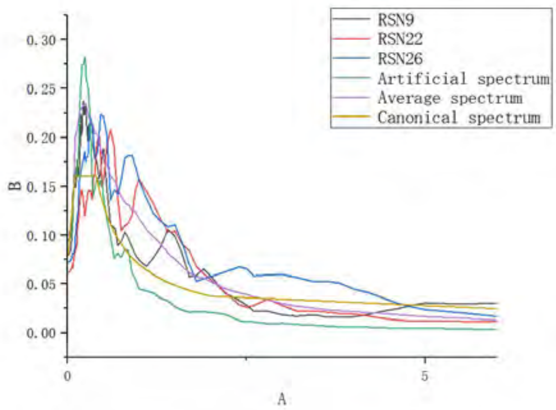


Fig 4.10 Seismic Wave Acceleration Response Spectrum and Normalised Spectral Curve

For the same building site, different defence intensities correspond to different peak accelerations. Time-course analyses of the same structure at different intensities require an adjustment of the peak acceleration with the aim of making the selected seismic maximum acceleration equal to the statistical maximum acceleration for the seismic intensity. That is

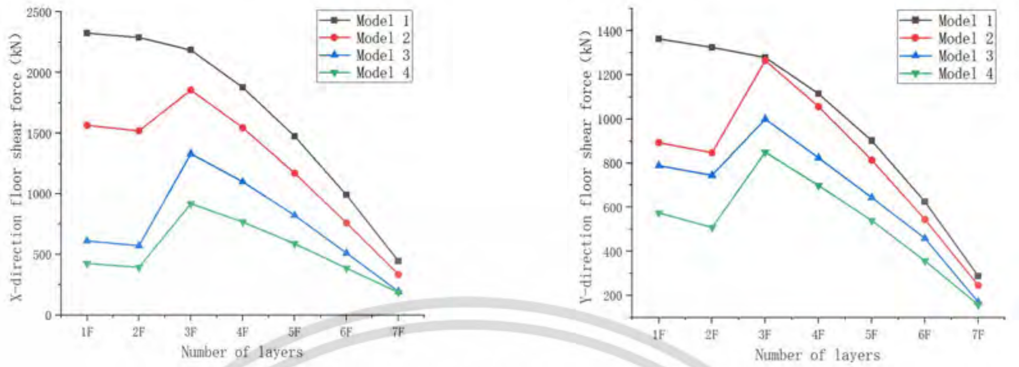
$$A_{(t)} = \frac{A_{\max}}{a_{\max}} a_{(t)} \tag{4.3}$$

Where $A_{\max}$ is the maximum acceleration counted at the corresponding intensity; $A_{(t)}$ is the adjusted seismic wave; $a_{(t)}$ is the selected seismic wave record; $a_{\max}$ is the maximum acceleration of the selected seismic record.

In the software MIDAS Gen it is possible to directly specify the maximum acceleration value for the selected wave, and the software automatically zooms in or out on the selected seismic wave without manual calculation, which is easy to operate.

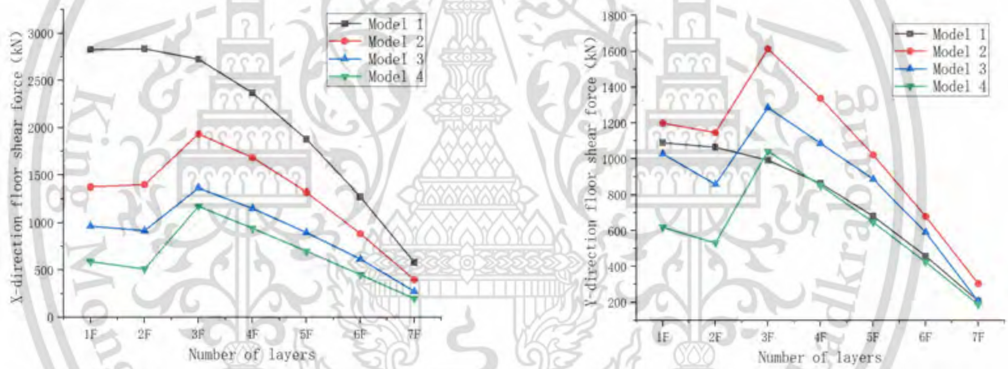
4.3.2 Analysis of maximum floor shear response

The maximum floor shear as defined in this subsection is the maximum value of the sum of the bottom shear of all columns in the same floor. The general floor shear force of ordinary regular structure is small on the top and large on the bottom, which means that the resistance of the next floor of the structure is required to be larger than that of the previous floor. The dropped floor structure is a vertical irregular structure, which is different from the normal structure. Through the calculation of Midas Gen, The maximum shear force of each floor calculated by the four models is shown in Figures 4.11-4.14.



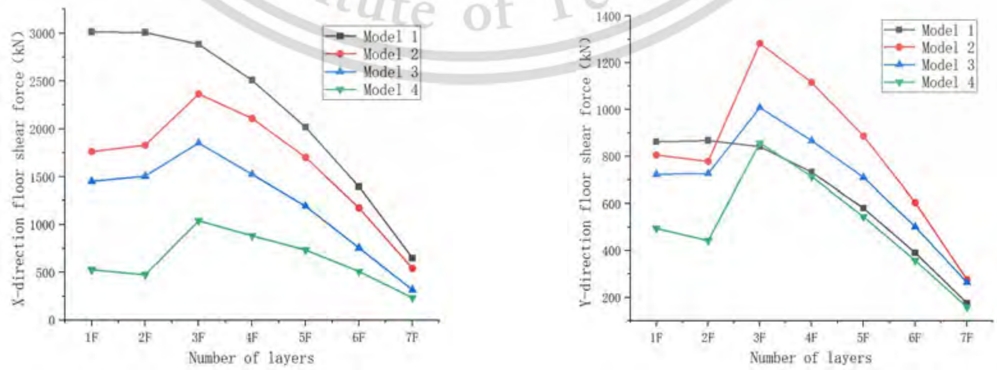
(a) X-direction (b) Y-direction

Fig 4.11 Maximum interstorey shear under RSN9 seismic action



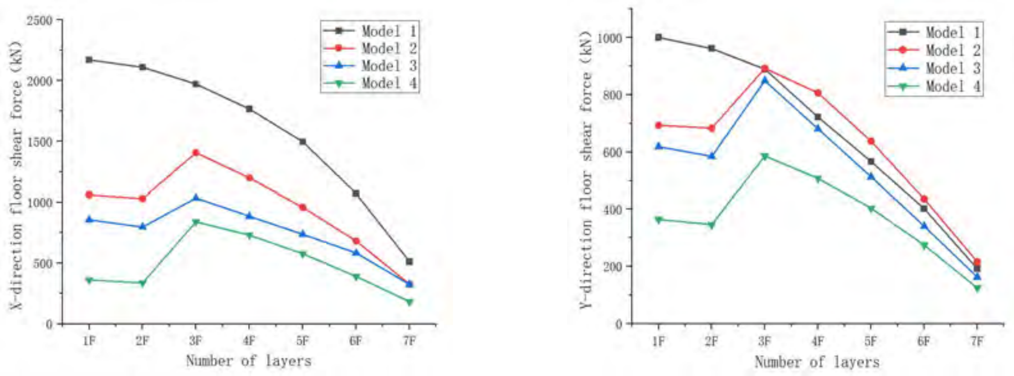
(a) X-direction (b) Y-direction

Fig 4.12 RSN22 Maximum interstorey shear under seismic action



(a) X-direction (b) Y-direction

Fig 4.13 Maximum interstorey shear under RSN26 seismic action



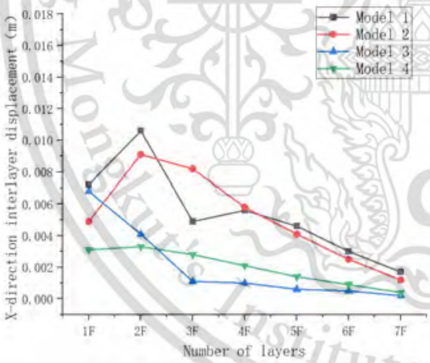
(a) X-direction (b) Y-direction

Fig 4.14 Maximum interstorey shear under synthetic seismic action

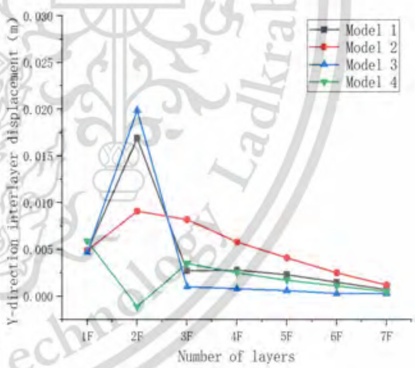
The above pictures are the shear curves of the floors of the four models in the X and Y directions under four kinds of seismic effects. According to the comparison of the table and the figure, it can be seen that, for this mountain stepped foundation frame structure, in the X direction, the floor shear forces of M2, M3 and M4 are smaller than that of M1, and the maximum reduction can be up to 2/3, and in the Y direction, basically, it also satisfies the conclusion, but due to the complexity of the forces of the mountain stepped foundation frame structure, and the structure's vertical irregularity, resulting in a few models do not satisfy this conclusion. After arranging the seismic isolation bearing, the seismic isolation bearing plays the role of damping and energy dissipation; at the same time, the shear force of the floors of M2, M3 and M4 becomes more and more uniform relative to M1, which is due to the role of the adjustment of the seismic isolation bearing, which attenuates the stiffness difference caused by the unequal height of the hilly terraced foundation frame structure, and avoids the destruction of the ground columns under the ground vibration, which is in agreement with the above conclusions. From the comparison of Figures 4.11-4.14, it can be seen that the change trend of the floor shear graphs of M2, M3 and M4 is almost the same, the floor shear of the upper part of the mountainous terraced foundation frame structure decreases gradually with the increase of the floor height, and the floor shear of the dropped floor part decreases gradually with the increase of the floor height, and there is a sudden change of floor shear between the 2nd floor and the 3rd floor, in which the 3rd floor floor The maximum shear force is due to the vertical irregularity of the structure, the upper foundation bears and does not transfer the floor shear force to the dropped floor part. According to the above table, it can be seen that under the same model and different ground vibration, the trend of floor shear growth or reduction is approximately the same, and under the same ground vibration and different models, the trend of floor shear growth or reduction is also approximately the same.

4.3.3 Analysis of floor-to-floor displacement response

Floor-to-floor displacement is the difference between the displacement of the previous floor and the next floor at the same time, generally taking the maximum displacement between floors. The angle of inter-storey displacement is the ratio of the maximum inter-storey displacement to the storey height. In order to meet the normal use requirements of this drop-storey structure, to prevent excessive deformation under different seismic effects, this subsection carries out the analysis of inter-storey displacements of different calculation models under the same seismic effect, The maximum inter-story displacements of each floor calculated by the four models are shown in Figures 4.15-4.18.

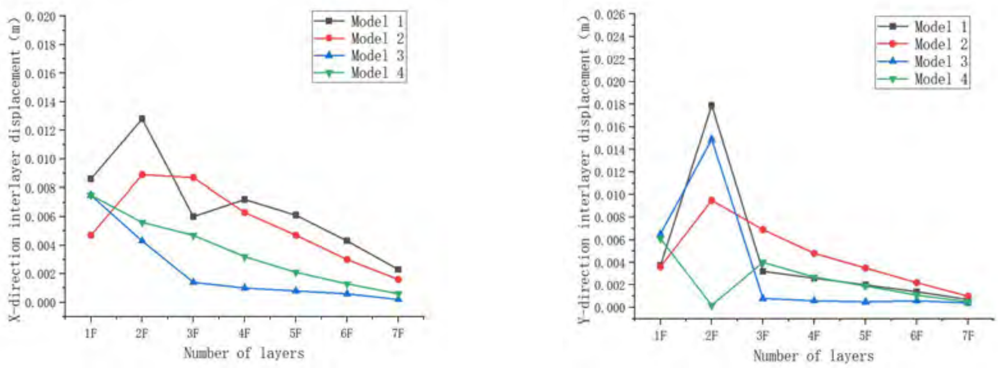


(a) X-direction



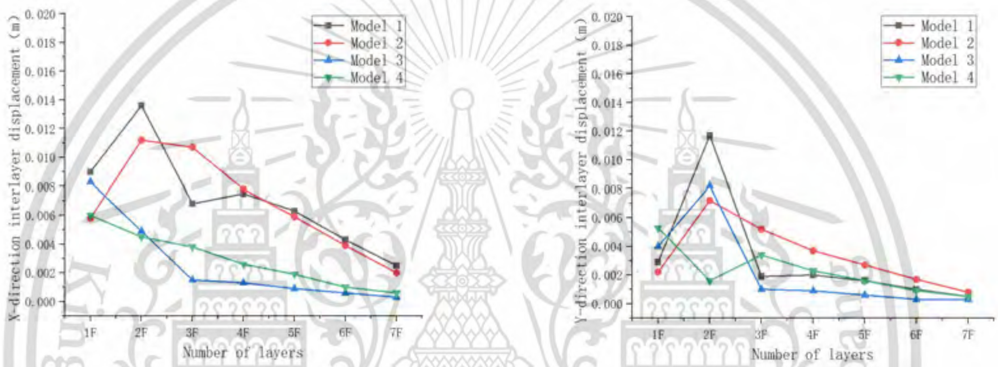
(b) Y-direction

Fig 4.15 Maximum interlayer displacements under RSN9 seismic action



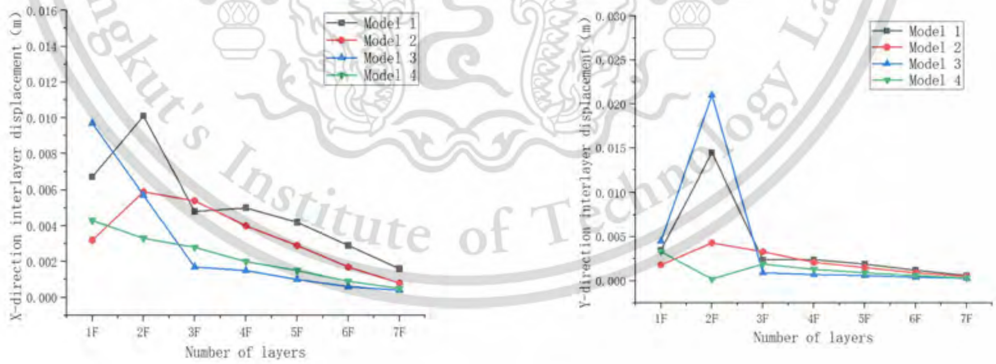
(a) X-direction (b) Y-direction

Fig 4.16 Interstorey displacements under RSN22 seismic action



(a) X-direction (b) Y-direction

Fig 4.17 Interstorey displacements under RSN26 seismic action



(a) X-direction (b) Y-direction

Fig 4.18 Interstorey displacements under synthetic seismic action

From Figs. 4.15-4.18, it can be seen that M1 is a structure without seismic isolation, and due to the vertical irregularity of the structure, the structure undergoes a sudden change in the second and third floors, so the interstorey displacements of

M1 in the first floor are larger than those of the other floors, and especially in the Y-direction, the interstorey displacements of M1 in the first floor are more prominent, because the difference between the spans of the structure in the X- and Y-directions is larger and the X- and Y-directions' M2 has seismic isolation bearings at the upper ground level, the restraint of the upper ground level is relatively weaker, and the lower ground level is solidly connected, so the inter-story displacement of the second story is larger than that of the other floors, but it is smaller than that of M1.M3 has seismic isolation bearings at the lower ground level, the restraint of the lower ground level is relatively weaker, the upper ground level is solidly connected, so the inter-story displacement of M3 at the first story in the X direction is larger, especially in the Y direction, because the span difference of the structure in the X and Y directions is larger, and the aspect ratio between X and Y directions reaches 2.2:1. M4 is the upper ground and lower ground are arranged with seismic isolation bearings, forming two unequal seismic isolation layers, the constraints on the structure of upper ground and lower ground become weaker, thus the structure generates horizontal translation, so the first floor interstorey displacement is relatively larger than that of other floors, overall speaking, M4 is the first floor interstorey displacement is relatively larger than that of M1, and overall speaking, M4 is the first floor interstorey displacement is relatively smaller than that of M1. Therefore, the first floor inter-storey displacement is larger than the other floors, and the overall inter-storey displacement of M4 is more uniform.

4.3.4 Analysis of factors affecting the structural dynamic response of single buildings

As mentioned in the preceding paper, the primary influencing factor on the dynamic response of the stepped foundation isolation frame structure in mountainous areas is the arrangement scheme of the seismic isolation layer. In this study, we initially design a foundation model, M1, without seismic isolation technology. Subsequently, three seismic isolation structural models, M2 to M4, are designed based on influencing factors to investigate the impact of different isolation layer arrangement schemes on the dynamic response of the stepped foundation frame structure in mountainous areas. Additionally, we explore the feasibility of setting seismic isolation supports at different elevation levels to form unequal heights of the isolation layer.

The arrangement schemes for the seismic isolation layers in the studied models are as follows: M2 places the seismic isolation bearing only at the bottom of the upper grounding column, with the lower grounding end fixed; M3 places the seismic isolation bearing only at the bottom of the lower grounding column, with both the lower and upper grounding ends fixed; and M4 arranges the seismic isolation bearing at the bottom of both the upper and lower grounding columns simultaneously, forming two seismic isolation layers at different elevation levels.Key findings from this chapter include:

1. The structural vibration periods of M2 and M3 are notably smaller than that of M4, indicating that the arrangement scheme of the seismic isolation layer significantly influences the period of the mountainous stepped foundation frame structure. Moreover, the seismic isolation model with the isolation layer arranged at different elevations demonstrates a more pronounced effect in prolonging the period compared to arrangements solely at the bottom of the upper or lower grounding columns. The overall torsional effect of the seismic isolated dropped layer is not negligible when the seismic isolation bearing is arranged only at the bottom of the upper or lower grounding column.

2. The overall leveling effect of the structure modeled by arranging the seismic isolation layers at the grounded ends of two different elevations is superior, categorizing it as a "seismic isolation translational type." Simultaneously, the influence of higher-order vibration patterns on the dynamic characteristics of the isolated structure can be effectively reduced by arranging the isolation layers separately.

3. Under the influence of multiple earthquakes, the floor acceleration, interstory displacement, and interstory shear of M2 and M3 exhibit noticeable differences from the other models. Specifically, the interstory shear of M2 is significantly larger, and its interstory acceleration is notably higher, leading to a substantial increase in the maximum interstory displacement angle at the lower grounded end of M2, surpassing code limits. This suggests that when the number of

dropped floors and spans is small, arranging the seismic isolation layer solely at the bottom of the upper grounding column can result in a significant increase in maximum interstory shear and displacement, exceeding specifications.

4. Compared to arranging the seismic isolation layer solely at the bottom of the upper or lower grounded column, placing the isolation layer at two different elevation levels significantly reduces the maximum interstory shear force and displacement angle of the ground floor and upper floors in the two main axis directions of the dropped-storey structure. This tends to level out the maximum interstory shear force and displacement angle of the floors.

5. The seismic performance of M4 is better than M1, M2, and M3, but the price of isolation bearings is relatively expensive. A lead core rubber isolation bearing with a diameter of 500 can reach 1200 RMB, and the construction process is more complex than ordinary structures, resulting in an increase in the construction period of the structure. Therefore, when the structure is in an area with high fortification intensity and sufficient construction time, M4 can be chosen; When the structure is in an area with low fortification intensity and sufficient construction time, M2 or M3 can be selected based on the actual terrain conditions; In areas with low seismic intensity and short construction periods, the size of the structure can be appropriately increased to achieve seismic reduction.

6. Dynamic analysis results of the seismic isolation structure reveal that after arranging seismic isolation bearings in the horizontal plane at different elevations to form unequal isolation layers, the seismic isolation layer enters a yielding state under seismic action. However, the horizontal limit deformation of the lead-core rubber seismic isolation bearing is not exceeded, indicating effective vibration isolation and energy consumption. The seismic isolation layer, when arranged separately, exhibits better performance in seismic action, reducing seismic energy consumption and ensuring shear deformation remains within reasonable limits. The horizontal shear deformation of the seismic isolation bearing is smaller than that at the upper or lower grounded end, with better seismic dissipation, especially when the seismic isolation layer is arranged at the upper grounded end, resulting in poor seismic dissipation.

4.4 SEISMIC DAMAGE PREDICTION FOR SEISMICALLY ISOLATED FRAME STRUCTURES WITH STEPPED FOUNDATIONS IN MOUNTAINOUS AREAS

The damage observed in frame structures during actual earthquake events is a complex outcome influenced by multiple factors. It is not feasible to control a single variable to determine the degree of influence of a specific factor on the seismic performance of the structure. When examining the significance of each factor in the overall seismic performance of the structure, each factor can be treated as a variable. By comparing the impact of different factors on the maximum interstory displacement angle index of the structure, the importance of each factor can be explored. In this study, the Midas Gen finite element analysis software is utilized. Specifically, one influencing factor is altered in the model setting to analyze the variations in the maximum interstorey displacement angle value of the structure under different intensities. The setting of the seismic isolation bearing is identified as one of the principal influencing factors affecting the seismic response of the mountainous terraced base isolation structure, as explored in the preceding paper.

In this paper, a mountainous stepped foundation frame structure M1 and an ordinary flat ground structure M5 are designed using structural design software Midas Gen in section 4.1.Seismic isolation bearings are added to the bottom of both columns of M1 and M5 to obtain M4 and M6.In this section, M1, M4, M5 and M6 are selected for the analysis, and for the sake of easy representation, the four models of M1, M4, M5 and M6 are re Then Midas Gen is used to carry out the dynamic time course analysis for the working conditions set by different influencing factors, and the maximum interstorey displacement angle values of the structure under the action of different intensity earthquakes are obtained, and the maximum interstorey displacement angle θmax is used as the evaluation index of the overall seismic performance of the structure, and the evaluation index of the damage state of the structure is shown in Table 11.Finally, according to the calculation results, the evaluation of the seismic isolation arrangement, the degree of structural regularity, the degree of setup of the seismic isolation and the structural damage state are shown in Table 11. Finally, according to the calculation results, the five influencing factors of seismic isolation, degree of structural regularity, intensity of defence, site category and seismic intensity are analysed to provide objective basis for the determination of the weight value of each influencing factor.

Table 11. Maximum interlayer displacement angles for different damage states

Damage status description	Damage status	θmax
Basically intact	DS_1	$\theta \leq 1/550$
Minor damage	DS_2	$1/550 < \theta \leq 1/250$
Moderate damage	DS_3	$1/250 < \theta \leq 1/120$
Serious damage	DS_4	$1/120 < \theta \leq 1/60$
Collapse	DS_5	$\theta > 1/60$

The RSN9 seismic wave was amplitude modulated according to the code and then input into N1, N2, N3 and N4 which were designed according to the 7 degree defence, class II site, and the dynamic time course analysis was carried out to obtain the maximum interstorey displacement angle of the four models, the maximum interstorey displacement angle and the damage state of the structure as shown in Table 12.

Table 12.Model damage state under RSN9 seismic

Model number	M1	M2	M3	M4
θmax	1/196	1/341	1/395	1/554
Destruction state	DS_3	DS_2	DS_2	DS_1

According to the table, the four models of N1, N2, N3 and N4, which are designed according to the 7-degree defence and Class II site, are in the states of Moderate damage, Minor damage, Basically intact, and Minor damage, respectively, under the RSN9 earthquake. "Moderate damage", "Minor damage", "Minor damage", "Basically intact".

4.4.1 Main seismic impact factors

For the five influencing factors of seismic isolation bearing, degree of structural regularity, fortification intensity, site category and seismic intensity, combined with the plan layout of M1 and M2, the design software Midas Gen is used to set up the working conditions of the two types of typical frame structures and carry out the dynamic time-history analysis by using the control variable method.

1. Seismic isolation bearing (X1), degree of structural regularity (X2)

This study focuses on the seismic performance of mountainous stepped-foundation seismically isolated frame structures, and the arrangement of seismic isolation bearings and the degree of regularity of the structure are taken as two important influencing factors because they have a greater impact on the seismic performance of the structure.

The four models N1, N2, N3 and N4 designed in this study have considered the two influencing factors of seismic isolation bearing arrangement and the degree of structural regularity at the time of structural design. The only variable between N1 and N3, N2 and N4 is the presence or absence of seismic isolation bearings, so that the influencing factor X1=0 when there is no seismic isolation bearing at the bottom of the structure, and when the seismic isolation bearing is installed at the bottom of the structure, so that the influencing factor X1=1. The only variable between N1 and N2, N3 and N4 is the degree of specification of the structure.This article proposes a new parameter β regarding the degree of structural regularity (X2). The meaning of parameter β is shown in Figure 4.19 and Formula 4.1.

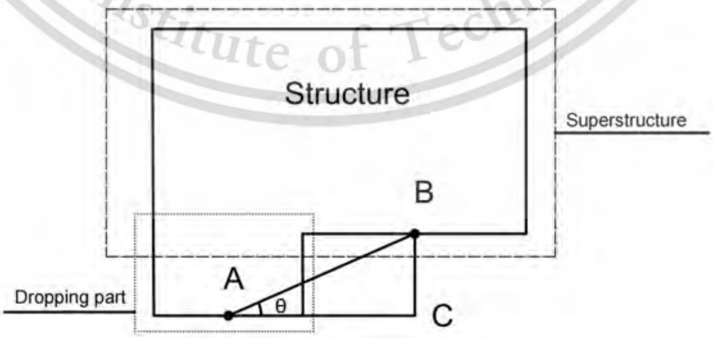


Fig 4.19 Simplified drawing of structural elevation

In Picture 3.6, A is the centre of gravity at the base of the dropped floor

portion of the structure, B is the centre of gravity at the base of the superstructure in the structure, and a right triangle ABC with AB as the hypotenuse is created. D_{BC} denotes the distance between B and C, and D_{AC} denotes the distance between A and C, and θ is the angle of inclination of the straight line AB, and the parameter β of the triangle are expressed as follows:

$$\beta = \arctan\theta \qquad \text{4.4)}$$

When the structure is an ordinary level-foundation frame structure $\theta = 0$, $\beta = 0$, when the structure is a hilly terraced foundation frame structure. β is evaluated according to formula 3.1.This paper mainly introduces a fuzzy inference-based seismic damage prediction method, the sample capacity is relatively small, this study only considers the two cases of structural rules and irregularities, so when the value of β is not 0, it represents that the structure is a mountainous stepped frame structure and an irregular structure, at this time, let $\beta = 1$.

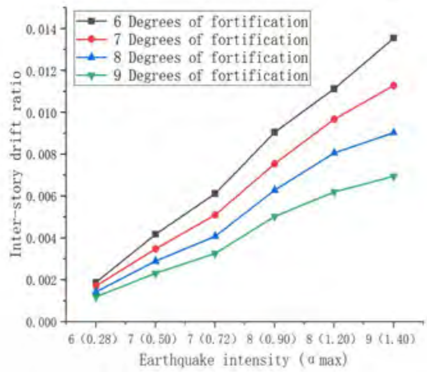
2. Intensity of defence (X3)

According to the seismic classification of frame structures in the code, for frame structures with heights lower than 30 m, the corresponding frame seismic classifications for structural defence intensities of 6, 7, 8 and 9 degrees are four, three, two and one, respectively. In this paper, 16 models are set up according to the structural defence level, see Table 13. Figure 4.20 shows the relationship between the maximum inter-storey displacement angle and the seismic intensity for N1, N2, N3 and N4, respectively, under different defence levels.

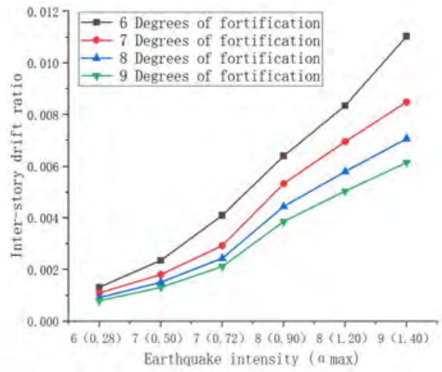
Table 13.Frame fortification intensity (X3) working condition setting

Fortification intensity	9	8	7	6
N1 series	N1-3-1	N1-3-2	N1-3-3	N1-3-4
N2 series	N2-3-1	N2-3-2	N2-3-3	N2-3-4
N3 series	N3-3-1	N3-3-2	N3-3-3	N3-3-4
N4 series	N4-3-1	N4-3-2	N4-3-3	N4-3-4

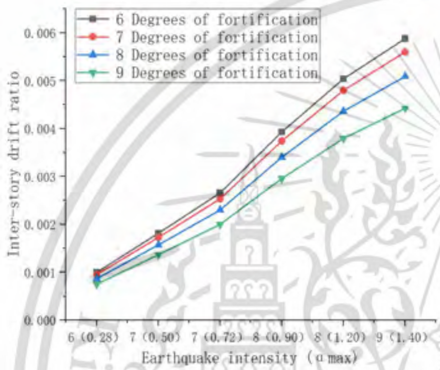
Note: The design conditions for the N1, N2, N3 and N4 series are the same except for the difference in seismic intensity. Each case is designed in accordance with Class II site and Seismic Group 2.



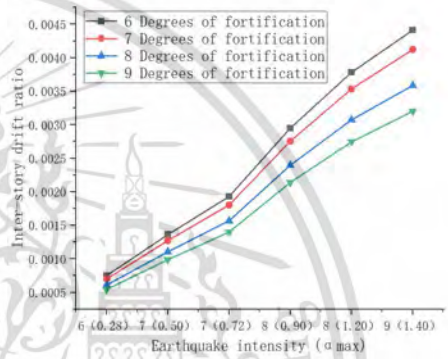
(a) N1 series comparison chart



(b) N2 series comparison chart



(c) N3 series comparison chart



(d) N4 series comparison chart

Fig 4.20 Maximum inter-storey displacement angle versus seismic intensity and defence intensity

Analysing the above graphs, the results show that the structural seismic performance improves with the increase of the structural defence intensity, in which the gap between the seismic performance of Grade III and Grade IV frames is smaller, while Grade I frames and Grade II frames have a significant effect on the improvement of the structural seismic performance; and the greater the intensity of the ground shaking is, the higher the intensity of the frame grade of the high intensity of the defence, the more obvious is the improvement of the seismic performance.

When the defence intensity of the structure is 6 degrees, X3 = 6; similarly, when the defence intensity is 7, 8 and 9 degrees, X3 takes the values of 7, 8 and 9 respectively.

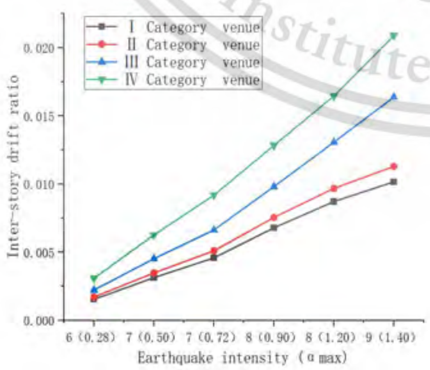
3. Site conditions (X4)

The structural displacement responses of N1, N2, N3 and N4 in different site conditions corresponding to the seismic response spectra are calculated respectively, and 16 models are set up in this paper based on the structural site conditions, and the working conditions are shown in Table 14.Fig. 4.21 shows the relationship between the maximum interstorey displacement angle and the site conditions for N1, N2, N3 and N4 in different defence levels, respectively.

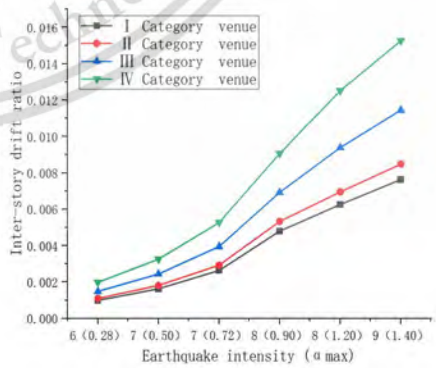
Table 14. Framework site conditions (X4) working condition settings

Site conditions	Ⅰ Category	Ⅱ Category	Ⅲ Category	Ⅳ Category
N1 series	N1-4-1	N1-4-2	N1-4-3	N1-4-4
N2 series	N2-4-1	N2-4-2	N2-4-3	N2-4-4
N3 series	N3-4-1	N3-4-2	N3-4-3	N3-4-4
N4 series	N4-4-1	N4-4-2	N4-4-3	N4-4-4

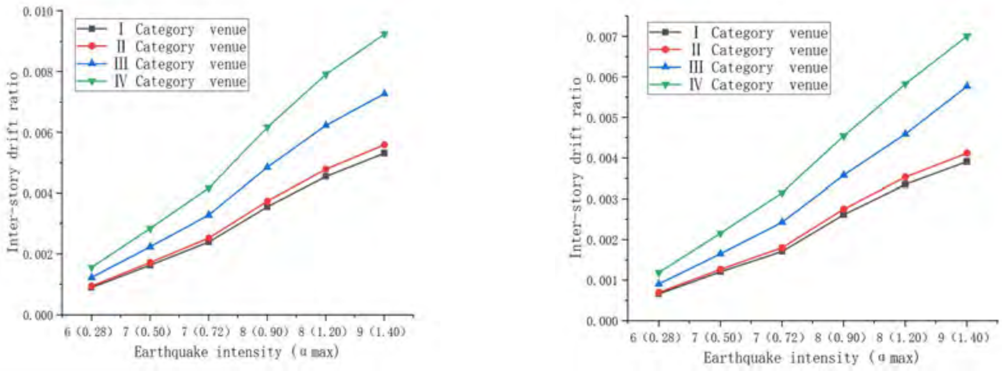
Note: The N1, N2, N3 and N4 series of conditions have the same design conditions except for differences in site types. Each case is designed in accordance with the 7th degree of defence and the 2nd design seismic group.



(a) N1 series comparison chart



(b) N2 series comparison chart



(c) N3 series comparison chart (d) N4 series comparison chart

Fig 4.21 Maximum interstorey displacement angle versus seismic intensity and site category

Analysing the above graphs, the trend of the influence of site conditions on seismic performance is consistent, under the same site conditions the seismic performance of N3 series is better than that of N1 series, and the seismic performance of N4 series is better than that of N2 series; when the site conditions are poorer, the rate of increase of the maximum structural interstorey displacement angle with the increase of the seismic intensity is improved. When the site conditions are the same, the maximum structural interstory displacement angle increases with the increase of seismic intensity, and the structural damage state is gradually aggravated; when the seismic intensity is the same, the worse the site conditions are, the larger the structural interstory displacement angle is, and the heavier the structural damage state is.

When the site conditions are class I, make X4 = 1; similarly when the site conditions are class II, class III, class IV, X4 take 2, 3, 4 respectively.

4. Seismic intensity (X5)

Seismic intensity is a direct reflection of the amount of energy released by an earthquake. Larger seismic intensities usually result in greater seismic effects, such as the amplitude and frequency of seismic waves. These effects directly affect the stresses on the structure, thus seismic intensity is a key factor that directly affects the seismic hazard of the structure. By taking seismic intensity as an input, a fuzzy inference model can learn the complex relationship between seismic intensity and structural damage, thus providing a prediction of the degree of structural damage. In this paper, seismic intensity is used as an independent variable for comparative analysis when studying the influencing factors X3 and X4. When the seismic intensity is 6 degrees and the maximum value of horizontal seismic influence coefficient is 0.05g, let X5=6; when the seismic intensity is 7 degrees and the maximum value of horizontal seismic influence coefficient is 0.10g, let X5=7; when the seismic intensity is 7 degrees and the maximum value of horizontal seismic influence coefficient is 0.15g, let X5=7.5; when the seismic intensity is 8 degrees and the maximum value of horizontal seismic influence coefficient is 0.20g When the intensity of the earthquake is 8 degrees, X5=8; when the intensity of the earthquake is 8 degrees and the maximum value of the horizontal seismic impact coefficient is 0.30g, X5=8.5; when the intensity of the earthquake is 9 degrees and the maximum value of the horizontal seismic impact coefficient is 0.40g, X5=9; and when the intensity of the earthquake is n, X5=n (n is the intensity of the specific earthquake).

4.4.2 Sample library of seismic data

A sample library of seismic data was obtained based on relevant analyses and literature, which is presented in Table 15.

Table 15. Sample library of seismic data

Number	Influencing factors										Number	Influencing factors									
	X1	X2	X3	X4	X5							X1	X2	X3	X4	X5					
					6	7	7.5	8	8.5	9						6	7	7.5	8	8.5	9
1	0	1	6	1	DS1	DS2	DS3	DS3	DS4	DS4	33	0	1	6	3	DS2	DS3	DS3	DS4	DS4	DS5
2	0	0	6	1	DS1	DS2	DS2	DS3	DS3	DS4	34	0	0	6	3	DS1	DS2	DS3	DS4	DS4	DS4
3	1	1	6	1	DS1	DS1	DS2	DS2	DS3	DS3	35	1	1	6	3	DS1	DS2	DS2	DS3	DS3	DS3
4	1	0	6	1	DS1	DS1	DS2	DS2	DS2	DS3	36	1	0	6	3	DS1	DS1	DS2	DS2	DS3	DS3
5	0	1	7	1	DS1	DS2	DS3	DS3	DS4	DS4	37	0	1	7	3	DS2	DS3	DS3	DS4	DS4	DS4
6	0	0	7	1	DS1	DS1	DS2	DS3	DS3	DS3	38	0	0	7	3	DS1	DS2	DS2	DS3	DS4	DS4
7	1	1	7	1	DS1	DS1	DS2	DS2	DS3	DS3	39	1	1	7	3	DS1	DS2	DS2	DS3	DS3	DS3
8	1	0	7	1	DS1	DS1	DS1	DS2	DS2	DS2	40	1	0	7	3	DS1	DS1	DS2	DS2	DS3	DS3
9	0	1	8	1	DS1	DS2	DS2	DS3	DS3	DS3	41	0	1	8	3	DS2	DS2	DS3	DS3	DS4	DS4
10	0	0	8	1	DS1	DS1	DS2	DS2	DS3	DS3	42	0	0	8	3	DS1	DS2	DS2	DS3	DS3	DS4
11	1	1	8	1	DS1	DS1	DS2	DS2	DS3	DS3	43	1	1	8	3	DS1	DS2	DS2	DS3	DS3	DS3
12	1	0	8	1	DS1	DS1	DS1	DS2	DS2	DS2	44	1	0	8	3	DS1	DS1	DS2	DS2	DS2	DS3
13	0	1	9	1	DS1	DS2	DS2	DS3	DS3	DS3	45	0	1	9	3	DS1	DS2	DS3	DS3	DS3	DS4
14	0	0	9	1	DS1	DS1	DS2	DS2	DS3	DS3	46	0	0	9	3	DS1	DS1	DS2	DS3	DS3	DS3
15	1	1	9	1	DS1	DS1	DS2	DS2	DS2	DS3	47	1	1	9	3	DS1	DS1	DS2	DS2	DS3	DS3
16	1	0	9	1	DS1	DS1	DS1	DS2	DS2	DS2	48	1	0	9	3	DS1	DS1	DS2	DS2	DS2	DS3
17	0	1	6	2	DS2	DS3	DS3	DS4	DS4	DS4	49	0	1	6	4	DS2	DS3	DS4	DS4	DS5	DS5
18	0	0	6	2	DS1	DS2	DS3	DS3	DS4	DS4	50	0	0	6	4	DS2	DS3	DS3	DS4	DS4	DS5
19	1	1	6	2	DS1	DS1	DS2	DS2	DS3	DS3	51	1	1	6	4	DS1	DS2	DS3	DS3	DS4	DS4
20	1	0	6	2	DS1	DS1	DS2	DS2	DS2	DS3	52	1	0	6	4	DS1	DS2	DS2	DS3	DS3	DS3
21	0	1	7	2	DS1	DS2	DS3	DS3	DS4	DS4	53	0	1	7	4	DS2	DS3	DS4	DS4	DS4	DS5
22	0	0	7	2	DS1	DS1	DS2	DS3	DS3	DS4	54	0	0	7	4	DS2	DS2	DS3	DS4	DS4	DS4
23	1	1	7	2	DS1	DS1	DS2	DS2	DS3	DS3	55	1	1	7	4	DS1	DS2	DS3	DS3	DS3	DS4
24	1	0	7	2	DS1	DS1	DS1	DS2	DS2	DS3	56	1	0	7	4	DS1	DS2	DS2	DS3	DS3	DS3
25	0	1	8	2	DS1	DS2	DS3	DS3	DS3	DS4	57	0	1	8	4	DS2	DS3	DS3	DS4	DS4	DS4
26	0	0	8	2	DS1	DS1	DS2	DS3	DS3	DS3	58	0	0	8	4	DS1	DS2	DS3	DS3	DS4	DS4
27	1	1	8	2	DS1	DS1	DS2	DS2	DS3	DS3	59	1	1	8	4	DS1	DS2	DS2	DS3	DS3	DS4
28	1	0	8	2	DS1	DS1	DS1	DS2	DS2	DS2	60	1	0	8	4	DS1	DS2	DS2	DS3	DS3	DS3
29	0	1	9	2	DS1	DS2	DS2	DS3	DS3	DS3	61	0	1	9	4	DS2	DS3	DS3	DS4	DS4	DS4
30	0	0	9	2	DS1	DS1	DS2	DS2	DS3	DS3	62	0	0	9	4	DS1	DS2	DS2	DS3	DS4	DS4
31	1	1	9	2	DS1	DS1	DS2	DS2	DS2	DS3	63	1	1	9	4	DS1	DS2	DS2	DS3	DS3	DS3
32	1	0	9	2	DS1	DS1	DS1	DS2	DS2	DS2	64	1	0	9	4	DS1	DS1	DS2	DS2	DS3	DS3

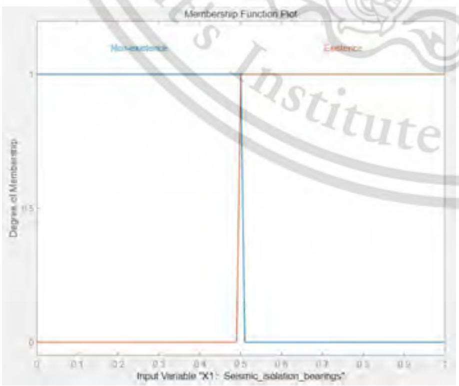
4.4.3 Establishment of a fuzzy inference model for earthquake damage prediction of structures

This paper establishes a fuzzy inference model based on the rules of fuzzy system with seismic isolation bearing X1, degree of structural regularity X2, intensity of defence X3, site category X4 and seismic intensity X5 as fuzzy inputs, and the damage state Y of the structure as fuzzy output. In order to accurately express the relationship between the damage state and each seismic influence factor, a nonlinear regression equation is established, and the equation is as follows:

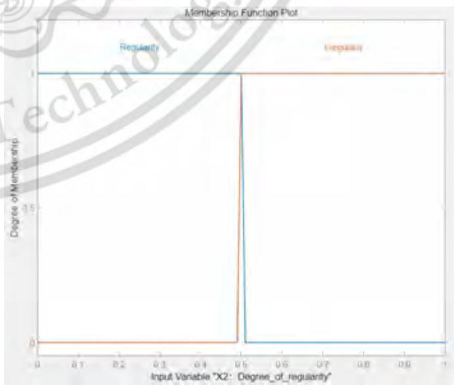
Y=f(X1, X2, X3, X4, X5) + error **(4.5)**

1. Determination of the Theory Domain and Affinity Function

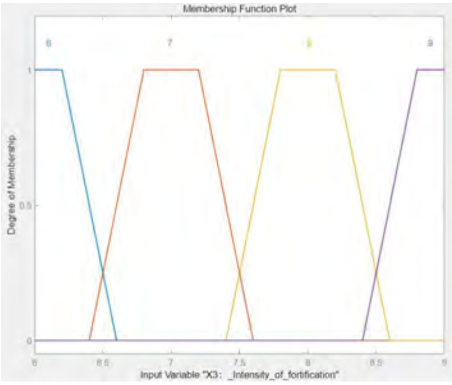
Here, the seismic isolation bearing domain is [0, 1], the fuzzy linguistic variables are "Non-existence", "Existence", and its affiliation function is trapezoidal, as shown in Fig. 4.22(a); the structural regularity domain The domain of structural regularity is [0, 1], the fuzzy linguistic variables are "Irregularly", "Regularly", and its affiliation function is trapezoidal as shown in Fig. 4.22(b); the domain of defence intensity is [6, 9], the fuzzy linguistic variables are "6 degrees", and the fuzzy linguistic variables are "6 degrees", and the fuzzy linguistic variables are "6 degrees", and the fuzzy linguistic variables are "6 degrees" and "6 degrees". 6 degrees", "7 degrees", "8 degrees", "9 degrees", and its affiliation function is trapezoidal, as shown in Fig. 4.22(c). 4.22(c); the venue category domain is [1, 4], the fuzzy linguistic variables are "Class I", "Class II", "Class III", " Class IV", and its affiliation function selects triangles, as shown in Fig. 4.22(d); the seismic intensity domain is [6, 9], and the fuzzy linguistic variables are "6 degrees", "7 degrees", and "7.5 degrees", "8 degrees", "8.5 degrees", "9 degrees" and its affiliation function is trapezoidal, as shown in Fig. 4.22(e). As shown in Fig. 4.22(e); the damage state domain is [0, 5] and the fuzzy linguistic variables are "Basically intact", "Minor damage", " Moderate damage", "Serious damage", "Collapse" and its affiliation function is trapezoidal, as shown in Fig. 4.22(f).



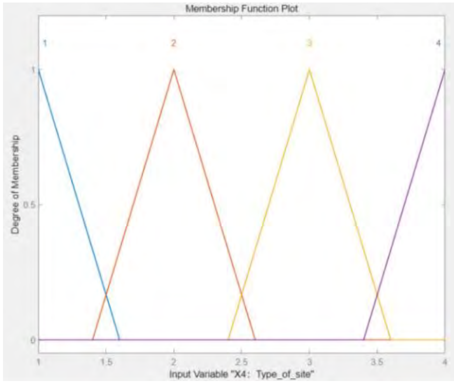
(a) Seismic isolation bearings



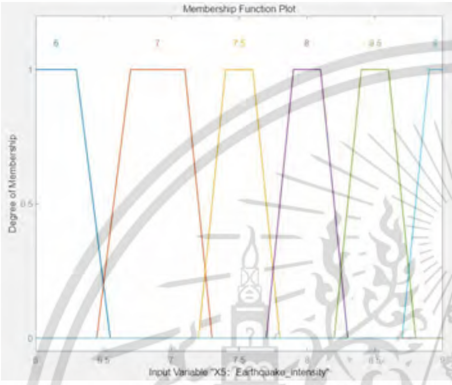
(b) Degree of structural regularity



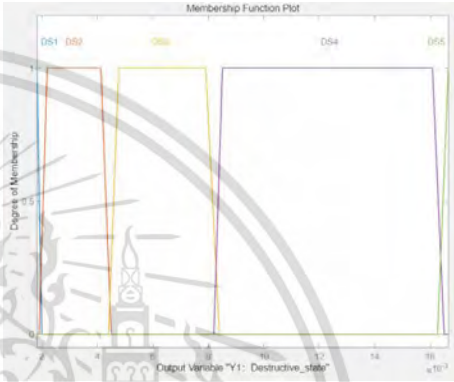
(c) Intensity of defence



(d) Type of site



(e) Seismic intensity



(f) Maximum angle of interlayer displacement

Fig 4.22 Affinity function

2. Fuzzy rule construction

The fuzzy rules for seismic isolation bearing, degree of structural regularity, intensity of defence, site category, seismic intensity and damage are constructed according to the sample library of seismic data in Table 29 as shown in Table 6, and since the fuzzy rules of this study reached 384, the fuzzy rules correspond to the sample library, and only 12 of them are shown in Table 16.

Table 16.Partial fuzzy rules

X1	X2	X3	X4	X5	Y
0	0	6	1	6	DS1
1	0	6	1	7	DS1
0	1	6	1	7.5	DS3
1	1	7	2	8	DS2

0	0	7	2	8.5	DS3
1	0	7	2	9	DS3
0	1	8	3	6	DS2
1	1	8	3	7	DS2
0	0	8	3	7.5	DS2
1	0	9	4	8	DS2
0	1	9	4	8.5	DS4
1	1	9	4	9	DS3

3.Fuzzy inference modelling

In this paper, the fuzzy inference model is implemented through the fuzzy logic toolbox in Matlab, and the fuzzy variables of the fuzzy inference model are set as shown in Figure 4.23. The argument domain, affiliation function is shown in Figure 4.24. The fuzzy rule setting process is shown in Figure 4.25.

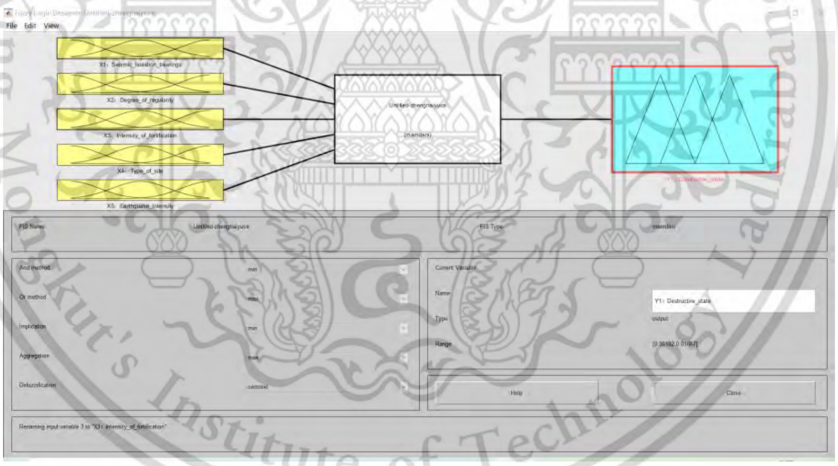


Fig 4.23 Fuzzy variable setting

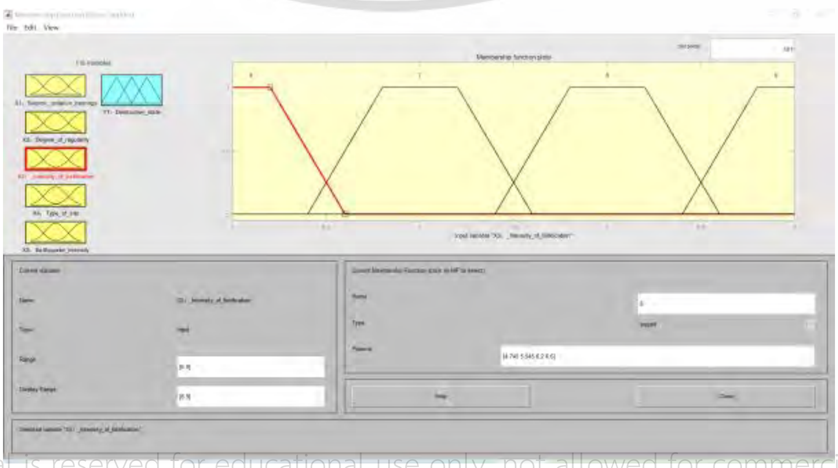


Fig 4.24 Thesis domain, affiliation function

Fig 4.25 Fuzzy rule setup

The specific fuzzy rules are as follows:

1. If X1 is 0 and X2 is 1 and X3 is 6 and X4 is 1 and X5 is 6 then Y1 is DS1
2. If X1 is 0 and X2 is 1 and X3 is 6 and X4 is 1 and X5 is 7 then Y1 is DS2
3. If X1 is 0 and X2 is 1 and X3 is 6 and X4 is 1 and X5 is 7.5 then Y1 is DS3

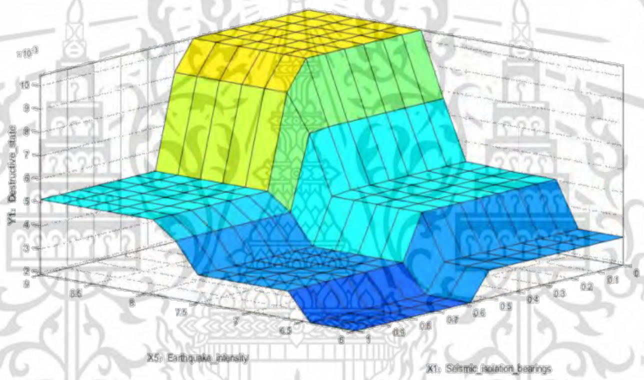
......

383. If X1 is 1 and X2 is 0 and X3 is 9 and X4 is 4 and X5 is 8.5 then Y1 is DS3
384. If X1 is 1 and X2 is 0 and X3 is 9 and X4 is 4 and X5 is 9 then Y1 is DS3

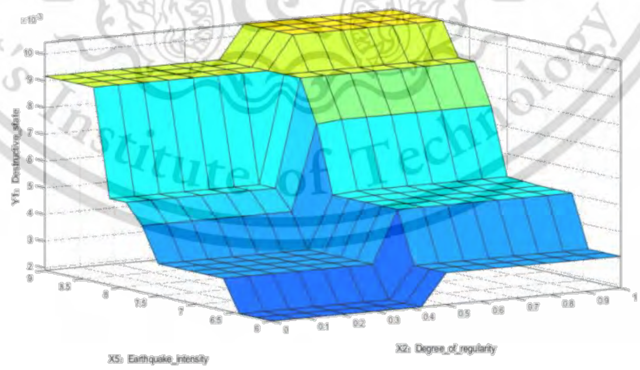
4.4.4 Multifactor fuzzy surfaces

The relationship between the inputs and outputs in the fuzzy inference model can be represented by the fuzzy surface in Fig. 4.26, which represents the combined effects of seismic isolation bearing, degree of structural regularity, intensity of defence, site category, seismic intensity and damage.

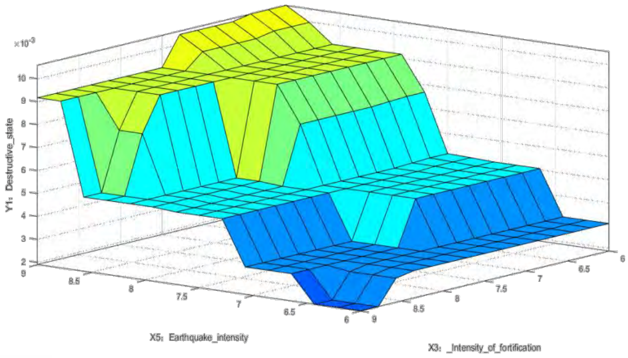
Figure a is the damage degree of the structure with the seismic intensity, seismic isolation bearing fuzzy surface, according to the surface diagram can intuitively see the seismic isolation bearing on the seismic performance of the structure has a greater impact, intuitively reflect the damage degree of seismic isolation structure and ordinary structure with the change rule of seismic intensity. Figure b is the damage degree of the structure with the seismic intensity, the degree of regularity fuzzy surface, according to the surface map can intuitively see the degree of regularity on the seismic performance of the structure has a greater impact, intuitively reflect the damage degree of the mountainous terraced foundation frame structure and ordinary frame structure with the change rule of seismic intensity. Figure c is the damage degree of the structure with the seismic intensity, defence intensity fuzzy surface, according to the surface map can intuitively see the defence intensity of the structure of the seismic performance has a greater impact, intuitively reflecting the damage degree of the structure of different defence intensity with the change rule of seismic intensity. Figure d is the damage degree of structure and seismic intensity, site category fuzzy surface, according to the surface can intuitively see the site category of the structure of the seismic performance of the greater impact, can intuitively reflect the structure of the damage degree of different site categories with the change rule of seismic intensity.



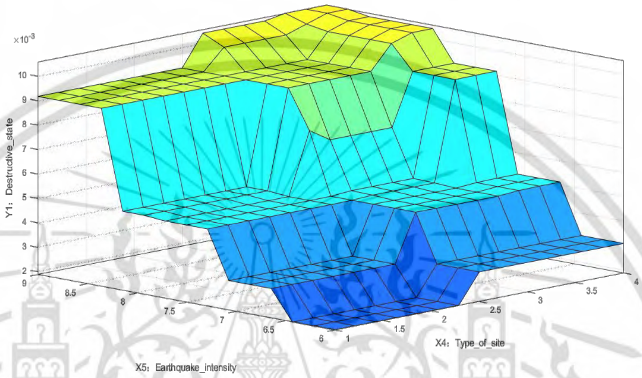
(a) Damage level and seismic intensity, fuzzy surfaces of seismic isolation bearings



(b)Fuzzy surfaces of damage and seismic intensity, degree of regularity



(c) Fuzzy surfaces of damage and seismic intensity and defence intensity



(d)Fuzzy surfaces of damage with seismic intensity and site type

Fig 4.26 Fuzzy surfaces

The arrangement of seismic isolation bearings, regularity of building structure, defence intensity, site category and seismic intensity are inputted into the fuzzy inference model, for example: a structure is arranged with seismic isolation bearings for a mountainous stepped seismic isolation frame structure, and the defence intensity of the structure is 6 degrees, the site category is Ⅳ, and the seismic intensity is 6.5, and the input vector is i.e., [1,1,6,4,6.5] and the output vector is [0.00309], corresponding to the maximum inter-story displacement angle of the structure is 0.00309, and the damage state is DS2 (Minor damage).

4.4.5 Model accuracy test

The comparison of the results obtained by the fuzzy inference model with the actual results of the test set consisting of four randomly selected samples is shown in Table 17, which shows that most of the data can be correctly reflected, but there is also a small amount of deviation in some of the data, but on the whole the model is well fitted, and the above errors in the model are acceptable.

Table 17. Comparison of model accuracy results

Number	Input vector	Actual result	Damage status	Projected results	Damage status	Goodness of fit
1	[1,0,7,3,8]	0.00348	DS2	0.00359	DS2	91.09%
2	[0,0,6,2,8]	0.00624	DS3	0.00690	DS3	89.42%
3	[1,0,7,2,7.5]	0.00162	DS1	0.00184	DS2	86.41%
4	[0,1,6,4,7.5]	0.0110	DS4	0.0135	DS5	77.27 %

CHAPTER 5

CONCLUSIONS AND OUTLOOK

5.1 CONCLUSION

This paper begins with the background and significance of the study of seismically isolated frame structures with stepped foundations in mountainous areas. We specify the research object as a low to medium-rise dropped-story building, and pay special attention to the effects of the presence or absence of seismic isolation bearings and the arrangement of seismic isolation bearings on the structural performance. In the paper, we describe the current state of research on seismic isolation technology and dropped-storey structures, detail the mechanical properties of lead-core rubber seismic isolation bearings and the implementation of seismic isolation bearings in the finite element analysis software Midas Gen. In this study, Midas Gen was used to structurally design the mountainous terrace foundation frame structure, and several seismic isolation structures were obtained by arranging seismic isolation bearings at different locations. Three natural seismic waves and one artificial seismic wave were selected and processed for multiple dynamic time course analysis. By observing the dynamic analysis results of the seismic isolation structures. Based on the analysis of structural construction costs and construction cycles, we have obtained the applicable conditions for various structures under different conditions . We found that after arranging the seismic isolation bearings at different elevations of the horizontal plane to form unequal isolation layers, the isolation layer enters into a yielding state under seismic action, but still does not exceed the horizontal ultimate deformation of the lead-core rubber seismic isolation bearing, which shows a significant effect of seismic isolation and energy dissipation. In particular, under multiple earthquakes, the seismic isolation drop layer model with separate isolation layers shows better performance of seismic isolation bearing, which can not only damp energy consumption, but also maintains small shear deformation, and can be restored to the original position more quickly after the disappearance of seismic wave action to maintain the structure's continued serviceability.

In order to improve the comprehensive disaster prevention capability of urban and rural areas, we have carried out earthquake damage prediction for building structures. Although the dynamic time-range analysis method can accurately calculate the seismic response of structures, its computational efficiency is relatively low. To improve the computational efficiency, in recent years, scholars at home and abroad have introduced methods such as machine learning to achieve fast prediction of time-range response for specific monolithic structures. In this paper, a fast prediction method of seismic response based on artificial intelligence technology is introduced with a mountainous stepped seismic isolation frame structure as the research object. We designed several typical frame structures using finite element software and performed dynamic time-range analyses of the structures using the control variable method. Through the analyses, we derived five factors that have a strong influence on the seismic performance of mountain step-isolated frame structures, including seismic isolation bearing arrangement, degree of structural regularity, fortification intensity, site category, and seismic intensity. Based on the results of the dynamic time-course analyses and combining these influencing factors, we established a seismic sample library with a sample capacity of 384. Suitable domains and affiliation functions were assigned to each influencing factor, and fuzzy rules were established based on the seismic sample library, and a fuzzy inference model was built using the fuzzy logic toolbox in Matlab. The model was established by randomly selecting data samples for several times, and the accuracy and stability of the model were verified. The experimental results show that the seismic influencing factors selected in this paper can accurately map the seismic damage prediction results of frame structures, and the method is accurate, fast and efficient, which can be applied to the rapid seismic damage prediction of step-isolated frame structures in mountainous areas.

5.2 OUTLOOK

In this paper, we focused on the seismic performance of seismically isolated frame structures with stepped foundations in mountainous areas, and we only compared and analysed the effects of the presence or absence of seismic isolation bearings and the arrangement of seismic isolation bearings on the structures. In future research, we can consider expanding the study object to footing-type structures, and study in depth the effects of the height of the structure, the height of the dropped storey section, and the span of the dropped storey section on the seismic performance of the structure.

When building the seismic sample database, we selected five seismic influence factors, and although this helps to initially understand the seismic response of the structure, it cannot completely and accurately simulate the real scenario. In addition, all the data are from finite element analysis, which lacks the support of real seismic data. In future research, we can consider increasing the types of influence factors and expanding the number of samples in the database to further improve the accuracy of the model, so that it can have a wider application in real earthquake prediction engineering. In addition, we can selectively replace some of the seismic impact factors on the basis of the model for further research. By comparing the results, we can derive the importance of the influence of each factor on the earthquake damage results. However, these ideas need to be further verified in practice to ensure the scientific validity and reliability of the study. Such an in-depth study can help to understand more comprehensively the influence of different factors on the seismic performance of structures and provide a more reliable basis for design and prediction in the field of earthquake engineering.

CHAPTER 6

APPENDIX

6.1 INTRODUCTION TO THE FINITE ELEMENT SOFTWARE MIDAS GEN

Midas Gen is a finite element analysis software widely used for structural analysis and design, with multidisciplinary modelling capabilities, allowing users to simulate and evaluate the performance of a wide range of structures, covering a wide range of areas such as buildings, bridges, steel, concrete and underground structures, making it a versatile structural analysis tool. The software offers a powerful pre- and post-processor with an intuitive graphical user interface that allows users to easily create, modify and analyse models. Models are constructed by drawing structures, applying boundary conditions and loading. In addition, Midas Gen supports a wide range of material types, including steel, concrete, timber, aluminium and glass, while offering a wide range of finite element element types for modelling the behaviour of different types of structures, from linear elastic to non-linear materials. These features make it a powerful and comprehensive structural analysis tool. Detailed features about the finite element software Midas Gen are listed below:

1. Static and dynamic analysis: The software supports a wide range of analysis types, including static, dynamic and nonlinear analysis, and can take into account complex behaviour of structures, such as nonlinear materials, large deformations and nonlinear contacts. This makes it suitable for a variety of engineering applications, including earthquake engineering.

2. Seismic analysis and design: Midas Gen has powerful seismic analysis and design functions that can be used to assess the seismic performance of structures. It supports response spectrum analysis, time-course analysis and seismic design, and can generate relevant reports.

3. Parametric design and optimisation: Users can use the software for parametric design and optimisation of structures to achieve optimum structural performance and cost. This helps engineers to optimise the design to meet specific performance and constraint requirements.

4. Automation and script programming: Midas Gen allows users to automate tasks using scripts to increase productivity and supports custom script programming to meet specific needs. This provides greater flexibility for advanced users.

5. BIM Integration: Midas Gen integrates with other Building Information Modelling (BIM) tools to support comprehensive engineering design and collaboration. This helps ensure consistency in design and construction.

6. Areas of application: 1. Midas Gen is widely used in the fields of architecture, civil engineering, structural engineering, bridge design, underground structures, harbour and marine engineering. It is used to analyse and design engineering projects of all sizes and types, from small buildings to large infrastructure projects.

In summary, Midas Gen is a feature-rich and flexible finite element analysis software for a wide range of structural engineering applications. It helps engineers to simulate and evaluate the performance of different structures to ensure the safety and reliability of engineering projects.

6.2 INTRODUCTION TO THE SOFTWARE MATLAB

Matlab (MATrix LABoratory) is an advanced technical computing software for numerical computation and data visualisation. It was developed by MathWorks and is widely used in science, engineering, finance, and other fields. Following are some of the key features and functions of Matlab software:

1. Numerical calculations and algorithms: Matlab provides a rich library of mathematical functions and algorithms for performing a variety of numerical calculations, including linear algebra, signal processing, optimisation, statistics and other operations.

2. Programming environment: Matlab has a powerful programming environment that supports scripting and function definition. Users can use Matlab language for algorithm development and scripting, as well as creating custom functions and applications.

3. Data analysis and visualisation: Matlab provides a rich set of tools and functions for data analysis and visualisation. Users can create high-quality charts, graphs, and animations to better understand the data.

4. Simulation and modelling: Matlab supports system simulation and modelling, which can be used to build and simulate complex dynamic systems. This is very useful in control system design, communication system analysis, etc.

5. Application development: Users can use Matlab to build stand-alone applications that can be integrated with other software and programming languages.Matlab provides tools such as App Designer to simplify the application development process.

6. Parallel computing and CPU acceleration: For tasks that require processing large-scale data or performing complex calculations, Matlab supports parallel computing and GPU acceleration to improve computational performance.

7. Toolboxes and add-ons: Matlab has a large number of toolboxes and add-ons for domain-specific applications, such as image processing, signal processing, control system design, and so on. These toolboxes extend the functionality of Matlab.

8. Cross-platform support: Matlab can run on multiple operating systems, including Windows, Mac and Linux, and users can share and deploy Matlab code between different platforms.

Overall, Matlab is a powerful technical computing software for scientific and engineering applications in several fields. Because of its rich functionality and flexibility, Matlab is widely used in both academia and industry.

6.3 TABLE OF SHEAR FORCES AT EACH FLOOR UNDER DIFFERENT SEISMIC EFFECTS.

Table18.RSN9 Floor shear force under earthquake action (kN)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	2324.50	1363.50	1565.60	893.01	612.17	788.67	426.90	574.43
2F	2289.30	1325.00	1518.80	847.27	572.57	745.10	395.04	508.53
3F	2185.00	1279.30	1856.10	1265.30	1330.50	999.89	919.24	849.38
4F	1877.80	1114.40	1544.90	1056.50	1099.03	824.31	768.01	698.61
5F	1475.20	901.40	1170.10	813.71	822.84	644.11	588.44	539.54
6F	989.82	624.94	760.46	544.49	511.54	458.88	387.41	356.58
7F	445.44	288.17	334.38	246.02	195.10	170.08	187.76	158.41

Table19.RSN22 Floor shear force under earthquake action (kN)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	2825.30	1090.50	1374.60	1199.00	964.24	1028.14	589.28	618.70
2F	2835.00	1065.00	1397.40	1147.30	917.24	858.60	510.57	530.58
3F	2726.10	992.53	1934.30	1613.90	1366.58	1286.14	1174.20	1044.00
4F	2368.00	863.37	1684.50	1337.70	1152.55	1087.23	942.86	851.93

5F	1878.00	680.51	1321.30	1022.80	895.37	887.62	699.99	647.03
6F	1274.00	458.34	884.99	679.32	615.77	590.15	450.57	424.54
7F	580.64	207.32	397.39	304.62	274.30	205.31	197.01	188.10

Table20.RSN26 Floor shear force under earthquake action (kN)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	3013.40	861.80	1762.10	805.94	1451.93	723.97	526.83	494.72
2F	3007.80	867.25	1830.30	778.20	1506.17	726.32	473.98	442.29
3F	2884.90	841.53	2365.40	1283.10	1852.17	1008.12	1039.00	857.24
4F	2508.00	732.33	2109.70	1115.90	1524.71	867.11	882.85	713.94
5F	2016.40	580.61	1702.60	886.97	1191.39	710.59	733.37	544.29
6F	1396.40	390.49	1172.30	604.60	755.50	501.66	509.33	357.38
7F	647.99	175.24	540.59	275.69	316.69	263.86	233.93	158.63

Table21.REN Floor shear force under earthquake action (kN)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	2170.40	1000.40	1061.90	693.61	857.35	618.58	362.75	364.11
2F	2109.70	961.37	1031.00	683.29	797.66	585.01	337.61	346.01
3F	1971.60	889.69	1405.60	892.38	1035.71	849.05	840.77	586.40
4F	1766.00	722.23	1199.20	806.36	887.27	681.04	731.30	507.90
5F	1495.40	566.38	959.43	637.66	737.83	513.29	578.21	403.36
6F	1070.90	401.95	683.65	435.74	584.31	340.54	391.43	274.89
7F	513.13	191.59	326.59	215.99	325.50	162.77	183.03	124.86

6.4 TABLE OF DISPLACEMENTS OF FLOORS UNDER DIFFERENT SEISMIC EFFECTS.

Table22.Interstory displacement under RSN9 earthquake (m)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y

1F	0.0072	0.0048	0.0049	0.0023	0.0068	0.0047	0.0031	0.0059
2F	0.0106	0.0169	0.0091	0.0068	0.0041	0.0199	0.0033	-0.0011
3F	0.0049	0.0027	0.0082	0.0052	0.0011	0.001	0.0028	0.0035
4F	0.0056	0.0028	0.0058	0.0037	0.001	0.0008	0.0021	0.0025
5F	0.0046	0.0023	0.0041	0.0026	0.0006	0.0006	0.0014	0.0017
6F	0.003	0.0015	0.0025	0.0015	0.0005	0.0003	0.0009	0.0011
7F	0.0017	0.0007	0.0012	0.0008	0.0002	0.0003	0.0004	0.0005

Table23.Interstory displacement under RSN22 earthquake (m)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	0.0086	0.0037	0.0047	0.0036	0.0075	0.0065	0.0075	0.0061
2F	0.0128	0.0179	0.0089	0.0095	0.0043	0.0069	0.0056	0.0002
3F	0.006	0.0032	0.0087	0.0069	0.0014	0.0008	0.0047	0.004
4F	0.0072	0.0026	0.0063	0.0048	0.001	0.0006	0.0032	0.0027
5F	0.0061	0.002	0.0047	0.0035	0.0008	0.0005	0.0021	0.0019
6F	0.0043	0.0014	0.003	0.0022	0.0006	0.0006	0.0013	0.0011
7F	0.0023	0.0007	0.0016	0.001	0.0002	0.0004	0.0006	0.0005

Table24.Interstory displacement under RSN26 earthquake (m)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	0.009	0.0029	0.0058	0.0022	0.0083	0.004	0.006	0.0053
2F	0.0136	0.0117	0.0112	0.0072	0.0049	0.0022	0.0045	0.0016
3F	0.0068	0.0019	0.0107	0.0052	0.0015	0.001	0.0038	0.0034
4F	0.0075	0.002	0.0078	0.0037	0.0013	0.0009	0.0026	0.0023
5F	0.0063	0.0016	0.0059	0.0027	0.0009	0.0006	0.0019	0.0016
6F	0.0043	0.001	0.0039	0.0017	0.0006	0.0003	0.001	0.0009
7F	0.0025	0.0005	0.002	0.0008	0.0003	0.0003	0.0006	0.0005

Table25.Interstory displacement under REN earthquake (m)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y

1F	0.0067	0.0035	0.0032	0.0018	0.0097	0.0045	0.0043	0.0033
2F	0.0101	0.0145	0.0059	0.0043	0.0057	0.044	0.0033	0.0002
3F	0.0048	0.0024	0.0054	0.0033	0.0017	0.0009	0.0028	0.0019
4F	0.005	0.0024	0.004	0.0021	0.0015	0.0007	0.002	0.0013
5F	0.0042	0.0019	0.0029	0.0015	0.001	0.0006	0.0015	0.0009
6F	0.0029	0.0012	0.0017	0.0009	0.0006	0.0004	0.0009	0.0006
7F	0.0016	0.0006	0.0008	0.0005	0.0004	0.0003	0.0005	0.0003

6.5 TABLE OF ACCELERATION OF EACH LAYER UNDER DIFFERENT EARTHQUAKES.

Table26.Floor acceleration under RSN9 earthquake (m/s^2)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	0.6794	0.5073	0.8530	0.4783	0.7115	186	0.6594	0.4267
2F	0.5832	0.6430	0.9708	0.5295	0.8954	0.4572	0.8009	0.3945
3F	0.6257	0.6597	0.6806	0.5427	0.6000	0.4708	0.5368	0.4256
4F	0.7138	0.6027	0.5667	0.5419	0.5001	106	0.4047	0.3961
5F	0.7800	0.6287	0.6314	0.4907	0.5598	0.3939	0.3771	0.3668
6F	0.8235	0.7069	0.7322	0.5247	0.6206	125	0.3909	0.4064
7F	0.8581	0.7840	0.8049	0.6273	0.6495	0.5142	0.4017	0.4588

Table27.Floor acceleration under RSN22 earthquake (m/s^2)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	0.4612	0.3976	0.6136	0.5283	0.5074	0.4877	0.4732	0.4172
2F	0.6197	0.5172	0.6913	0.5050	0.7403	0.5118	0.6234	0.4196
3F	0.7369	0.7517	0.5848	0.6490	0.5221	0.4678	0.3931	0.4111
4F	0.8906	0.9148	0.5588	0.7689	0.5310	145	0.3845	0.3848
5F	1.0750	1.0408	0.6468	0.8729	0.5333	0.4151	0.3760	0.3763
6F	1.2232	1.1153	0.7054	0.9273	0.5335	138	0.3923	0.3878
7F	1.3306	1.1627	0.7525	0.9982	0.5458	0.4711	0.4054	0.4080

Table28.Floor acceleration under RSN26 earthquake (m/s^2)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	0.7773	0.2614	0.8446	0.5518	0.7693	0.4718	0.5906	0.3417
2F	0.7073	0.3250	0.8678	0.7624	0.8697	0.6297	0.7202	0.5614
3F	0.9568	0.3949	0.7114	0.5548	0.7122	0.4788	0.4900	0.4089
4F	1.2467	0.4634	0.5304	0.5102	0.5698	0.4731	0.3754	0.3727
5F	1.4599	0.5080	0.6971	0.4928	0.7198	0.4758	0.3631	0.3370
6F	1.6356	0.5493	0.8766	0.5589	0.9206	0.4801	0.4242	0.3551
7F	1.7927	0.5712	1.0153	0.6418	1.0927	0.4897	0.4758	0.3692

Table29.Floor acceleration under REN earthquake (m/s^2)

Floor number	M1		M2		M3		M4	
	X	Y	X	Y	X	Y	X	Y
1F	0.8135	0.6239	0.8625	0.6043	0.8756	189	0.7989	0.3843
2F	0.6632	0.6445	0.9781	0.6521	0.9441	0.5813	0.8811	0.4693
3F	0.7331	0.8006	0.6969	0.5143	0.6413	0.4557	0.4966	0.3924
4F	0.7180	0.8066	0.5983	0.6341	0.5381	0.4520	0.3903	0.3478
5F	0.8898	0.7635	0.6539	0.6338	0.5348	0.4511	0.3999	0.2972
6F	0.9661	0.8207	0.7266	0.5972	0.5418	0.4986	0.4066	0.3314
7F	1.0292	0.9306	0.7908	0.6585	0.5481	0.5360	0.4107	0.3803

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AI-Driven Predictive Analysis of Seismic Response in Mountainous Stepped Seismic Isolation Frame Structures

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ABSTRACT

In this paper, we propose a unique method for rapid prediction of seismic response of stepped seismic isolation frame structures in mountainous areas using artificial intelligence (AI), based on which the results of seismic response can be used to determine the damage level of stepped seismic isolation frames in mountainous areas under seismic action, and thus to make seismic damage prediction. In order to fill the key research gap in this field, several 7-story typical RC frame structures were designed in this study using the structural design software Midas Gen. The dynamic time-course analysis of the structures was carried out by the control variable method to obtain five factors that have a strong influence on the seismic performance of mountainous step-isolated frame structures, which are: the arrangement of seismic isolation bearings, the degree of regularity of the structure, the intensity of defense, the type of the site, and the seismic intensity. And based on the results of the dynamic time course analysis, a seismic sample library with a sample capacity of 384 is established by combining these influencing factors. Each influence factor is given a suitable domain and affiliation function, and fuzzy rules are established according to the seismic sample library, and a fuzzy inference model is established by using the fuzzy logic toolbox in MATLAB. Random sampling are confirmed the stability and accuracy of model for different times to build a framework. The results show that the method of analysis is correct, fast and efficient and the seismic related selected factors can predict and map the seismic damage prediction of model structure. This method can also be applied to rapid seismic damage prediction for SSIFS (stepped seismic isolation frame structures) in rocky areas.

Keywords: the mountainous step-isolated frame structures, seismic response, earthquake prediction, fuzzy inference modelling, dynamic time course analysis

INTRODUCTION

Mountainous environments are inherently more susceptible to seismic activity due to their complex geological formations, steep inclines, and constant danger of landslips. There are promising mitigation strategies to overcome earthquake prone, this study develops SSIFS (Stepped Seismic Isolation Frame Structures) to resolve challenges (Dang et. al., 2017; Huang et. al., 2018; Zubovich et. al., 2022). To reduce the seismic load to high lever, the efficient ground motion isolation has provided by these design. This is proficient at different levels to integrating seismic isolation bearings. It is a big challenges for forecasting about SSIFS that how it can react seismically in hilly areas (Bao et. al., 2022; Cody et. al., 2020). Old and traditional mechanism in engineering are failed to deal with these relationship to these domains. However, vibration prediction patterns are more challenging task which different areas are involved at different levels. These create variation in exertion and checking properties in rock creations due to different areas conditions (Frame, 2020).

To deal with these kinds of difficulties, a modern forecasting technique is needed to evaluate the complex seismic response of SSIFS in different rocky areas. This is basically non-linear behavior due to variant relationship of

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