

REVIEW

A Review of the Application of Incremental Dynamic Analysis in Isolation Systems

Una revisión de la aplicación del análisis dinámico incremental en sistemas de aislamiento

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ABSTRACT

The Incremental dynamic analysis (IDA) method is an emerging calculation technique that accurately estimates the failure probability of structures, typically means the collapse rates of structures during the earthquakes. It has been widely utilized in the analyzing and designing processes of various engineering projects, including traditional and seismic isolation structures. This paper systematically reviews the application of IDA in the traditional seismic isolation structure, the special seismic isolation structure and other unique structures. It mainly focuses on the considerations of multiple factors that affect the safety of seismic isolation structures, the reliability of IDA in its structure design process, the guidance that IDA results have provided for the design scheme selection of complex structures, and the utilization of IDA in seismic isolator design. This article offers an overview of applying IDA in such a wide range of structures, proving its practical values in both assessing and designing processes. It also implies some directions for future investigation to increase its accuracy and calculation speed.

Keywords: Incremental Dynamic Analysis; Seismic Isolation; IDA; Fragility Curves.

RESUMEN

El método de análisis dinámico incremental (IDA) es una técnica de cálculo emergente que estima con precisión la probabilidad de fallo de las estructuras, lo que típicamente significa las tasas de colapso de las estructuras durante los terremotos. Ha sido ampliamente utilizado en los procesos de análisis y diseño de diversos proyectos de ingeniería, incluyendo estructuras tradicionales y de aislamiento sísmico. Este documento revisa sistemáticamente la aplicación de IDA en estructuras de aislamiento sísmico tradicionales, estructuras de aislamiento sísmico especiales y otras estructuras únicas. Se centra principalmente en las consideraciones de múltiples factores que afectan la seguridad de las estructuras de aislamiento sísmico, la confiabilidad de IDA en su proceso de diseño estructural, la orientación que los resultados de IDA han proporcionado para la selección del esquema de diseño de estructuras complejas y la utilización de IDA en el diseño de aislantes sísmicos. Este artículo ofrece una visión general sobre la aplicación del IDA en una amplia gama de estructuras, demostrando su valor práctico tanto en la evaluación como en el diseño de procesos. También implica algunas direcciones para futuras investigaciones para aumentar su precisión y velocidad de cálculo.

Palabras clave: Análisis Dinámico Incremental; Aislamiento Sísmico; IDA; Curvas de Fragilidad.

INTRODUCTION

Traditional structures use their strength and stiffness to resist the earthquake effects, nonetheless, the seismic isolation structure absorbs the earthquake energy by introducing an isolation layer into certain levels

within the structure. Thus, seismic isolation structures usually demonstrate better seismic performance in terms of the reduced story shear forces and the maximum story drift. However, the application of isolators into a structure will not only makes them more complex, but also bring multiple failure modes for those structures. In this case, more accurate and comprehensive methods are often suggested to be used in analyzing and assessing those structures. The incremental dynamic analysis (IDA) method, as a probability theory based analyzing method, becomes one of the necessities. It can precisely expect the collapse of a complex structure during earthquake situation.

However, at the very beginning, there is only the classic static method. The principle of the classic static method is to convert seismic action into static loads and estimate the seismic force by empirical formulas, mainly including the Seismic Coefficient Method and the Equivalent Lateral Force Method. The Seismic Coefficient Method was proposed by Riki Sano in 1916, who advocated that multiplying the seismic force by a coefficient could estimate the seismic action force on the structure.⁽¹⁾ After the 1923 Great Kanto Earthquake in Japan, this method began to be widely used. The advantage of this method is its simplicity, but its calculation accuracy is insufficient for complex structures.

The equivalent lateral force method, as a calculation method of pseudo-static force, simplifies the seismic action to the equivalent lateral force at the bottom, and this force is distributed along the height in a certain proportion. It takes into account the design earthquake intensity of the area where the structure is located, the hardness of the land, and the distance from the epicenter of the earthquake. Compared with the seismic coefficient method that only considers the seismic intensity, it is more accurate. This method is still used in the structural design of various countries nowadays. For example, it exists in ASCE 7-10⁽²⁾ of the United States and anti-regulations of China.⁽³⁾

Response spectrum analysis (RSA) method is a widely used dynamic analysis method for calculating the seismic forces of structures in modern times. Its concept was jointly proposed by Biot and Housner in the 1940s according to Liu.⁽⁴⁾ By studying the relationship between earthquakes and structural responses, the structural period was correlated with the acceleration of seismic waves, and this new method was summarized. The response spectrum method takes into account the seismic risk of the area where the structure is located, the type of land, the distance from the seismic fault zone, the natural vibration period of the structure and the damping ratio. Therefore, it is more accurate than the traditional static method. In addition, the mode-superposition response spectrum method is based on the RSA, while considering multiple mode shapes of the structure and combining them using methods such as Square Root of Sum of Squares (SRSS) or Complete Quadratic Combination (CQC).

As a more accurate method for calculating seismic action, the time-history analysis method can numerically integrate the motion equation within each minute moment to obtain the dynamic response of buildings to earthquakes. Then, through recursive calculation, the complete time-history response is obtained. These solution methods mainly include 1) the acceleration method exemplified by Newmark- β , 2) the Runge-Kutta method, and 3) the Nigam-Jennings method. The core of time-history analysis is to directly solve the dynamic equation, while the RSA is applied by statistically averaging the spectral curves. Therefore, the time-history analysis method is often used in some complex structures as a supplement to the response spectrum method. For instance, the Standard for seismic isolation design of buildings (GB/T 51408-2021) stipulate that the isolated structure should undergo supplementary verification⁽⁵⁾ using the time-history analysis method.

If the stiffness of the structure changes during an earthquake (such as material damage, structural deformation, etc.) is taken into account, a nonlinear analysis of the structure is required. Nonlinear static analysis is one of the commonly used methods for evaluating the action of structures under static conditions. Common nonlinear static analysis methods include: Pushover method, capacity spectrum method, displacement coefficient method, etc. The Pushover method is currently an important means^(6,7) for performance analysis of structures. Its principle is to analyze the response of the structure by applying an increasing horizontal force to it until the state of structure failure is reached. During the analysis process, the process from elasticity to failure of the structure can be known.

The IDA analysis method was first proposed by Bertero in 1977,⁽⁸⁾ and in 2002, Vamvatsikos introduced this method into the engineering field.⁽⁹⁾ Its principle is to conduct a large number of time-history analyses on a structure, then obtain the relationship between the seismic Intensity measure and the structural Damage measure, and calculate the probability of structural collapse. First, it is necessary to confirm the intensity indicators of the earthquake, such as acceleration, earthquake magnitude, velocity, etc. Afterwards, confirm the indicators for judging structural damage. The common ones are the story drift of the structure and the force exerted on the isolation bearings, etc. Finally, a large number of seismic waves are selected for input, gradually increasing the seismic intensity until the structure is determined to be damaged. By recording the seismic intensity index of the structure at this time, the failure probability can be calculated.

This article provides an overview of the IDA applied in the design and evaluate phases of structures. Firstly, it reviews the IDA method applied in traditional simple seismic isolation structures, including the seismic isolated

frame and shear wall structures. After that, some cases of special and complex seismic isolated structures with the utilization of IDA are depicted, such as a novel double skin structure and a masonry building with affordable fiber reinforced elastomeric bearings. Moreover, some other unique structures employing IDA method are also reviewed like the one with a weak floor at its top as a tuned mass damper and the super high-rise structure contains 128 stories and with a total height of 598m. Finally, the studies of using IDA to assist designing and optimizing seismic isolators are depicted. The overview map of this article is shown in figure 1.

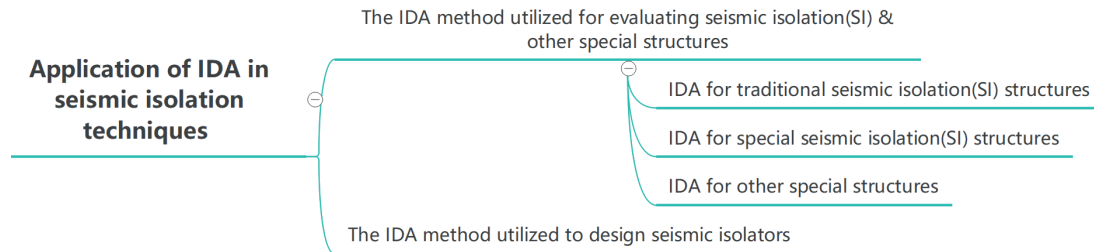


Figure 1. Overview map

METHOD

This section explains the methods used in review processes to ensure transparency and reproducibility, including the search strategy, the selection criteria and the organizational structure.

Search strategies

The search engine used in this literature review includes the Web of Science, Scopus, CNKI and google scholar. Only those literatures related to this article will be collected. The key words of this article include: Seismic isolation, incremental dynamic analysis (IDA), fragility curves, seismic analysis and isolators. Furthermore, some logical symbols are used in the search, such as AND, OR, NOT and their combinations. In terms of time, this paper focuses on investigating the relevant literature in the past 20 years, and gives priority to the relevant studies within the past five years. In addition, this article imposes no restrictions on the language of the literature reviewed, however, the majority of the sources are in English.

Selection criteria

Only articles that are related to the application of IDA in SI and some special structures will be selected, while the rest will be excluded. Specifically: 1) The research content of the article must include IDA and be highly relevant to the analysis and design of SI or other special structures and building components. Exclude the application of IDA in other fields, such as evaluating the failure probability of some other system. 2) The article should contain actual modeling and calculation processes. Pure theoretical framework research, as well as non-research articles such as news reports and viewpoints, are excluded. 3) The selected articles should have a clear process, definite conclusions, and include detailed analysis procedures. Exclude articles for which the full text is unavailable.

Organization of this literature review

This article first reviews IDA for traditional seismic isolated structures and selects four representative articles for research. After that, the IDA for special seismic isolated structures were reviewed, and six articles were selected. Then, IDA for other special structures was reviewed and seven articles were selected. Finally, four articles on the design of seismic isolators using IDA were reviewed.

DEVELOPMENT

The IDA method utilized for evaluating seismic isolation(SI) & other unique structures

IDA for traditional seismic isolation(SI) structures

In numerous studies, the conventional IDA method has been applied to a diverse range of typical isolation structures.

Isolated frame structure

Xu et al.⁽¹⁰⁾ performed IDA method on an 8-story base isolated frame structure. Intensity measures (IM) were selected as PGA, while the maximum story drift θ_{max} of the superstructure and the maximum displacement of isolators were taken as parameters representing two types of failure modes.⁽¹⁰⁾ Finally, IDA and fragility curves for both the superstructure and isolators were generated under various limit states.⁽¹⁰⁾

Isolated frame shear-wall structure

Apart from the implementation of IDA on frame structures, the utilization of IDA on frame shear wall structures is also studied. Zhao et al.⁽¹¹⁾ adopt the maximum displacement of isolation layer and the maximum story drift of frame shear wall superstructure to represent the two failure modes of SI structures. Furthermore, based on the findings of IDA method, it is suggested by Zhao et al.⁽¹¹⁾ that despite the implementation of SI techniques to reduce structural seismic response, there still exists a potential risk of collapse during an extreme earthquake event. The assessment of such risk is one of the crucial reasons for utilizing IDA.

Frame-core tube base-isolated structure

Wu et al.⁽¹²⁾ proposes an IDA method based on series analysis of the isolation layer, superstructure, and lower structure of an isolation system. A 23-story frame-core tube base-isolated structure is analyzed. The maximum displacement of the isolation layer and the maximum story drift of the superstructure are used to evaluate two failure modes of the isolation system.⁽¹²⁾ Finally, fragility curves for the isolation layer, superstructure, and overall structure were obtained respectively. Wu et al.⁽¹²⁾ discovered that while isolated structures can significantly reduce seismic response, the isolation layer is prone to failure before the superstructure and has a similar probability of failure as the overall structure. This highlights the necessity of considering multiple potential failure modes

Structures of various stiffness

Sabet et al.⁽¹³⁾ used the IDA method to investigate how isolated structures perform under different superstructure stiffness, plane irregularity types, and earthquake types. In the study of Sabet et al.⁽¹³⁾, a total of 72 structures with varying heights ranging from 8-32 stories and different geometries were analyzed. Therefore, IDA can be effectively employed to investigate the general seismic behavior patterns exhibited by various isolation systems.

IDA for special seismic isolation(SI) structures

For the design of complex SI structures, the Incremental Dynamic Analysis (IDA) is a more precise and valuable methodology.

Partially base-isolated structures

Parsaeimaram et al.⁽¹⁴⁾ proposes a model for partially base-isolated structures, known as Double-Skin Semi-Base-Isolated Buildings. In this model, the external shear wall and frame structure are fixed-base structures while the inner core is base-isolated with a gap between it and the outer structure.⁽¹⁴⁾ A 10-story double-skin structure without base isolation techniques was used as a control model, while another double-skin structure with a base-isolated inner core was compared.⁽¹⁴⁾ The two models were analyzed by using IDA method.

Parsaeimaram et al.⁽¹⁴⁾ discovered that coupling beams connecting the inner and outer structures can adjust the period and story drift of the semi-base-isolated buildings. By increasing the number of layers connected by coupling beams between the inner core and outer structure, control over story drift is achieved.⁽¹⁴⁾ Moreover, Parsaeimaram et al.⁽¹⁴⁾ initially believed that coupling beams installed on the topmost floor of the structure would effectively mitigate maximum story drift of the overall structure, surpassing that achieved by a single structure without the outer structure. However, based on the results of IDA, the fragility curve indicates that the IIC-10th (the structure connected at the top) has the highest probability of collapse,⁽¹⁴⁾ suggesting that the design scheme of the model IIC-10th may not be optimal.

This is a typical example of applying IDA to evaluate seismic performance of complex structures. When assessing building safety with multiple parameters, some structures may excel in controlling certain factors but have a higher overall risk of collapse. By using the IDA method to determine the probability of structural collapse, a more comprehensive and direct safety assessment can be obtained, especially for those complex SI structures.

Top story as Tuned mass damper(TMD)

Manchalwar et al.⁽¹⁵⁾ employed the top weak story as a tuned mass damper (TMD) to enhance the seismic performance of the overall structure during earthquakes. Subsequently, an IDA method was conducted on that structure, the results demonstrate that such implementation of TMD significantly improves structural seismic response by reducing deformation and collapse risk.⁽¹⁵⁾

Isolated unreinforced masonry buildings

IDA method can be applied not only to RC structures, but also to unreinforced masonry buildings which are still popular in some areas due to their low cost. In this study,⁽¹⁶⁾ affordable fiber reinforced elastomeric bearings were used as SI devices for unreinforced masonry buildings. Firstly, five models considering the variations in

geometry and building configuration were established.⁽¹⁶⁾ Then, fragility curves for both isolated and non-isolated structures were developed using IDA method. The results indicate that the use of fiber reinforced elastomeric isolator can significantly improve seismic performance.⁽¹⁶⁾

Isolated steel structures

Furthermore, IDA analysis method can also be used in steel structure. Rakicevic et al.⁽¹⁷⁾ propose a new Seismic Isolation System, which is a combination of viscous damper and spring, called Hybrid Seismic Isolation System (H-SIS). Rakicevic et al.⁽¹⁷⁾ applies this system to a steel structure with three layers, each with a height of 0,75m, a length of 4,5m and a width of 1,5m. Rakicevic et al.⁽¹⁷⁾ then carried out shaking table tests on it with 10 seismic waves, of which 8 were real seismic waves and 2 were artificial waves. After that, two models are reproduced with and without H-SIS by SAP2000, those models then have been analyzed. It is observed that the conclusion obtained by SAP2000 modeling analysis is very similar to that obtained by shaking table analysis.⁽¹⁷⁾ Finally, Rakicevic et al.⁽¹⁷⁾ use IDA method to analyze the structure. All these three methods show that the H-SIS designed by Rakicevic et al.⁽¹⁷⁾ can effectively control the vibration of the building structure and improve its seismic performance.

Consideration of possible collision at the bottom

The isolated structure will move horizontally during the earthquake. In addition to considering the maximum horizontal displacement limit of the isolation bearings, the possibility of collision happening at the structure bottom under earthquake should also be considered. A new vulnerability calculation method is proposed to calculate the probability of collision at the bottom of isolated structures.⁽¹⁸⁾ Different from traditional fragility calculation methods, robust fragility curves also takes into account various uncertainties and their effects on probability. These uncertainties include the uncertainty of seismic waves and the uncertainty of the structure itself, including the mass of superstructure, the mass of basement, the stiffness of superstructure, the yield force of the isolators, and the stiffness of the isolators before and after the yield. This method is applied to a single layer isolation structure and an 8-layer isolation structure. It is found that the mass of the superstructure and the mechanical parameters of the isolators, such as yield force and post-yield stiffness, have the greatest influence on the displacement of the foundation, but the stiffness of the superstructure has little influence on the displacement of the bottom.⁽¹⁸⁾

Use seismic isolation to strengthen the existing buildings

Different from the traditional isolation structure design, some isolation structures are modified according to the existing houses, so there are new challenges in construction, design and safety evaluation. Cardone et al.⁽¹⁹⁾ proposed a seismic isolation method for strengthening the existing buildings, and analyzed the fragility curves with IDA's method. Then the collapse risk of the modified isolated structure is evaluated. Cardone et al.⁽¹⁹⁾ first set up three frame structures of 8, 6 and 4 floors designed according to Gravity Load Design (GLD) rules to represent the buildings designed under the Italian design rules before 1970. In addition, Cardone et al.⁽¹⁹⁾ also considered two other 6-story buildings, a Low Seismic Resistance (LSR) building and a High Seismic Resistance (HSR) building, these two types represent the houses designed under the Italian design codes (LSR) from 1974 to 1996 and the houses designed under the modern codes (HSR).

Cardone et al.⁽¹⁹⁾ have adopted two isolation systems in this structure: 1. a system with Friction Pendulum Bearings(FPBs) only; 2. A system with combined high Damping Rubber Bearings and Sliding Bearings(HDRBs +SBs). Then, Cardone et al.⁽¹⁹⁾ take a variety of failure modes to carry out IDA analysis, and draws the corresponding conclusion. Cardone et al.⁽¹⁹⁾ found that the collapse risk of frame structure buildings designed only according to GLD mainly depends on the superstructure. However, for seismic resistant reinforced concrete frame buildings, the main failure causes of structures equipped with HDRBs + SBs seismic isolation systems are buckling and cavitation. In addition, For those equipped with Friction Pendulum Bearings(FPBs) isolation systems, the main cause of failure is exceeding the maximum displacement capacity of the isolators.⁽¹⁹⁾

IDA for other special structures

The IDA method is applicable to a variety of special structures beyond SI structures.

Structures with BRBs

To assess the effectiveness of controlling story drift under different combinations of buckling restrained braces (BRBs) and viscous dampers (VDs), seismic vulnerability analysis was conducted on a super high-rise building using IDA by He et al.⁽²⁰⁾ The structure currently under construction has 128 storeys and a height of 598m, It adopts the frame-core-outtrigger system.⁽²⁰⁾

He et al.⁽²⁰⁾ proposed three models: 1) a control model without BRB and VD; 2) a model with BRB outriggers at the top of the structure and improved viscously damper outriggers (IVDOs) at the lower part of the building;

and 3) a model with conversely set BRB outriggers and IVDOs based on model 2).

In terms of IDA method, it was found that peak ground velocity (PGV), as an intensity measure (IM), is more suitable for super high-rise building IDA analysis than peak ground acceleration (PGA),⁽²⁰⁾ because IDA method using PGV as IM can have lower computational requirements while maintaining the same level of accuracy.⁽²⁰⁾ Moreover, PGV as an intensity measure(IM) yields a higher failure probability than PGA as an IM,⁽²⁰⁾ leading to more reliable outcomes. For the design scheme, He et al.⁽²⁰⁾ highlights that the placement of IVDOs in the lower part of the structure results in reduced inter-story drift and a lesser probability of failure in the upper part.

Outer steel frame and inner core tube

IDA can also be used in the frame core tube structure. He et al.⁽²¹⁾ have analyzed the vulnerability of a 15-story composite structure of outer steel frame and inner core tube, and found that the rigid connected structure is not always superior to the semi-rigid connected structure, and the collapse probability of the semi-rigid connected structure is lower than that of the rigid connected structure in the rare event of large earthquakes. In other words, the semi-rigid connection between the structural steel frame and the internal concrete core tube allows a certain rotation, which can absorb and dissipate a certain amount of energy during an earthquake, thereby enhancing the collapse resistance of the structure.⁽²¹⁾ Similarly, Cheng et al.⁽²²⁾ also use IDA method to analyze the vulnerability of a 99 m frame core tube structure in the long period multiple-dimensional earthquake waves, the results show that the structure is more likely to collapse during a long period earthquake.⁽²²⁾

Steel-concrete composite structure

Many programs are available for IDA analysis, including ETABS, SAMP2000, and more. Zhang et al.⁽²³⁾ use MIDAS Gen software to build and analyze a complex high-rise structure. The structure is a steel-concrete composite structure, which is 90 meters high and consists of steel frame beams on the outside and concrete core tubes on the inside. A total of 15 seismic waves were selected for IDA analysis, and combined with the change of concrete strength over time, the fragility curves of the structure in different periods were drawn. It is concluded that there is an increased risk of collapse in the later stages of the structure's use.⁽²³⁾ Specifically, when the structure was hit by a rare earthquake(PGA=0,4g) after 60 years of use, the probability of its collapse was 0,108, 11,3 % higher than its design failure probability of 0,097.⁽²³⁾ This study is a typical innovative and practical case of IDA method combining other factors to predict the structure.

Complex gymnasium

As a large and complex structure, the gymnasium is often served as a refuge during the events of earthquake, so it's necessary to conduct the research on its seismic performance. Lu et al.⁽²⁴⁾ selected 12 seismic waves and used IDA method to analyze the vulnerability of a 4-story gymnasium with a height of 22,6m, a length of 90m and a width of 72m. At the same time, the damage indices for the steel and concrete frame composite structure part and the spatial steel truss part are also set. That is, the limit of severe damage for steel and concrete frame structure part is 0,02. The limit of severe damage of spatial steel truss part is taken as the mid-span deflection-span ratio exceeds 1/150 or the shear strain at the support exceeds 66,7 %. It turns out that the elastic supports that support the stadium's steel truss roof play a decisive role in the event of severe damage.⁽²⁴⁾

Bridge designs

Bridge design and construction is another area in where IDA can be effectively utilized. Huang et al.⁽²⁵⁾ analyzed the vulnerability of a long-span cable-stayed bridge. The span of the bridge is 566m, with 56 pairs of cables on both sides of the bridge. The model was modeled and calculated by TECS program developed on MSC.Marc. First, Huang et al.⁽²⁵⁾ applied an El-Centro wave to the bridge and continuously increased the peak ground acceleration(PGA) of the wave. When the PGA increased to 1,5g, the plastic hinge at the lower end of the main tower column of the bridge occurred and as the displacement increased to a certain value, the bridge eventually collapsed.

Huang et al.⁽²⁵⁾ believe that the deformation of the structure can better reflect the damage of the structure than the force on the structure, so the horizontal displacement of the top of the bridge tower is used as a parameter to judge the safety of the structure, that is, the DM index in IDA. Huang et al.⁽²⁵⁾ use 22 actual seismic waves to carry out IDA analysis of this structure, and obtains its structure fragility curves according to IDA curves. Finally, Huang et al.⁽²⁵⁾ comes to the conclusion that the bridge still has a strong anti-collapse ability even under the action of a huge earthquake and the most critical component of the bridge is the tower columns, especially the bottom section of them.

In addition, Wang et al.⁽²⁶⁾ presented a multi-dimensional fragility analysis method and used this method to analyze a highway bridge through SAP2000 modeling calculation. The new analysis method uses the flexural ductility of pier column and the displacement limit state of support as two indexes to judge the safety of bridge,

and a fragility surface instead of a single curve is obtained. Finally, based on this, the collapse probability of the bridge is obtained. The collapse probability of bridge based on multiple failure modes of the entire system is greater than that calculated for a single component, which makes the calculation result more reliable.⁽²⁶⁾

The IDA method utilized to design seismic isolators

IDA is widely utilized not only for the design of various structures, but also for the assessment and design of isolators.

Isolators for bridges

Zhang et al.⁽²⁷⁾ employed 250 seismic records as inputs to devise appropriate isolators for a bridge, utilizing two methods - IDA and Probabilistic Seismic Demand Analysis (PSDA) - to generate fragility functions. The results indicate that the damage probability of the bridge is significantly influenced by the performance of the isolators.⁽²⁷⁾ A fragility curve can be employed to identify optimal combinations of mechanical parameters for isolation devices.⁽²⁷⁾ Specifically, when the stiffness of the isolators is similar to that of the column, its influence on damage potential is negligible,⁽²⁷⁾ making it a more reasonable choice.

Zhang et al.⁽²⁷⁾ employed a three-dimensional graph in their study; however, this does not imply that the second type of Intensity Measures (IMs) was taken into consideration. Only Peak Ground Acceleration (PGA) was employed as the sole IM and the three-dimensional coordinates here only represent the mean values of fragility curve of different isolators, in order to reflect the corresponding failure probabilities associated with each individual isolator.

Isolators with multiple lead and rubber cores

Altalabani et al.⁽²⁸⁾ utilized IDA method to design three types of square isolators, including those with one, two, and four lead and rubber core, specifically for special frame structures such as tunnel-form structure. Additionally, CFRP and steel layers were applied to the surface of the rubber cores to enhance the energy dissipation capacity of the isolators. Finally, this novel type of isolators was implemented in a five-story tunnel form frame structure.⁽²⁸⁾ By utilizing the IDA method, a comparison was made between the results obtained from the structure using the new isolator and those without it.⁽²⁸⁾ The results indicate that even under severe earthquakes, the proposed rectangular isolators can still meet the Immediate Occupancy (I.O) performance level.⁽²⁸⁾

Triple friction pendulums

A triple friction pendulums for base-isolated high-rise buildings is designed and optimized using vulnerability analysis by Xu et al.⁽²⁹⁾ The study used 30 seismic records to determine the damage state of the structure through the displacement and acceleration of the structure. The Multi-Objective Genetic Algorithm (Moga) is used to optimize the design of the isolation bearing, and finally the collapse probability of the target building is less than 10 % under the consideration of the maximum earthquake.⁽²⁹⁾ In addition, compared with traditional Genetic Algorithm (GA) design, Moga uses a smaller bearing size, which saves economic costs.⁽²⁹⁾ Furthermore, in Mokhtari et al.⁽³⁰⁾'s study, IDA analysis is carried out on a 6-story base isolation structure with Friction Pendulum Bearings. After completing the DIA analysis, this article also mentions the loss-recovery approach, which is a method to assess the resilience of a structure after an earthquake.⁽³⁰⁾

DISCUSSION

This paper reviews the application of IDA method in seismic isolation and other special structures. As is well established, traditional structures typically require only one parameter to indicate structural failure, namely a single failure mode represented by the maximum story drift. However, for seismic isolation(SI) structures, in addition to the aforementioned parameter which may cause damage to the superstructure, it is also necessary to consider the maximum displacement of the isolation layer. Thus the IDA for complex structures often consider the multiple failure modes as the requirements to define structural collapse.

Furthermore, those enough consideration about the multiple failure modes usually bring the benefits of accurately judging the safety level of structure designs. Take the maximum story drift as an example, sometimes a structure with the less story drift will have the highest collapse rates according to the IDA results. This makes IDA method a necessity especially for analyzing those novel or complex structures. The utilization of IDA in the super high-rise building and the designing of the innovative isolators has further proven its feasibility and reliability in engineering practices.

However, the IDA calculation method has its own limitations, such as an overly large amount of calculation. Therefore, the future research directions can focus on the following fields: 1) By combining IDA with the Artificial neural network(ANN), the computational efficiency of IDA can be improved. Specifically, it involves applying the IDA analysis method to a large number of models to obtain enough input and output data, training

the models derived from these data, and identifying the corresponding functions. The desired result can be directly obtained by applying the derived function, saving a great deal of analysis time. However, the above methods have been studied more for relatively simple structures such as Bridges and tunnels, but have been applied less in the practice of building construction. This represents a potential gap in existing research. 2) Combined with Geographic Information System (GIS). Once the collapse risk of the structure can be rapidly calculated, then the probability of damage to all structures and traffic in a region can be possibly calculated. After that these results can be visualized on a map by GIS, this facilitates the formulation of risk management strategies in response to earthquakes, typhoons or other damages. In addition, a renovation plan can also be formulated to minimize the overall casualty rate of the region during disasters, while maintain the same cost. All the above-mentioned applications possess significant practical value.

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