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Research Article

An Idea of a Comprehensive Incremental Analysis Method Considering Multiple Intensity Measures and Failure Modes in Seismic Isolated Structures

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ABSTRACT

Incremental dynamic analysis(IDA) is an emerging and accurate method to analysis the failure probability of a structure based on probabilities. Many researches has been done for using this method to the structures, especially the isolated structures. However, ordinary IDA method only considered single intensity measures(IMs) or single failure models of structure, limited researches have been done for IDA considering both multiple IMs and failure modes. This article mainly reviewed some of the important applications of IDA method in isolated structures, especially those IDA method considering multiple factors. Thus the ideas of a new comprehensive IDA(CIDA) method could be put forward, this CIDA method will considered multiple IMs and failure modes. The new CIDA method would be presented as a potential graph in 3D and more investigations can be done in the future, as this article focuses on the literature review part.

Keywords: Incremental dynamic analysis, IDA, seismic isolation.

INTRODUCTION

IDA is a technique that evaluates the likelihood of structural collapse caused by earthquakes. It can reflect the random characteristics of ground motion and the collapse resistance of structures under different strong earthquakes. This method has been researched by many scholars on its application of predicting the failure rate of a certain structure or buildings. This article will review the ordinary IDA method, the IDA method considering multiple intensity measures(IMs) and the IDA method considering multiple failure modes of seismic isolation structure. Finally this article will provide a potential novel CIDA method, which will be investigated in further research.

THE ORDINARY IDA METHOD

In this article, the Ordinary IDA method is referred, which considers only a single intensity measure (typically PGA) and a single failure model (usually the maximum story drift for conventional structures), without taking into account region-specific earthquake possibilities. The specific steps of the Ordinary IDA are as follows:

- IDA curve for single earthquake wave data

The IDA curve of a single seismic record initially normalizes the peak ground acceleration(PGA) of the same seismic wave, taken Anza 1956(PEER,2001) for example, as depicted in Figure 1 It is then scaled up, taken earthquake Anza 1956(PEER,2001) for example, as shown in Figure 2, and the seismic wave data is amplified at various proportions. Multiple nonlinear dynamic time-history analyses are conducted on the same structure, yielding maximum response data (typically maximum story drift) for each time-history analysis performed on the structure, taken Anza 1956(PEER,2001) for example, as illustrated in Figure 3.

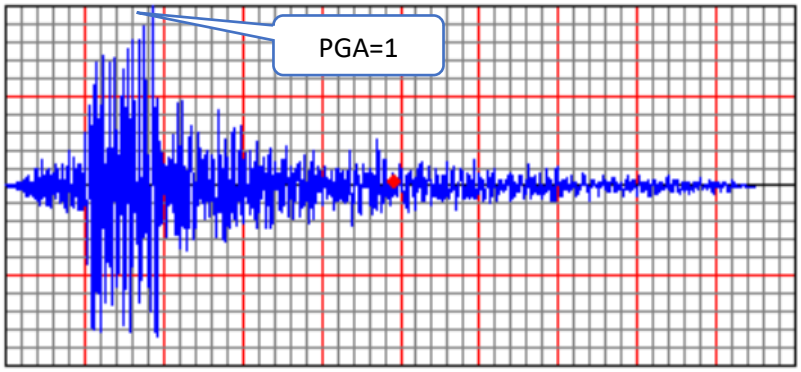

Figure 1 The normalized earthquake wave data Anza 1956(PEER,2001)

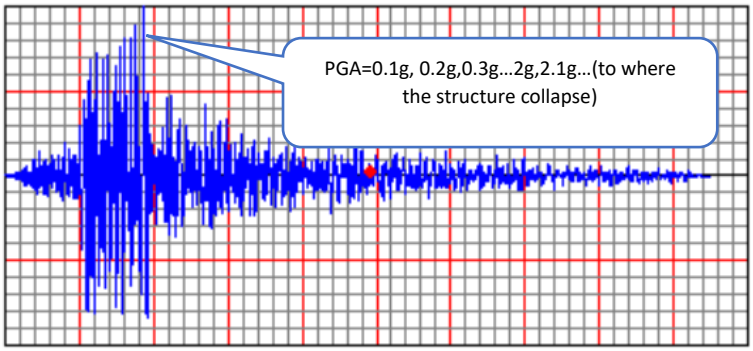

Figure 2 Seismic wave data amplified at various proportions of Anza 1956(PEER,2001)

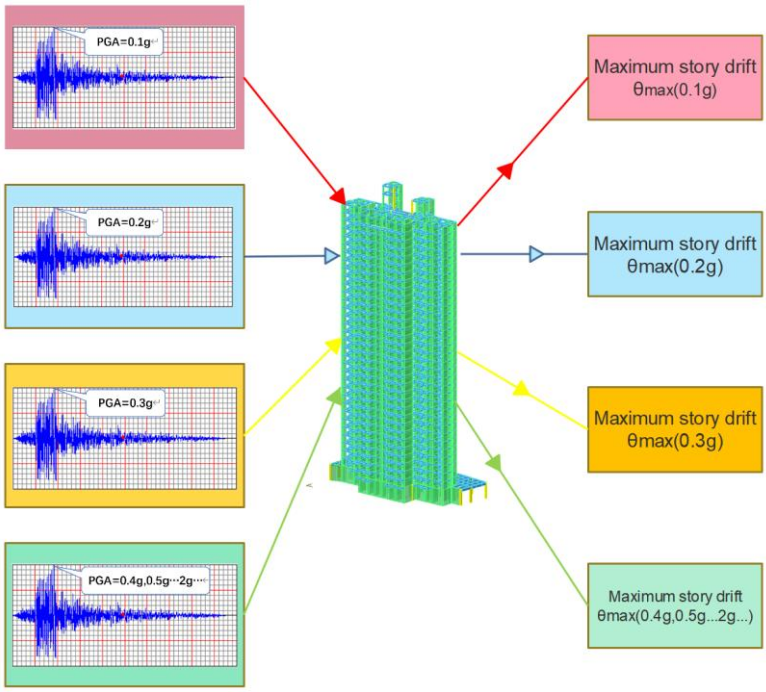

Figure 3 The maximum story drift associated with different PGA of Earthquake Anza 1956(PEER,2001)

These data are typically plotted on a coordinate system, with the ordinate representing the damage measure (DM), which in this case is maximum story drift, and the abscissa representing the intensity measure (IM), which refers to peak ground acceleration (PGA). The resulting curve is known as an incremental dynamic analysis (IDA) curve for a single seismic wave, as illustrated in Figure 4.

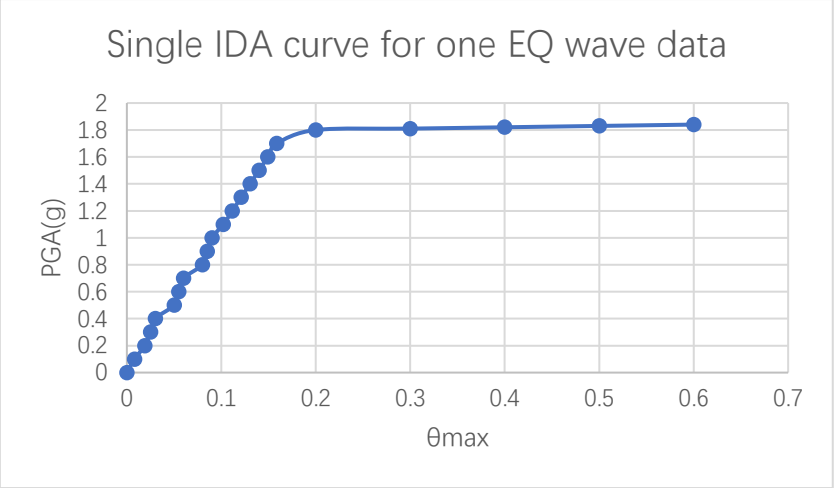

Figure 4 Example IDA curve for single EQ wave data

- IDA curves for multiple earthquake wave data

After obtaining the IDA curve for a single seismic record, select different seismic records and repeat the aforementioned steps for the same structure to generate multiple IDA curves on a shared coordinate system (as illustrated in Figure 5).

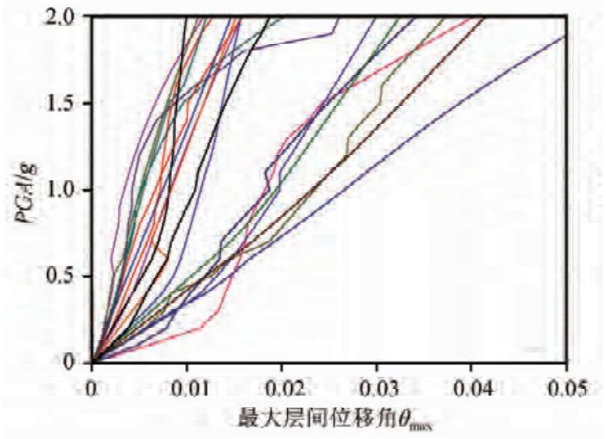

Figure 5 IDA curves for multiple EQ wave data(Xu et al., 2022)

In principle, all seismic records are eligible for selection as seismic waves for time-history analysis. However, unless investigating special cases such as comparing the collapse resistance of a structure under different epicenter distances or examining the collapse resistance of a structure under a single or limited number of seismic waves, it is recommended to select natural seismic records that resemble those likely to happen at the site so that the utilized seismic waves more closely reflect actual conditions.

The isolation design response spectrum utilized (MOHURD & SAMR, 2021) can effectively reflect the differences on site Class (which represents the hardness and composition of the ground), distance from the epicenter (represented by Design Seismic Category), and the structural damping ratios. Subsequently, a seismic wave record similar to the isolation design response spectrum(MOHURD & SAMR, 2021) will be selected, following the same selection rules as those for isolation design process.

- Calculation of seismic failure probability based on IDA results.

The calculation of seismic failure probability is primarily based on data obtained from each time-history analysis, which is then processed using Matlab. The specific formulas and steps used are as follows:

1) The limit state is defined. Given that this experiment primarily focuses on the isolation structure, the criterion for determining structural collapse is based on the maximum story drift limit value of the structure under rare earthquake according to the Standard for seismic isolation design of building (MOHURD & SAMR, 2021). Taking 2TSSLB-SI as an example in this study, during rare earthquakes, the upper shear wall structure should not exceed a maximum story drift of 1/250, while the lower frame structure of the large basement should not exceed a maximum story drift of 1/100 (MOHURD & SAMR, 2021). This represents the capacity parameter of the limit state (denoted as c), and exceeding it would indicate structural collapse.

2) It has been observed that both IM and engineering demand parameter EDP follow a lognormal distribution. Upon data processing, the correlation between IM and EDP can be established as follows: $\ln(EDP) = A + B\ln(IM)$, where A and B in this formula represent linear regression coefficients. By utilizing the aforementioned formula, the mean $\tilde{c}$ and standard deviation β_c of the maximum story drift for a given structure can be derived.

3) The engineering demand parameter EDP (here denoted as d) and the capacity parameter of the limit state(c) are considered as random variables, assuming a lognormal distribution according to Lv(2009). The failure probability can be determined using the following formula:

$$P_f(d \geq c|y) = F_R(y) = \Phi\left(-\frac{\ln\tilde{c} - \ln\tilde{d}}{\sqrt{\beta_c^2 + \beta_d^2}}\right)$$

Subsequently, the curve depicting structural vulnerability $F_R(y)$ is plotted.

The fragility curve depicted in Figure 6 illustrates the likelihood of structural collapse at varying levels of peak ground acceleration (PGA).

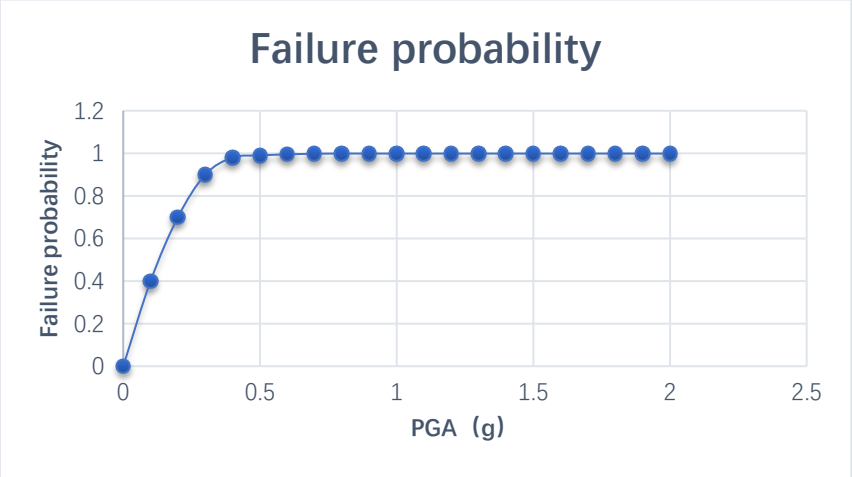

Figure 6 The fragility curve for failure probability under various PGA

- Limitations of the Ordinary IDA method

The Ordinary IDA method has three primary limitations: 1) It solely considers the maximum story drift as the criterion to represent only one failure model. 2) It only takes into account PGA as the intensity measure (IM). 3) It does not incorporate earthquake probabilities of different regions.

IDA CONSIDERED MULTIPLE IMS

If the single IM is used as the abscissa and the probability of collapse is used as the ordinate, a fragility curve can be obtained. However, when different combinations of IMs are used as two horizontal coordinates, such as 1) PGA & Richter magnitude, 2) PGA & epicentral distance, and 3) PGA & earthquake duration, distinct fragility surfaces will be generated, similar to that illustrated in Figure 7.

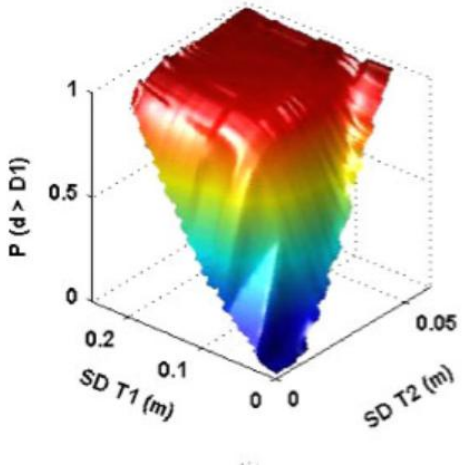

Figure 7 IDA surfaces with two IMs.(Seyedi et al., 2009)

To obtain more accurate failure probability results for 2TSSLB-SI, the IMs combinations with minimum calculated standard deviations will be selected.

IDA CONSIDERED MULTIPLE FAILURE MODELS

For structures subjected to seismic forces, there exist numerous failure models besides exceeding the maximum story drift. By considering multiple failure models and selecting the most critical outcome (i.e., the result with the highest probability of failure), one can accurately estimate the actual likelihood of structural failure.

For SI structures, this study considers the parameters of four failure models: 1) limiting story drift of superstructure, 2) maximum compressive force of isolators, 3) maximum tensile force of isolators, and 4) maximum displacement of isolators. By taking into account these four distinct failure modes, the resulting multiple fragility curves will be like Figure 8.

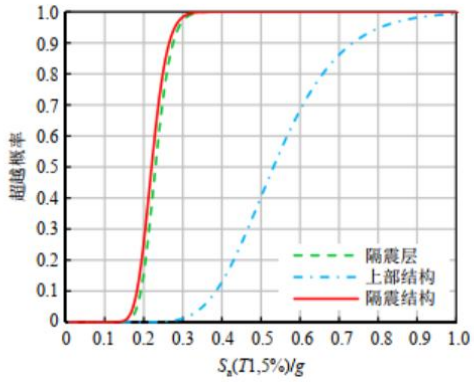

Figure 8 Fragility curves of multiple failure models(Wu et al., 2017)

IDEAS OF A POTENTIAL NOVEL COMPREHENSIVE IDA METHOD (CIDA)

By simultaneously considering multiple failure models and combinations of IMs, multiple fragility surfaces can be obtained within the same three-dimensional coordinate system. If the region-specified earthquake probability density are combined (as shown in Figure 9) and multiplied by a fragility surface, a damage probability surface that accounts for earthquake probabilities in a specific region can be derived. For instance, using the region-specified earthquake probability density of a a seismic precautionary intensity zone of 8 degrees to calculate, the resulting graph of damage probability surface is roughly similar to Figure 10. Similarly, combining different fragility surfaces with earthquake probability density in this region yields various damage probability surfaces (as illustrated in Figure 11).

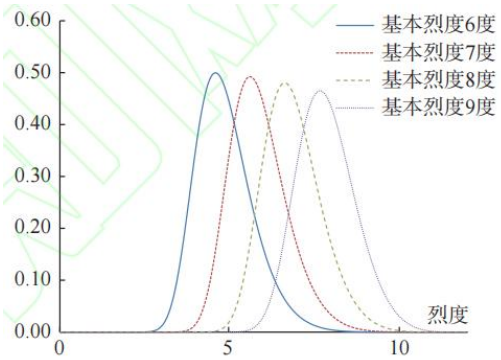

Figure 9 Region-specified earthquake probability density（Liu et al., 2023）

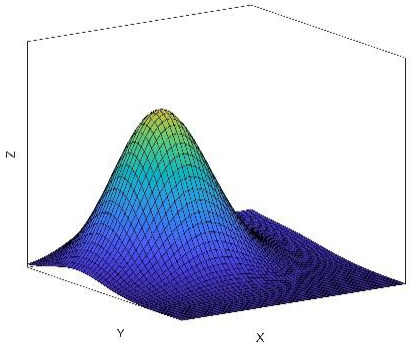

Figure 10 Damage probability surface(appearance, not real)

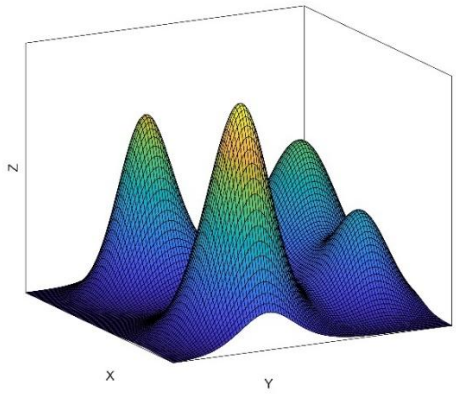

Figure 11 Damage probability surfaces by different failure models(appearance, not real)

Based on Figure 11, it is possible to identify the failure models with the highest damage probability in this area. Implementing certain reinforcement measures can effectively reduce the likelihood of damage and enhance structural safety.

CONCLUSIONS

This article reviewed some researches of IDA used in predicting the failure rate of structures, especially the seismic isolation structures. By analyzing those defects of those existing methods, this article provide an idea of a comprehensive novel IDA (CIDA) method, which will consider multiple intensity measures and failure modes of an isolated structures. However, further researches can be done to test and verify the idea of the CIDA method.

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