Seismic Fragility Analysis of Main Building of a Power-Generation Plant Based on SPO2IDA

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Abstract. The SPO2IDA method utilizes the backbone curve obtained from static-pushover (SPO) analysis to approximate the incremental dynamic analysis (IDA) curve. It is a parameter analysis method based on static-pushover analysis, and essentially represents an improved R-μ-T relationship. SPO2IDA utilizes the information obtained from the SPO curve to generate necessary estimates of various response statistics associated with the limit-state. In this study, the SPO2IDA method is combined with seismic fragility analysis, and the seismic fragility analysis method based on SPO2IDA is applied to assess the seismic behavior of the main building of a power-generation plant. The probability of exceeding four limit states for this structure is calculated using the SPO2IDA-based seismic fragility analysis method and compared with the results from an IDA-based seismic fragility analysis method. The research shows that the fragility analysis results based on SPO2IDA can offer robust scientific evidence for the prediction of seismic damage and losses of the main building of a power-generation plant.

Keywords: SPO2IDA, Static-pushover, Incremental dynamic analysis, Seismic fragility, Main building of a power-generation plant.

1 Introduction

Seismic fragility is described as the likelihood of a structure or system experiencing varying degrees of damage when subjected to different levels of seismic intensities. This probabilistic description quantitatively expresses the seismic performance of an engineering structure or system and describes the correlation between seismic intensity and the extent of structural damage from a macro perspective. The fragility curve of an engineering structure can be obtained through empirical or analytical methods. Empirical methods involve studying past seismic damage reports to derive fragility curves, while analytical methods involve calculating and assessing the seismic behavior of the engineering structure. However, due to the limited availability of reliable seismic damage data in many regions globally, analytical methods are

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often the only feasible approach for obtaining structural fragility curves. Therefore, the ability of analytical methods to provide accurate fragility assessments for engineering structures serves as a strong basis for seismic design and risk assessment.

To assess seismic fragility, IDA can be used to study and analyze structural responses under various seismic excitations. IDA calculates the conditional probability of a structure exceeding or reaching a particular limit state under different intensities of ground motions. Although the IDA fragility assessment method based on elastic-plastic time history analysis of structures subjected to numerous ground motions has gained recognition among seismic engineering researchers in recent years, it requires significant computational resources and time. Each IDA curve needs to be interpolated at multiple points, and each seismic record needs to be scaled multiple times to ensure accuracy. Due to the time cost, this method is not widely used in engineering practice, necessitating the use of simplifications.

In their study, Vamvatsikos and Cornell (2006)[1] proposed that the nonlinear dynamic response could be estimated using the static pushover (SPO) curve through empirical relationship analysis of characteristic segments of incremental dynamic analysis curves from various systems. As a result of this research, the SPO2IDA method was developed, aiming to convert the SPO curve into an approximate incremental dynamic analysis result.

This paper aims to introduce this simplified and efficient fragility analysis method. To demonstrate its applicability to the main building structure of a power-generation plant, which may have an irregular overall layout, uneven mass and stiffness distribution, and poor overall seismic performance, the fragility analysis of the main building of a power-generation plant is conducted using this method and compared with the IDA-based fragility analysis results.

2 Fragility analysis methodology based on SPO2IDA

The SPO2IDA method utilizes the backbone curve of SPO analysis to approximate IDA curve. This method has been validated in both SDOF and MDOF systems. It can be considered as being equivalent to a powerful R-μ-T equation, utilized for the estimation of seismic response in structures. To obtain the approximate IDA curve using the SPO2IDA method, the structure is first subjected to a static pushover analysis. In this analysis, a lateral load pattern that is proportional to the first mode of vibration is applied to the structure. Then, a tri-linear or quad-linear envelope function is used to approximate the backbone curve of the SPO curve, as Fig. 1[2]. The backbone curve is characterized by five essential parameters, exhibiting elastic behavior at F_y, a positive normalized hardening slope α_h at the ductility level μ_c, and a negative stiffness section with a slope of $-\alpha_c$ after exceeding μ_c. If a quad-linear model is adopted, the backbone curve is divided into four segments. The fourth segment of the backbone curve corresponds to a horizontal residual plateau with a constant strength, typically denoted as rp. By inputting these parameters into the SPO2IDA method, we can obtain the median curve as well as the 16th and 84th quantile curves of IDA curve.

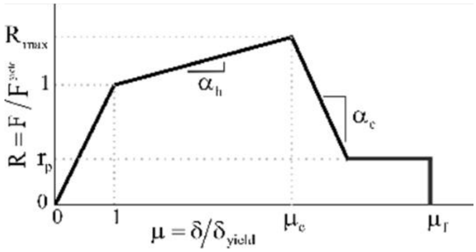

Fig. 1. Backbone curve of the SPO curve.

To scale the dimensionless R-μ coordinates of SPO2IDA to different pair of EDP-IM coordinates, namely the 5% damped first mode spectral acceleration $S_a(T_1, 5\%)$ and the maximum interstory drift ratio (θ_{max}), the following calculation process can be performed easily:

$$S_a(T_1, 5\%) = RS_a^{yield}(T_1, 5\%) \tag{1}$$

$$\theta_{roof} = \mu\theta_{roof}^{yield} \tag{2}$$

Where θ_{roof} is the roof displacement ratio, $S_a^{yield}(T_1, 5\%)$ and θ_{roof}^{yield} represent the spectral acceleration and roof displacement at the yield point, respectively.

Once the roof displacement ratio θ_{roof} is known, the maximum inter-story drift ratio θ_{max}, can be extracted from the results of the SPO analysis, as the correspondence between these two EDPs is always available for each loading increment. Therefore, the only unknown parameters in Equations (1) and (2) are $S_a^{yield}(T_1, 5\%)$ and θ_{roof}^{yield}. To determine θ_{roof}^{yield}, we assume it is equal to the yield roof displacement ratio obtained from the SPO analysis. If we have the elastic stiffness k_{roof} of the median IDA curve, with θ_{roof} as the EDP, we can use this information to calculate $S_a^{yield}(T_1, 5\%)$. An approximate calculation method for k_{roof} is proposed by Fragiadakis and Vamvatsikos [3]:

$$k_{roof} = \frac{4\pi^2 H}{C_0 T_1^2 g} \tag{3}$$

Where H is the building height, "g" represents the acceleration due to gravity, T1 is its fundamental period, and C_0 is the participation coefficient of the first mode, which can be determined based on FEMA-365. With this information, the equation for calculating $S_a^{yield}(T_1, 5\%)$ is as follows:

$$S_a^{yield}(T_1, 5\%) = k_{roof}\theta_{roof}^{yield} \tag{4}$$

In summary, the steps involved in generating an approximate IDA curve from a single SPO analysis are as follows[5]:

- Perform a SPO analysis using a proportionally scaled lateral load pattern based on the first mode
- Approximate the results using a quad-linear or tri-linear model.

- Convert the results from SPO2IDA, represented in standardized R-μ coordinates, to the relationship between $S_a(T_1, 5\%)$ and θ_{roof}.
- Use Equations (1)-(4) to generate the IDA curves in terms of $S_a(T_1, 5\%)$ and θ_{max}, where θ_{max} is obtained from the mapping relationship between θ_{roof} and θ_{max} derived from the SPO results.

Since SPO2IDA provides the 50th, 16th and 84th percentile curves, through a single SPO analysis, the median curve and its corresponding dispersion can be calculated by the aforementioned methods.

According to [6], the fragility curve for each limit state can be calculated using the following equation:

$$P\left[IM_f^{LS} \le im\right] = \Phi\left[\frac{\ln(im) - \ln\mu}{\beta}\right] \tag{5}$$

Based on the three IDA quantile curves simulated from the static pushover analysis of the structure, parameters of the logarithmic normal fragility model can be fitted for each limit state. However, as the SPO-based IDA approximation method does not offer individual IDA curves but only quantile curves, the estimation of fragility parameters can be carried out using the following approach:

$$\begin{cases} \ln\mu = \ln\left(S_a^{50\%}\right) \\ \beta = \ln\left(S_a^{50\%}\right) / \ln\left(S_a^{16\%}\right) \end{cases} \tag{6}$$

When conducting an IDA analysis on a single deterministic numerical structural model, the obtained response distribution reflects the variability between different inputs. However, one may also wish to consider uncertainties related to seismic records, modeling, cognitive aspects, and structural capacity. FEMA P-58 suggests using a minimum default dispersion value of 0.6 to derive collapse fragility functions based on SPO2IDA results. In this study, we refer to FEMA P-58 and take a total uncertainty β of 0.6.

3 Case Study

The power-generation plant main building prototype, as described in reference [8], is chosen as the focus of this study. SAP2000, a structural analysis software, is employed to construct the numerical model of the main building, with the model parameters being in line with those specified in reference [8]. Figure 2 displays the three-dimensional numerical model of the main building.

Using a lateral load pattern that is proportional to the first mode of vibration, a static pushover analysis is conducted on the numerical model. The obtained SPO curve is illustrated in Figure 3.

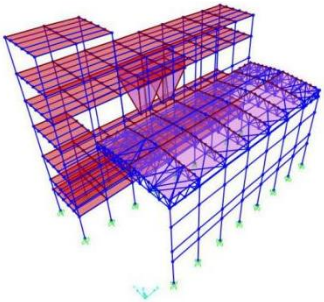

Fig. 2. Three-dimensional FEM model

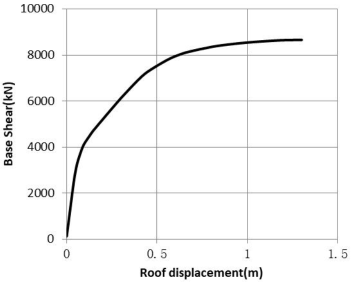

Fig. 3. SPO curve

Following the work of De Luca et al. [2], the backbone curve of a Single Degree of Freedom (SDoF) system is approximated using a piecewise linear fit. The fit can consist of up to four segments: elastic, hardening, softening, and, if necessary, a residual plateau can be added. Based on the SPO curve shape of the main building, the backbone curve of the bilinear fit is adopted in this study.

To capture the elastic segment of the backbone curve, a linear segment is employed with a tangent stiffness that aligns with the capacity curve at 5%-10% of the peak or nominal yield base shear. It is common practice to use the peak value for this purpose as it provides a rapid estimation without requiring multiple iterations.

The backbone curve of the SPO curve formed according to the above principles is shown in Figure 4.

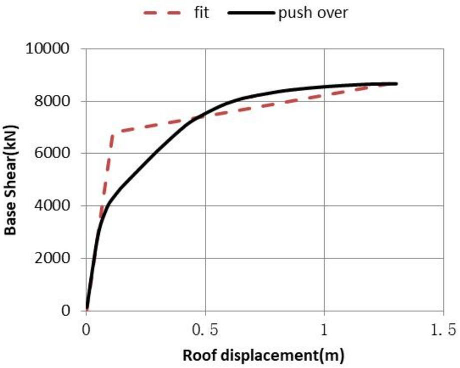

Fig. 4. Backbone curve of SPO curve

Approximate IDA curves were obtained using SPO2IDA, including the median IDA curve and its 16% and 84% quantile curves, as shown in Figure 5. Using the median responses provided by these three curves, the total uncertainty β=0.6 suggested by FEMA P-58, and the four performance levels defined in reference [8], fragility curves for the four performance levels can be derived. These fragility curves are shown in Figure 6. The logarithmic normal distribution parameters for the structural fragility based on SPO2IDA for the main building are listed in Table 1.

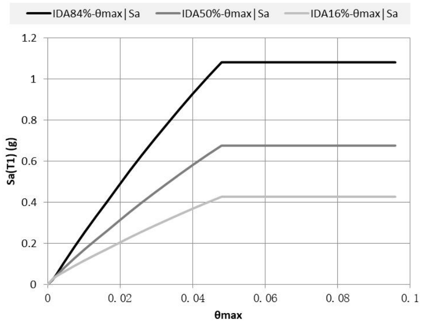

Fig. 5. Approximate IDA curves based on SPO2IDA

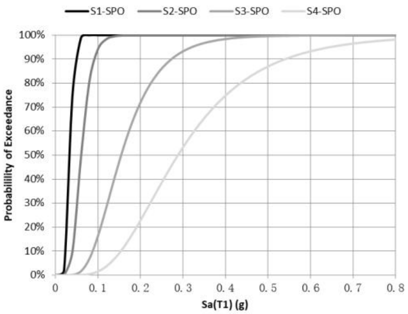

Fig. 6. Fragility curves based on SPO2IDA

Table 1. The logarithmic normal distribution parameters based on SPO2IDA

Performance Level	**$S_a(T_1, 5\%)$ (g)**	
	μ	*β*
S1	0.034	0.6
S2	0.060	0.6
S3	0.154	0.6
S4	0.288	0.6

It is indicated in the statistical analysis of the 14 IDA curves derived from the analysis in reference [8] that the 16%, 50%, and 84% quantile IDA curves are represented as dashed lines in Figure 7. Additionally, the 16%, 50%, and 84% quantile IDA curves obtained using the SPO2IDA method in this study are depicted as solid lines in Figure 7. By comparing the two methods, it can be observed that the results obtained by both methods are very close. The slope of the quantile curves in the diagonal segments, the corresponding values on the y-axis in the straight segments, and the turning points from the diagonal to the straight segments all show consistency.

The fragility curves for the main building corresponding to the four performance levels, as obtained through the IDA method in reference [8], are represented by dashed lines in Figure 8. In this study, the SPO2IDA method is utilized to estimate the fragility parameters of the structure and generate the fragility curves, which are depicted as solid lines in Figure 8. The parameters of the fragility curves obtained by both methods, as well as the deviations between the two calculation methods, are listed in Table 2. It can be observed that the mean values of the fragility curves obtained by the two methods are not significantly different, with a maximum deviation of 17.01% observed for performance level S1. The deviation gradually decreases from S1 to S4, reaching a minimum deviation of only 0.81% for performance level S4. This consistency aligns with the nearly overlapping results of the 50% quantile IDA curves in Figure 8 when the maximum inter-story drift ratio is less than 0.04. Furthermore, Figure 8 and Table 2 demonstrate that the standard deviation (β) of the fragility curves obtained by the two methods exhibits a deviation of 17.65%. This discrepancy arises from the different definitions of the standard deviation β utilized in the two methods. The IDA method calculates β using Equations (7) to (9), while the SPO2IDA method has its own approach.

$$\beta = \sqrt[2]{\beta_{(D|IM)}{}^{2} + \beta_{c}{}^{2}} \tag{7}$$

$$\beta_{(D|IM)} \cong \sqrt{\frac{{}_{i=1}^{M}(\ln(d_i) - \ln(a(IM)^{b}))^{2}}{M-2}} \tag{8}$$

$$\beta_c = 0.25 \tag{9}$$

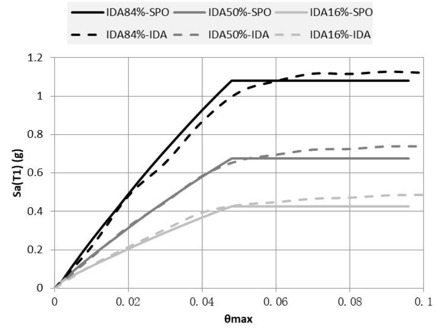

Fig. 7. IDA curves of two methods

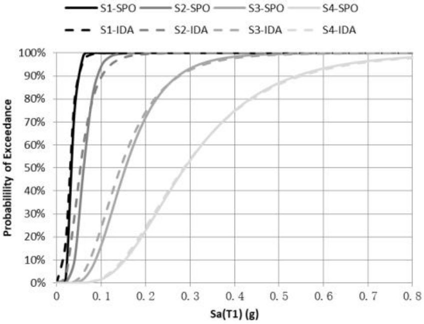

Fig. 8. Fragility curves of two methods

Table 2. The logarithmic normal distribution parameters based on SPO2IDA

Performance Level	$S_a(T_1, 5\%)$（g）				Deviation between two methods	
	IDA		SPO2IDA			
	μ	β	μ	β	μ	β
S1	0.0289	0.5122	0.0338	0.6	17.01%	17.65%
S2	0.0528	0.5122	0.0604	0.6	14.46%	17.65%
S3	0.1433	0.5122	0.1544	0.6	7.78%	17.65%
S4	0.2856	0.5122	0.2880	0.6	0.81%	17.65%

4 Conclusion

The SPO2IDA method employed in this study utilizes the backbone curve obtained from SPO analysis to approximate IDA curve. Building upon this method, a seismic fragility analysis procedure is proposed. The procedure is applied to a main building of a power-generation plant, where the SPO2IDA analysis is conducted to estimate the probability of exceeding four limit states of the structure under different earthquake intensities. In order to validate the SPO2IDA-based fragility analysis, a comparison is made between the results obtained from this method and the conventional IDA-based fragility analysis. The study reveals that there is some deviation between the two methods, but this deviation falls within an acceptable range. Therefore, for the main building of a power-generation plant, the SPO2IDA-based fragility analysis method is deemed suitable, efficient, and recommended. By employing the SPO2IDA-based fragility analysis, a strong scientific basis is provided for predicting seismic damage and losses in the main building of a power-generation plant. This analysis aids in understanding the vulnerability of the structure and allows for informed decision-making regarding risk mitigation and resilience enhancement.

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