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# SEISMIC ANALYSIS OF MULTISTORY BUILDINGS SUBJECTED TO SYNTHETIC MOTIONS COMPATIBLE WITH DESIGN SPECTRUM ACCORDING TO VIETNAMESE STANDARD

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**ABSTRACT**

*Currently, TCVN 9386: 2012 Standard is adopted in the design practice of civil engineering in Vietnam. For structural seismic analysis as well as seismic risk assessment, usually, engineers prefer the response spectrum method rather than time history analysis due to the lack of ground motion records in the past. The method using the response spectrum cannot be used to exactly predict the nonlinear response of a structure subjected to earthquakes. However, it is a more suitable method for design purposes due to the fact that it could predict the maximum response of a structure based on the response spectrum. In this study, we used a random simulation method to promulgate the ground acceleration in accordance with seismic conditions in Vietnam. Subsequently, the ground acceleration was adjusted to match the response spectrum according to the current Vietnam standard. Numerical simulations were then conducted to evaluate the structural response and seismic vulnerability of a building subjected to the proposed ground motion by using different analytical methods.*

**Key words:** multistory buildings, earthquake response, seismic analysis, fragility curve

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## 1. INTRODUCTION

For structural response analysis of the buildings subjected to earthquake loads, various approaches could be adopted. In case of linear structures, the time-history response can be analyzed by direct integration method or mode superposition technique. In addition, to predict the maximum response of linear structures, the response spectrum-based method based on mode superposition technique could be applied. The equivalent static lateral force method used for simple structures is a simplified technique of response spectrum-based method. However, the response spectrum-based method adopts the linear input spectrum, which is convenient for design in practice. In case of nonlinear structures, the response must be analyzed by using direct integration. Accordingly, the input ground motion time-histories, e.g., acceleration time histories, must be taken into consideration. These acceleration time-histories could be derived from past records based on the equivalent conditions between the considered region and the original region where ground motions were recorded. Moreover, they could be numerically generated based on the earthquake conditions of the selected area.

The response spectrum-based method [4,5] could not be used to accurately analyze the nonlinear response of a structure. However, it is a suitable method for design purposes in practice due to the fact that it could predict the maximum response of a structure based on the response spectrum. Therefore, in design practice, this method has been adjusted so that it could be applied to nonlinear structures. Specifically, instead of using the elastic input spectrum, the nonlinear input spectrum was adopted by calibrating the elastic counterpart considering the energy dissipation capacity of the nonlinear system; and, a specific design standard uses a specific approach to calibrate the elastic spectrum. After a nonlinear spectrum constructed, it can be applied to an equivalent elastic structure to analyze the maximum response by using the response spectrum method. Thereby, the displacement response of a nonlinear structure is deduced by multiplying the displacement response of the elastic counterpart by the displacement amplification factor. As a result, the non-linear response analysis adopting this approach is inaccurate in some cases, due to the fact that the deviation of the analytical results depends on many factors.

Nowadays, in Vietnam, the TCVN 9386: 2012 Standard [1] (reconstructed based on TCXDVN 375: 2006 Standard) entitled "design standard for earthquake-resistant buildings" under the Ministry of Science and Technology, was constructed based on the Eurocode 8 "*Design of structures for earthquake resistance*" with considering Vietnam's specific seismic regional conditions. This standard used the Motion Parameter Zonation Map of Vietnam. However, due to the lack of ground motion records in the past, the seismic design used time-histories analysis is quite difficult for application in the design practice in Vietnam [2].

So far, there have been a number of studies used simulation algorithm for ground motion but mainly depends on the theory of probability distribution without paying attention to region-specific earthquake in Vietnam. Therefore, in order to overcome this situation, it is necessary to develop an alternative approach to generate ground motions by physically simulating the earthquake source and propagated mechanism, which compatible with the specific seismic regional conditions in Vietnam. This approach aims to meet sufficient data for the seismic design according to the various methods specified with the Vietnamese standard.

In this study, numerical simulations were exerted to evaluate the structural response of structures subjected to the earthquake ground motions by using various analytical methods. Thereby, the applicability of the proposed methods was discussed in detail.

## 2. GENERATION OF SYNTHETIC ACCELEROGRAMS COMPATIBLE WITH DESIGN SPECTRUM

The ground accelerations of earthquakes are used as the input data for nonlinear time history structural analysis. In the first method, the ground accelerations can be artificially generated by calibrating directly the real acceleration time history data recorded at locations having similar ground characteristics to the construction site; for example, the same soil type specified in design standard [1,3] but different in the magnitude of ground motion. In the second method, new ground accelerations were generated with elastic amplitudes and phase angles in accordance with specific rules. In addition, ground accelerations could also be generated by simulating the forming mechanism of the earthquake and the wave propagation to the surveyed construction sites. This method is quite complex and difficult for engineers in design practice because it involves numerous factors when modeling and using many theoretical concepts in seismic engineering. Currently, this method is paid much attention by some researchers in Japan, USA, etc. to simulate earthquakes with a strong magnitude that may occur in the future. In this study, the method proposed by M. Boore et al. [6,7] was adopted.

The stochastic method proposed by Boore [6,7,8] assumes that ground motion is distributed with random phase over a time duration related to earthquake size and propagation distance. The ground motion is characterized by its spectrum - this is where the physics of earthquake process and wave propagation are contained. The total spectrum of the motion at a site $S(M_0,R,f)$ is considered as a combination of earthquake source ($E$), path ($P$), site ($G$) and type of motion ($I$).

$$S\left(M_0,R,f\right)=E\left(M_0,f\right)P(R,f)G(f)I(f) \qquad (1)$$

where $M_0$ is the seismic moment that is related to the seismic magnitude $M$ by

$$M=\frac{2}{3}\log M_0-10 \qquad (2)$$

$R$ is the distance from source to site and $f$ is frequency. The source $E(M_0,f)$: is based on the source spectral shape AS00 [6]. The path $P(R,f)$ accounts the effects of geometrical spreading, attenuation and the increase of duration with distance due to wave propagation and scattering. The site $G(f)$ accounts the effects due to local site geology and is separated to amplification $A(f)$ and attenuation $D(f)$: $G(f) = D(f)A(f)$. The motion type $I(f)$ for acceleration is defined as $I(f) = (2\pi f)^2$.

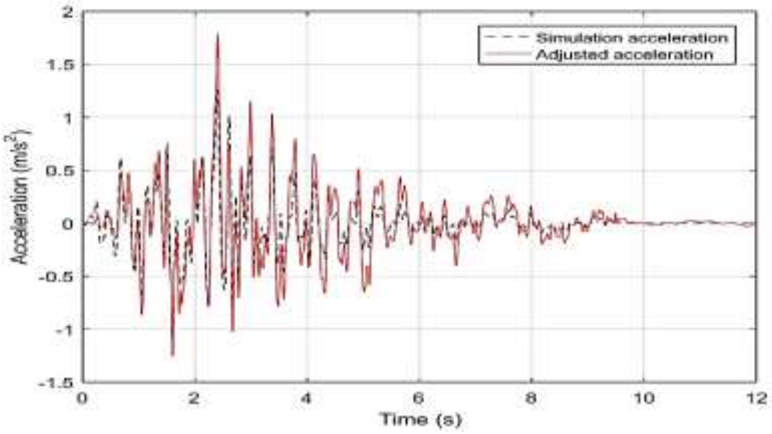
The details of the aforementioned parameters were introduced in Ref. [6].

Table I illustrates the seismic parameters for the northern region of Vietnam used for simulation of ground accelerations [2].

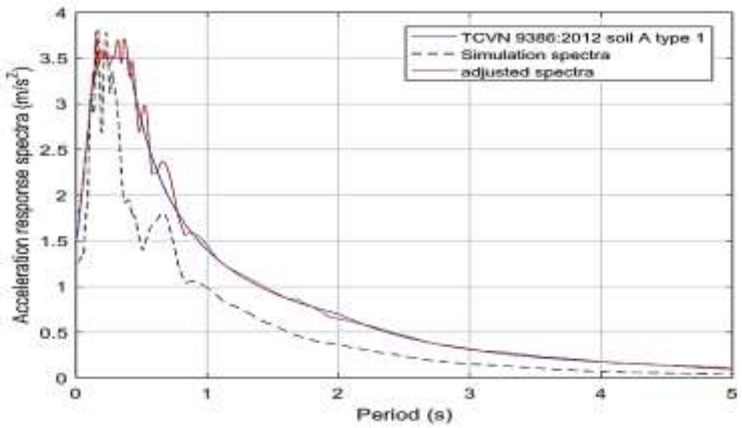
**Table 1** Model parmeters for the predicted ground motions in North region in Vienam [2]

| No. | Parameters | Value |
|---|---|---|
| 1 | $R_{\theta\phi}$, $F$, $V$, $R_0$ | 0.63, 2, 0.71 and 1 km |
| 2 | Crustal density, $\rho_s$ | 2.7 g/cm$^3$ |
| 3 | Crustal shear | 3.4 km/s |
| 4 | Seismic moment, $M_0$ | 5.20x10$^{24}$ dyne.cm |
| 5 | Duration, $T_d$ | 9.50 s |
| 6 | Rupture velocity | 0.8 $V_s$ |
| 7 | Elastic attenuation | $Q = 180f^5$ |
| 8 | Stress drop | 50, 100 and 150 bars |

The selected area used in this study located in Hai Chau District, Da Nang City. The soil type is assumed to be rock (Type A according to TCVN 9386: 2012). The simulated and adjusted spectra according to TCVN 9386:2012 are presented in Figure 1.




a). The simulated and adjusted accelerations




b). Acceleration response spectrum

**Figure 1** The simulated and adjusted spectra according to TCVN 9386:2012

## 3. STRUCTURAL DETAILS AND MODELING APPROACH

### 3.1. Structural Modeling

The characteristics of the selected building were illustrated as follows:

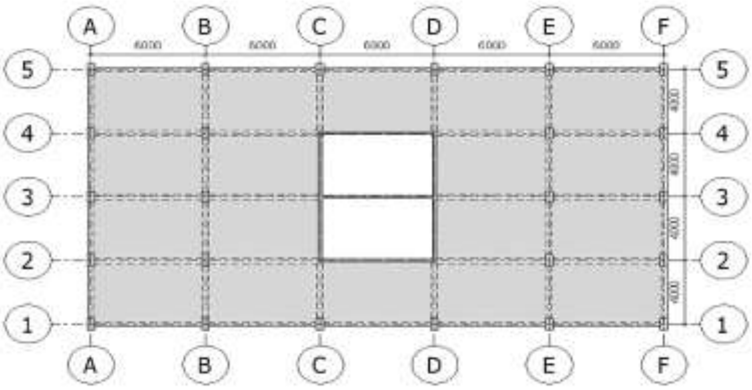



**Figure 2** Plan of the typical floor

## 3.2. Characteristics of Structural Components

- Column cross section: 400x700 mm; Beam cross section: 300x600 mm; Slab thickness: 120 mm
- Material type: Reinforced concrete C30/37

## 3.3. Boundary Condition

The boundary conditions of the structural building was assumed to be fixed on the ground at the location of columns and structural walls.

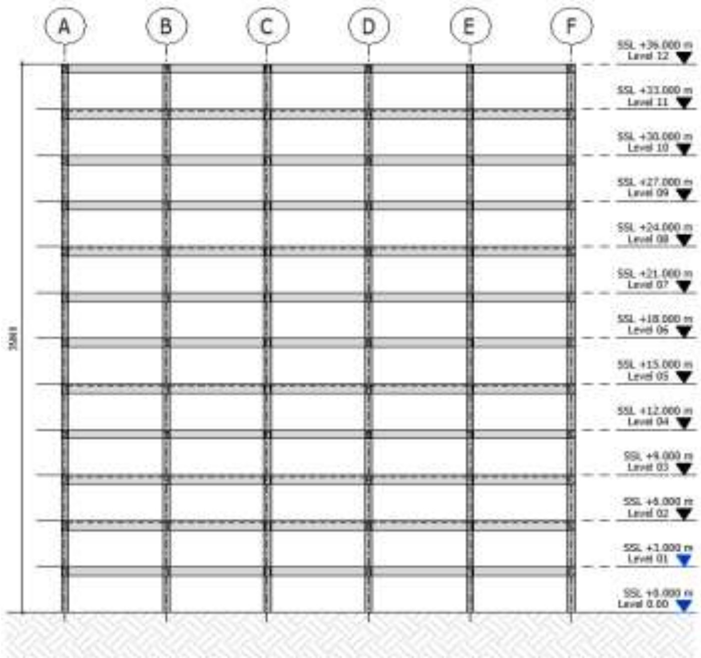


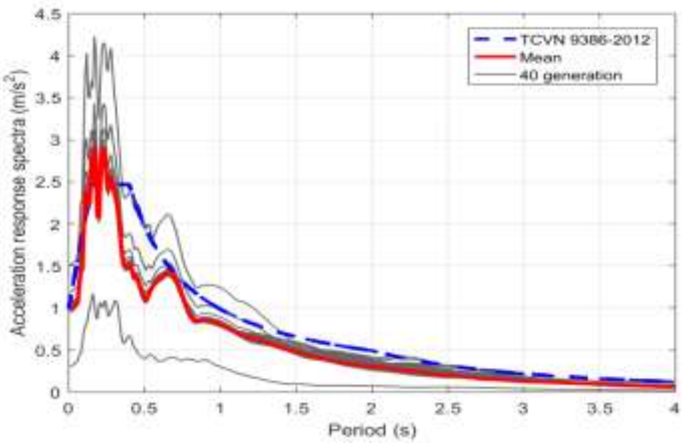

**Figure 3** Cross-section of the building

## 3.4. Seismic Parameters

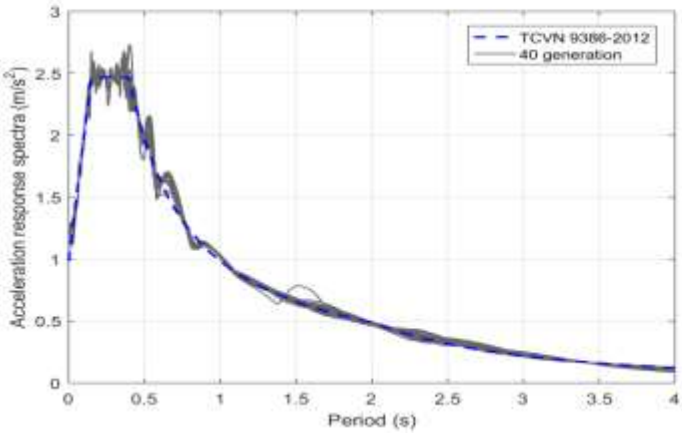
### *3.4.1. The parameters according to acceleration response spectrum*

- The building is located in Hai Chau District, Danang City, Vietnam with $a_{gR}$ = 0.1006
- Soil type A; Importance factor 1.0; - Damping coefficient 0.05 (5%)

### *3.4.2. The parameters according to time-histories*




a). Before adjusting ground acceleration




b). After adjusting ground acceleration

**Figure 4** Elastic response spectra

From the data of the response spectrum recorded in Hai Chau District, Da Nang city, Vietnam, a total of forty ground accelerations (THA01-THA40) according to the depiction in Section II above. The results of simulated and adjusted ground accelerations were shown in Figure 4.

### 3.5. Analytical Method

The structural analysis was performed in both linear and nonlinear approach considering the effects of P-Delta and Large Deflection.

## 4. LINEAR AND NONLINEAR SEISMIC RESPONSE

### 4.1. Story Deflection Results

#### *4.1.1. The analytical results of lateral story deflection*

**Table 2** Lateral story deflection results

| Deflection (mm) | | | | $DEF_{THA}$-$DEF_{RS}$ (%) | | |
|---|---|---|---|---|---|---|
| **Stories** | **RS** | **Linear** | **Nonlinear** | **Floor** | **Linear** | **Nonlinear** |
| 12 | 33 | 35.1 | 29.4 | 12 | + 6.2% | - 10.8% |
| 11 | 29.4 | 31.6 | 26.8 | 11 | + 7.3% | - 8.9% |
| 10 | 25.7 | 28 | 24.1 | 10 | + 9.1% | - 6.2% |
| 9 | 22.1 | 24.5 | 21.4 | 9 | + 10.9% | - 3.1% |
| 8 | 18.6 | 21 | 18.6 | 8 | + 12.7% | + 0.2% |
| 7 | 15.2 | 17.4 | 15.8 | 7 | + 14.7% | + 4.2% |
| 6 | 11.9 | 14 | 12.9 | 6 | + 17.5% | + 8.8% |
| 5 | 8.9 | 10.7 | 10.1 | 5 | + 19.8% | + 13.6% |
| 4 | 6.2 | 7.6 | 7.4 | 4 | + 22.1% | + 18.8% |
| 3 | 3.9 | 4.8 | 4.8 | 3 | + 24% | + 24.2% |
| 2 | 2 | 2.6 | 2.7 | 2 | + 27.6% | + 33% |
| 1 | 0.7 | 0.9 | 1 | 1 | + 30.4% | + 41.1% |

#### *4.1.2. Discussion*

In case of the linear analytical model, the displacement results according to the TH method were greater than those according to the RS method. The difference between two analytical methods was shown to be a maximum of 30.4% at the first story and a minimum of 6.2% at the 12th story.

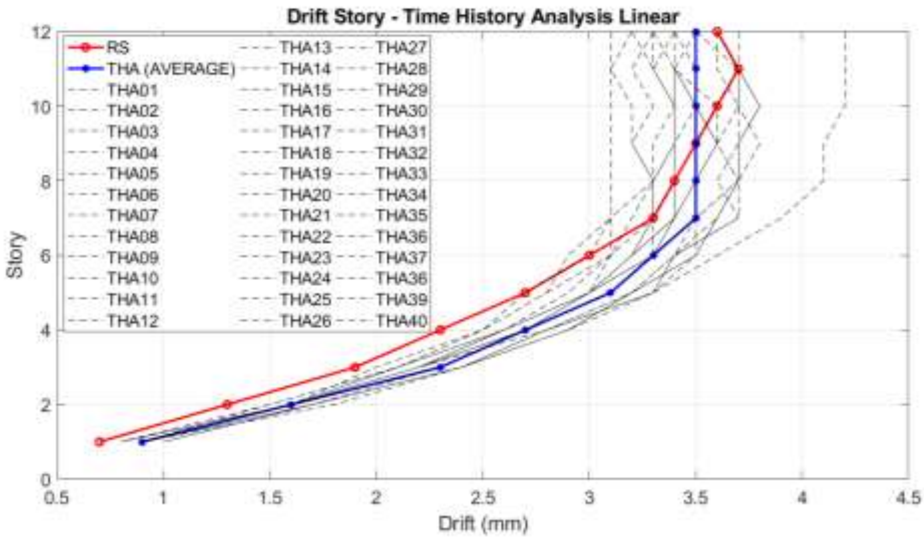
By using the nonlinear analytical model, the displacement results according to the TH method were greater than those according to the RS method. The difference between two analytical methods was shown to be a maximum of 41.1% at the first story and a minimum of 0.2% at the 8th story. From the 9th story, the differences gradually reduced in a range of 3.1%-10.8%.

## 4.2. Story Drift Results

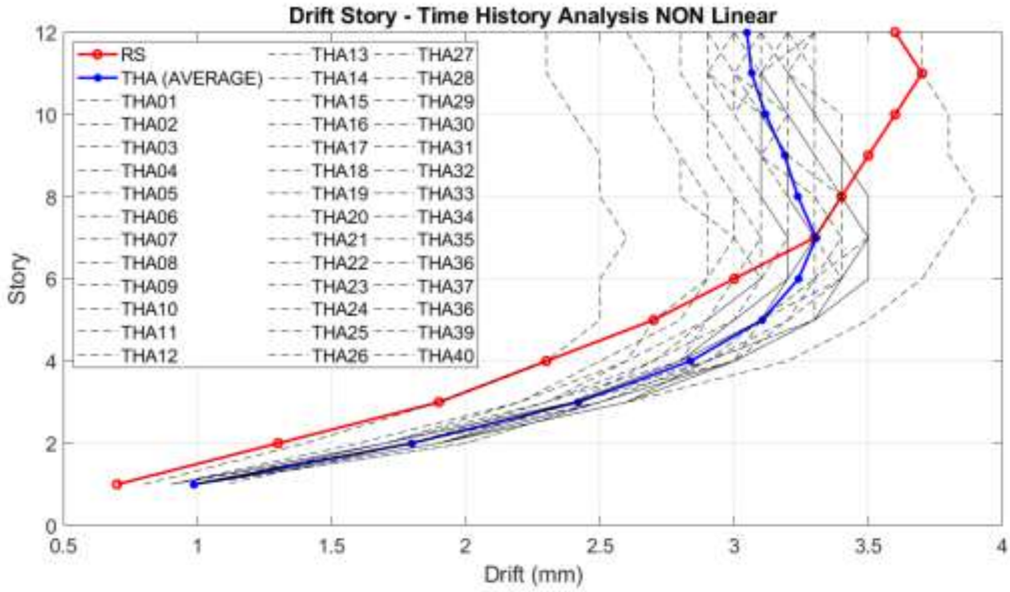
### *4.2.1. The analytical results of lateral story drift*

**Table 3** Lateral story drift results

| Drift (mm) | | | | $DRI_{THA}$-$DRI_{RS}$ (%) | | |
|---|---|---|---|---|---|---|
| **Stories** | **RS** | **Linear** | **Nonlinear** | **Stories** | **Linear** | **Nonlinear** |
| 12 | 3.6 | 3.5 | 3 | 12 | - 2.8% | - 15.3% |
| 11 | 3.7 | 3.5 | 3.1 | 11 | - 5.1% | - 17.2% |
| 10 | 3.6 | 3.5 | 3.1 | 10 | - 1.5% | - 13.4% |
| 9 | 3.5 | 3.5 | 3.2 | 9 | + 1.1% | - 8.9% |
| 8 | 3.4 | 3.5 | 3.2 | 8 | + 3.7% | - 4.8% |
| 7 | 3.3 | 3.5 | 3.3 | 7 | + 4.7% | + 0.2% |
| 6 | 3 | 3.3 | 3.2 | 6 | + 10.5% | + 8% |
| 5 | 2.7 | 3.1 | 3.1 | 5 | + 14.7% | + 15% |
| 4 | 2.3 | 2.7 | 2.8 | 4 | + 18.7% | + 23.4% |
| 3 | 1.9 | 2.3 | 2.4 | 3 | + 20.3% | + 27.2% |
| 2 | 1.3 | 1.6 | 1.8 | 2 | + 26.2% | + 38.3% |
| 1 | 0.7 | 0.9 | 1 | 1 | + 30.4% | + 41.1% |




a. Linear




b. Nonlinear

**Figure 5** Analytical results of lateral story drift

### *4.2.2. Discussion*

The dotted lines in Fig. 5 illustrate the results of story drift analyzed using the response spectrum (RS) method, while the solid ones illustrate the results of story drift analyzed using time history method (TH).

In case of the linear analytical model, the story drift results according to the TH method were greater than those according to the RS method. The difference between two analytical methods was shown to be a maximum of 30.4% at the first story and a minimum of 1.1% at the $9^{th}$ story. From the $9^{th}$ story, the differences gradually reduced in a range of 1.5%-2.8%.

By using the nonlinear analytical model, the story drift results according to the TH method were greater than those according to the RS method. The difference between two analytical methods was shown to be a maximum of 41.1% at the first story and a minimum of 0.2% at the $7^{th}$ story. From the $8^{th}$ story, the differences gradually reduced in a range of 4.8%-15.3%.

## 5. SEISMIC FRAGILITY CURVES

A seismic fragility curve [9,10] expresses failure probability of a structure or a mechanical system subjected to earthquakes as a function of a ground motion index, e.g., peak ground acceleration (PGA) and peak ground velocity (PGV).

The fragility curve $F_r(a)$ is the conditioned probability of failure or a damage state given that $A = a$:

$$F_r(a) = P\left[D \geq \delta_0 \middle| A = a\right] \tag{3}$$

where the failure or the specific damage state is characterized when the structural response taking into account random properties of response and critical limit due to uncertainty in loadings, material properties, dimensions exceeds a critical limit ($D \geq \delta_0$).

A commonly accepted assumption for a fragility curve is that $F_r(\bullet)$ is a cumulative probability function of the log-normal distribution:

$$F_r(a; A_m, \beta) = \Phi\left[\frac{\ln(a/A_m)}{\beta}\right] \quad (4)$$

where Φ(•) is the standard Gaussian cumulative distribution function while $A_m$ and $\beta$ are respectively median and logarithmic standard deviation.

In this section, using the data collected from 40 nonlinear time-history analyses, we establish the fragility curves of the building by means of the lognormal assumption. The MLE method [11,12] is used to determine the parameters of the log-normal curves.

The failure of the frame depends on the inter-storey drift i.e. the relative horizontal displacement of two adjacent floors. Under the excitation of a ground acceleration $a_i(t)$ the inter-storey drift of the $k^{th}$ storey is defined as $\delta^k(t)$. Failure or damage occurs if $D = \max_{t,k}|\delta^k(t)| \geq \delta_0$, where $\delta_0$ is the seismic resistance in terms of the interstorey drift limit of the building. Three cases were considered: $\delta_0 = H/300$, $\delta_0 = H/200$ and $\delta_0 = H/100$. The three inter-storey drift limits (1%, 1.5%, 3%) correspond to different damage states that can be connected respectively to minor, moderate and severe damages. They can also refer to different seismic performance levels as immediate occupancy, life safety and collapse prevention.

Fragility curves of the building, corresponding to three critical thresholds $\delta_0$ obtained by MLE method, are presented in Figure 6.

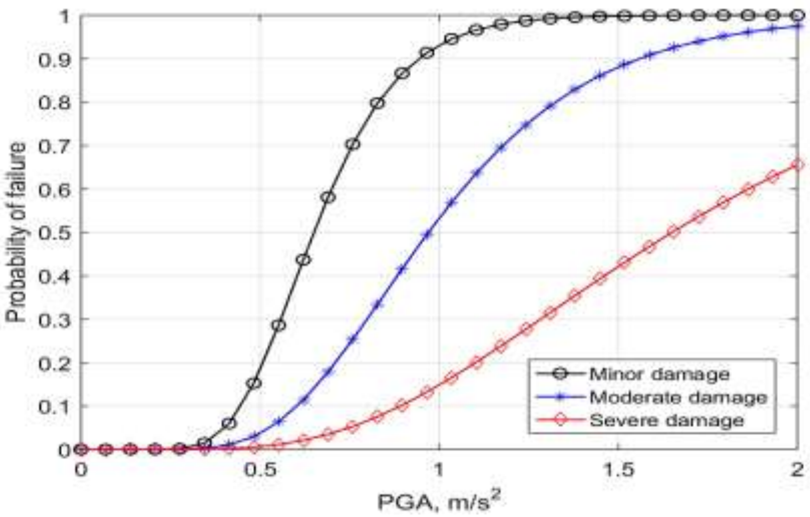



**Figure 6** Fragility curves of the building according to three critical thresholds

## 6. CONCLUSIONS

The present study illustrated the analytical results on the structural behavior of a building subjected to ground accelerations generated from the random simulation method and calibrated in accordance with the Vietnam standard TCVN 9386: 2012. It was found that the characteristics of the input ground acceleration and the dynamic properties of the building are two major factors affecting the seismic behavior of the structure. From the analytical results, it was found that the analytical results based on a linear model using two RS and TH methods were analogous. Meanwhile, the analytical results based on a nonlinear model showed a big difference between two RS and TH methods from the 8th floor, i.e 2/3 of the building height. Moreover, the seismic fragility curves according to the three destructive thresholds of the structure were also established to assess the seismic vulnerability of the building.

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