Influence of random soil parameters on seismic reliability of underground structure

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Abstract

The underground structure in the soil is difficult to repair after the earthquake, and the rescue is also a difficult problem. Therefore, reasonable determination of seismic reliability of underground structure can ensure the seismic capacity of underground structure in seismic analysis and design. The response of underground structure in earthquake is mainly controlled by the deformation of surrounding soil. In addition to the uncertainty of ground motion and structural material and form, the uncertainty of soil parameters is the key factor affecting its seismic reliability. The seismic reliability analysis of underground structure is a stochastic dynamic problem. For the determined underground structure, in order to study the influence of the randomness of soil parameters, it is necessary to control the influence of the randomness of ground motion. Here, the method of generating the ground motion which belongs to the same probability complete set is used to control the variables. In order to improve the calculation effect and accuracy, an improved Monte Carlo simulation method is used to select the sample points, and the dynamic time history analysis is carried out with and without considering the randomness of soil parameters. The probability that the inter-storey drift ratio does not exceed the limit value given in the code is defined as the seismic reliability of subway station. The results show that ignoring the randomness of soil parameters will underestimate the potential earthquake disasters faced by underground structures, and reduce the requirements for the seismic capacity of underground structures. The influence of randomness of soil parameters on seismic reliability of underground structures should be included in the future seismic research.

Keywords: Subway station structure; Randomness of soil parameters; Seismic reliability; Monte Carlo simulation method; Uncertainty analysis

Introduction

Subway station structure plays the role of urban lifeline in urban rail transit. Once it is damaged by earthquake, it is very difficult to repair the structure and rescue the personnel. Generally speaking, the randomness of structural seismic reliability mainly comes from two aspects. One is the randomness of ground motion, including frequency, intensity, propagation direction and other parameters [1]-[3]. On the other hand, it is the randomness of the structure itself, including the structural form and the material properties of the structure itself [4] [5].

Different from the above ground structure, the mechanical behavior of subway station during earthquake is mainly controlled by the deformation of soil, and the influence of soil parameter randomness on the seismic reliability of the structure can not be ignored.

It is a new trend to improve the seismic design method to predict the influence of soil conditions on seismic reliability of underground structures. In fact, the evolution of geological conditions occurs at all times, and even the soil properties of the same site have great variability [6]. For seismic analysis, in addition to the physical and mechanical parameters such as soil density and void ratio, it is worthier of attention to the shear wave velocity of soil. In the seismic code of China and the United States, shear wave velocity is used as the basis for site classification [7]-[9]. Some studies on the influence of shear wave velocity on seismic response have also been published [6] [10] [11]. In view of the uncertainty of shear wave velocity in soil, Toro et al. [12] established a shear wave velocity profile model based on the analysis of more than 500 shear wave velocity profiles. The model simplifies the analysis and takes into account the inter layer correlation of soil layers. This paper uses this method for reference, and establishes the shear wave velocity profile which is suitable for the model studied in this paper by Monte Carlo simulation method, and takes it as the input parameter of seismic analysis.

The purpose of this paper is to study the influence of the randomness of soil parameters on the seismic reliability of structures. Therefore, the randomness of ground motions should be eliminated or unified in the seismic reliability analysis of certain subway station structures. Liu et al. [13] used the idea of random function to reduce the number of random variables needed to generate ground motions to one. The ground motions generated by this method belong to the same probability complete set. For this kind of uncertainty problem, the same randomness of ground motions can be ensured statistically by generating ground motions according to the above method for dynamic time history analysis.

In conclusion, in order to explore the influence of soil parameters randomness on the seismic reliability of subway station structure, this paper uses Monte Carlo simulation method to generate random ground motion and shear wave velocity profiles, which are used as input parameters for dynamic time history analysis. For underground RC frame structures such as subway stations, the inter-storey drift ratio is an effective seismic performance evaluation index [14] [15]. The inter-storey drift ratio limit values of underground RC frame structure in elastic and elastoplastic state are also given in Chinese seismic codes [7] [8]. It is a reasonable method to define the probability of not exceeding the limit of inter-storey drift ratio given in the codes as the seismic reliability of subway station structure. The seismic reliability of subway station structure with and without considering the randomness of soil parameters is calculated respectively. The results show that the seismic damage risk of underground structure will increase without considering the randomness of soil parameters. Therefore, in the seismic analysis and design of underground structures, it is necessary to treat soil parameters as random variables for uncertainty analysis.

Point selection strategy

When sampling with Monte Carlo simulation method, the selection of sample points must be representative. The traditional Monte Carlo simulation method uses the method of generating random numbers to select sample points. When the number of sampling is less, the distribution of sample points will be uneven. In order to ensure the uniformity of sampling and reduce the cost of calculation, an improved Monte Carlo simulation method is adopted in this paper, that is, the Latin hypercube sampling method [16] is used to evenly divide the interval of generating random number, and then random points are selected in each new area, so as to ensure the uniformity of sample points. It is worth mentioning that, based on the randomly generated (0,1) interval obeying uniformly distributed sample points, the method of inverse CDF transform can be used to sample random variables of any distribution form [17].

Therefore, the point selection strategy of this paper is as follows: (1) according to the number of representative points n, the (0,1) interval is evenly divided, and n new areas are obtained; (2) Sampling points are randomly selected in each new area; (3) Through the inverse CDF transformation of the above sample points, random variable sampling under arbitrary distribution is completed.

Finite element model

The model studied in this paper is a typical two-story three span subway station structure in Shanghai. The height and width of the subway station structure are 12.37m and 20.9m respectively. The total height and width of the soil structure interaction model shown in Figure 1 are 60.5m and 1000m respectively. A 280m wide infinite element boundary is set on both sides of the site to eliminate the influence of seismic reflection.

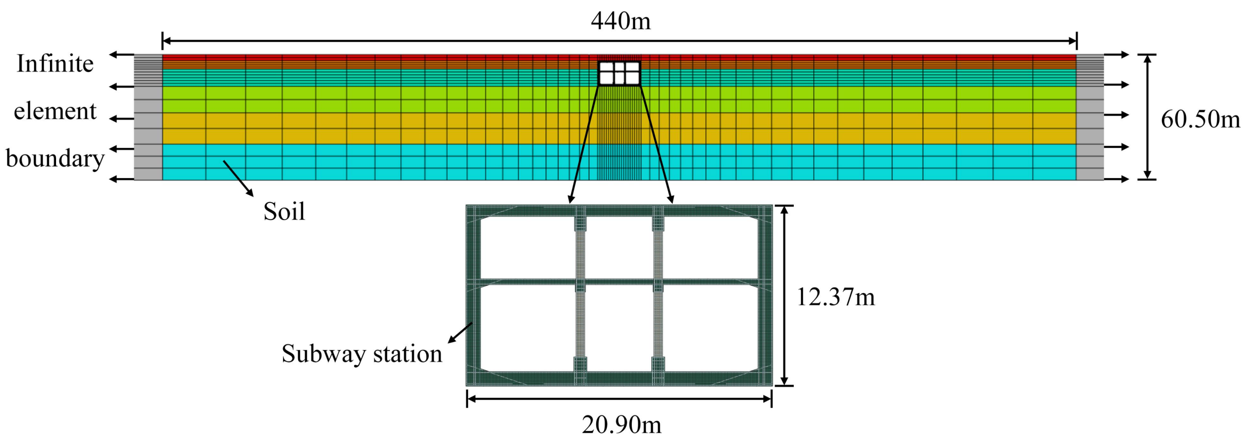


Figure 1. Soil structure interaction model

Soil parameters and shear wave velocity profile

Soil parameters

The soil parameters of the original site are shown in Table 1.

Table 1. Soil layer information

Soil layer	Soil name	Mass density ($kg•m^{-3}$)	Cohesion (kPa)	Angle of internal friction (°)	The mean of the shear wave velocity(m/s)	The standard deviation of the shear wave velocity(m/s)
S1	Brown yellow silty clay	1920	16.90	25.00	101	9.25
S2	Grey silty clay	1670	11.00	11.20	130	14.24
S3	Dark green silty clay	1950	44.0	16.40	292	44.38
S4	Grassy yellow, gray sandy silt	1820	2.00	31.10	278	42.26
S5	Gray clay	1770	17.00	15.20	231	43.66
S6	Gray silty clay interbedded with silt	1840	8.00	28.10	279	24.55

Shear wave velocity profile

Toro [12] established a shear wave velocity profile model considering the correlation between soil layers, which assumes that the shear wave velocity obeys lognormal distribution at any depth. In order to facilitate the application of the model in different site conditions, Toro [12] analyzed more than 500 shear wave velocity profiles, divided the site into different categories according to the equivalent shear wave velocity within 30 meters depth, V_{s30}, and gave the model parameters with different correlations.

Assuming that V_s obeys lognormal distribution at any depth, the shear wave velocity of layer i can be expressed as follows:

$$V_s(i) = \exp\left\{\ln\left[V_{s,m}(i)\right] + X_i \cdot \sigma_{\ln V_S}\right\} \quad (1)$$

Among them, $V_{s,m}(i)$ is the mean value of $V_s(i)$, $\sigma_{\ln V_S}$ is the natural logarithm of the standard deviation of $V_s(i)$, both are calculated according to the data in table 1; X_i is a standard normal distribution random variable, which represents the standard deviation number between $\ln\left[V_s(i)\right]$ and $\ln\left[V_{s,m}(i)\right]$ in the logarithmic space.

The correlation of X_i can be expressed by Eq. (2):

$$X_i = \begin{cases} \varepsilon_i & i = 1 \\ \rho_{IL} \cdot X_{i-1} + \varepsilon_i \cdot \sqrt{1-\rho_{IL}^2} & i \geq 2 \end{cases} \tag{2}$$

ε_i is a standard normal distribution random variable with a mean value of 0 and a standard deviation of 1; ρ_{IL} is the correlation coefficient between layer *i* and layer *i-1*, and C can be expressed as a function of depth *d* and layer thickness *t*, as shown in Eq. (3):

$$\rho_{IL}(d,t) = \left[1-\rho_d(d)\right]\rho_t(t) + \rho_d(d) \tag{3}$$

Where, $\rho_d(d)$ and $\rho_t(t)$ represent depth correlation coefficient and layer thickness correlation coefficient respectively, and their definitions are shown in Eq. (4) and Eq. (5) respectively:

$$\rho_d(d) = \begin{cases} \rho_{200}\left[\dfrac{d+d_0}{200+d_0}\right]^b & d \leq 200m \\ \rho_{200} & d > 200m \end{cases} \tag{4}$$

$$\rho_t(t) = \rho_0 \exp\left(\frac{-t}{\Delta}\right) \tag{5}$$

Among them, ρ_{200} , d_0 , b , ρ_0 and Δ are all related parameters of the model, which are determined according to the average shear wave velocity V_{s30} in the field within 30 m depth. According to reference [12], the values of the above five parameters are $\rho_{200} = 0.98$, $d_0 = 0$, $b = 0.344$, $\rho_0 = 0.99$, $\Delta = 3.9$ respectively.

The random shear wave velocity profile generated in this paper is shown in Figure 2. In order to describe the variation range of shear wave velocity profile, the profiles at $\mathrm{Exp}(\ln V_s \pm 2\sigma_{\ln V_s})$ are given. It can be seen from the figure that three randomly generated samples are roughly distributed in this range. In addition, it can also be noted that with the increase of depth, the overall trend of shear wave velocity increases, but there will be local reentry.

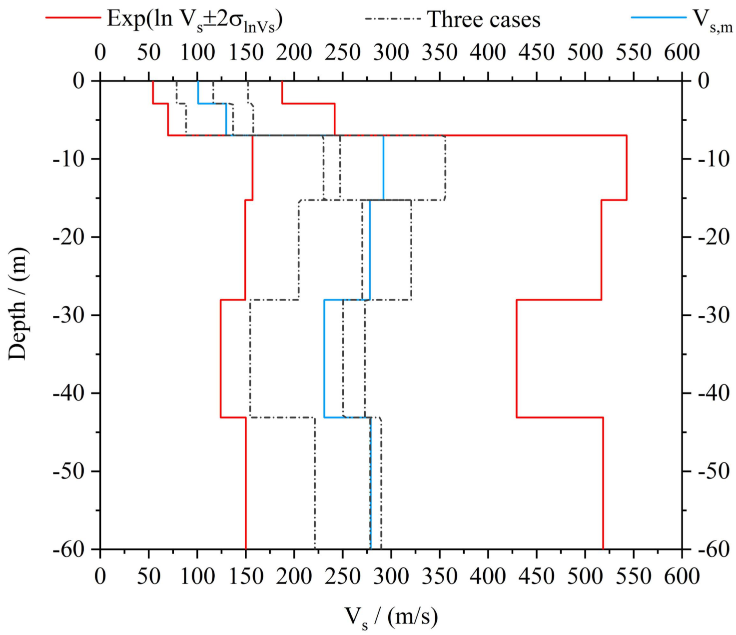


Figure 2. Shear wave velocity profile

Influence of randomness of soil parameters on reliability of subway station

In order to explore the influence of soil parameter randomness on the seismic reliability of subway station structure, the random shear wave velocity profile is used as the input parameter. According to the random ground motion generation method proposed by Liu et al. [13], the ground motions under the same probability complete set are obtained to control its influence on the seismic reliability of the structure. This method only needs to provide the phase angle θ, Figure 3 shows a typical time history acceleration-ground motion curve.

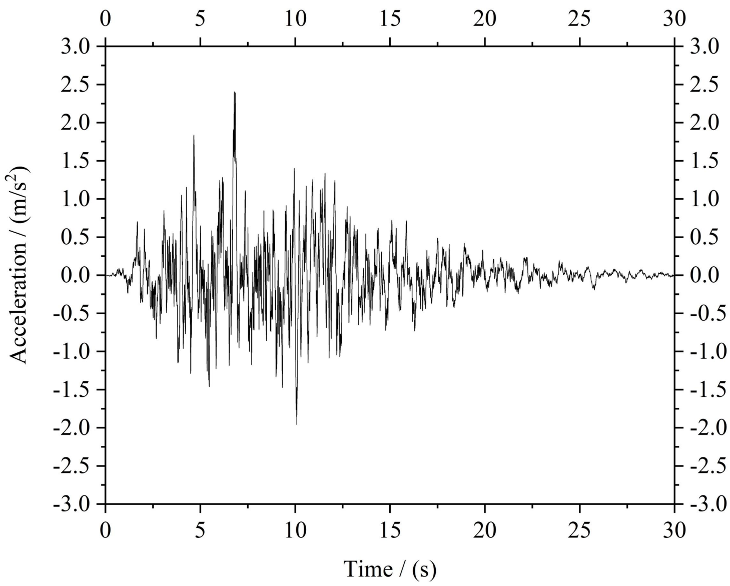


Figure 3. Typical ground motion

The inter-storey drift ratio is an effective index to evaluate the seismic performance of underground RC frame structure. Here, the reliability r of subway station structure is defined as the probability of not exceeding the specified inter-storey drift ratio limit. In China's seismic codes [7] [8], the limit of inter-storey drift ratio of underground RC frame structures under elastic and elastic-plastic state is given, as shown in Table 2.

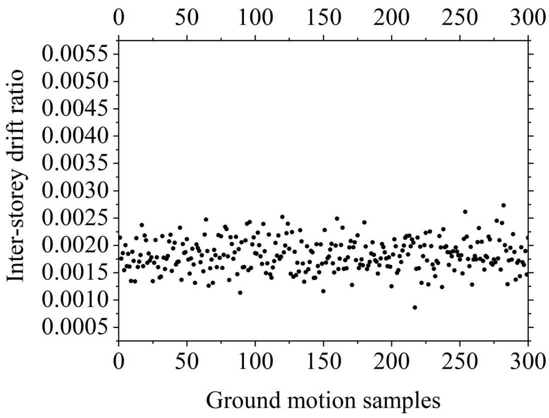
Table 2. Limit of the inter-storey drift ratio in Chinese codes

Chinese codes	Applicable objects	ES	EPS
Code for seismic design of subway structures (DG/TJ 08-2064-2009)	Concrete frame structure	1/550	-
	Reinforced concrete frame structure	-	1/250
Standard for seismic design of underground structures (GB/T 51336-2018)	Single-layer or double-layer rectangular section structure	1/550	1/250
	Three-storey and above rectangular section structure	1/1000	1/250

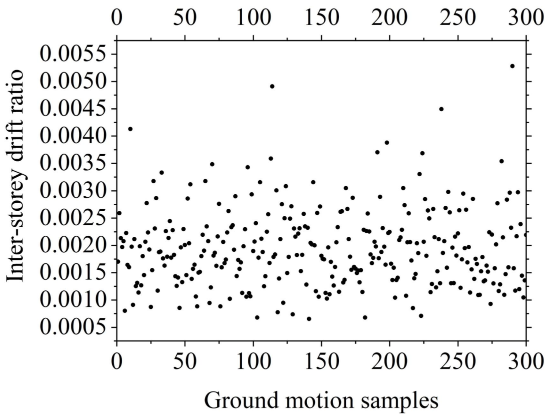
Note: ES is the elastic state, EPS is the elastic-plastic state.

The seismic reliability analysis of the soil-structure interaction model studied in this paper involves a total of seven basic random variables, which are respectively the shear wave velocity of six soil layers and the phase angle of ground motion. According to the point selection strategy described in Chapter 2, 300 sample points, i.e., 300 cases of different ground motion and shear wave velocity profiles, were generated. The dynamic time history analysis was conducted for the above 300 working conditions (considering the randomness of soil parameters) and the original site condition using only the above 300 ground motions (without considering the randomness of soil parameters). The maximum interlayer displacement Angle in each working condition was extracted, and the inter-storey drift ratio corresponding to the ground motion samples was drawn in Fig. 4. Fig. 4 (a) is the distribution of inter-storey drift ratio without considering the randomness of soil parameters, and Fig. 4 (b) is the distribution of inter-storey drift ratio with the randomness of soil parameters considered.

Compared with figure 4 (a) and Figure 4 (b), it can be seen that under the premise of the same seismic samples, the inter-storey drift ratio distribution is more dispersed when considering the randomness of soil parameters, which well illustrates the influence of randomness of soil parameters on the seismic response of underground structures. Taking the maximum value as an example, the maximum value of inter-storey drift ratio without considering the randomness of soil parameters is about 0.0027, and the minimum value is about 0.0008; Considering the randomness of soil parameters, the maximum value of inter-storey drift ratio is about 0.0053, and the minimum value is about 0.0006. The maximum difference between the two cases is as high as one time. In the seismic analysis and design, if the influence of random soil parameters on the seismic response of underground structures is not fully considered, the seismic risk of the structure will be underestimated.



(a)The randomness of soil parameters is not considered



(b)The randomness of soil parameters is considered

Figure 4. Distribution of inter-storey drift ratio

According to the code for the limit value of inter-storey drift ratio, the seismic reliability index of subway station structure is defined as the probability of not exceeding the limit value given in the code, which are the reliability R_e in elastic state and the reliability R_{ep} in elastic-plastic state. Table 3 lists the reliability of subway station structure with or without random soil parameters.

Table 3. Comparison of reliability

	The randomness of soil parameters is not considered	The randomness of soil parameters is considered
R_e	0.5300	0.4833
R_{ep}	1	0.9867

Note: R_e is the reliability of elastic state, R_{ep} is the reliability of elastic plastic state.

It can be seen from Table 3 that the seismic reliability of subway station without considering the randomness of soil parameters is always greater than that of subway station with considering the randomness of soil parameters in both elastic and elastic-plastic states. In the elastic-plastic state, without considering the influence of soil parameter randomness on the seismic reliability of subway station, the reliability reaches 100%. Obviously, such evaluation will reduce the construction requirements of underground structures and bring potential risk factors. Therefore, reasonable consideration of the randomness of soil parameters is the key step to ensure the seismic capacity of underground structures.

Conclusions

The seismic reliability of underground structures contains many uncertainties. Compared with the above ground structures, the most important source of uncertainty is the uncertainty of soil parameters. In this paper, the improved Monte Carlo simulation method is used to generate representative sample points. By controlling the ground motion variables under the same probability complete set, the seismic reliability of subway station structure with and without considering the randomness of soil parameters is studied. The results show that when the randomness of soil parameters is not considered, the seismic response distribution of the structure is more concentrated. And the maximum value of inter-storey drift ratio is only half of that considering the randomness of soil parameters, which will underestimate the potential seismic disaster of underground structures. According to the limit value of inter-storey drift ratio given by the code, the seismic reliability of subway station structure is defined. It is found that the corresponding seismic reliability will be overestimated without considering the influence of random soil parameters on the seismic response of subway station structure, which will reduce the seismic demand of underground structure and increase the risk of earthquake. Therefore, in the seismic analysis and design of underground structures, the uncertainty of soil parameters should be considered, and the seismic reliability of underground structures should be analyzed combined with the real site conditions to ensure the seismic capacity of underground structures.

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