Effect of soil properties on seismic response of underground station

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Abstract

The soil dynamic properties are the main factors affecting soils' and structural seismic responses. The present paper conducts a numerical analysis to study the effect of uncertainty of elastic modulus at layered soil site using statistic method. A layered soil model is used. The elastic modulus of the concerned soil layer obeys normal distribution with a variant coefficient of 0.2. Eight input ground motions are used to avoid the calculation contingency. The analysis results show that the changing of soil elastic modulus has various influences on structural internal forces with different input ground motions. Whereas the story drift obeys quite similar normal distribution to that of the elastic modulus of the concerned soil layer. And the performance-based seismic design of underground structure should be paid well attention in engineering practice.

Keywords: Soil dynamic properties; Seismic response; Underground station; Statistic method.

1. Introduction

Currently, the soil properties, used for conduct research on geotechnical earthquake engineering, are usually determined through dynamic triaxial or resonant column tests [1-3]. However, the test results are of large-discreteness due to the complex influence factors on dynamic shear modulus and damping ratio. Based on earthquake damage investigation and site seismic response analyses, it is well known that the soil dynamic properties, including dynamic shear modulus and damping ratio, are the main factors affecting soils' seismic responses. Thus, whether the soil dynamic properties are consistent with the actual situation or not has distinct influences on the reliability of analysis results [4-5].

Wen et al. [6] studied on seismic soil-structure interaction and found that the high frequency seismic response spectra is abundant in the hard rock layers in the Middle East of the United States. Dashti et al. [7] conducted centrifuge tests on underground reservoir structures to study the influence of backfill soil type. The test results showed that soft and hard soils have distinct influences on structural dynamic behavior and dynamic earth pressure. Zlatanoviä et al. [8] revealed that the soft clay soil, compared with the sand of medium-compactness, is of smaller shear stiffness and larger damping. And more earthquake energy is dissipated in soft soil, which leads to a weaker amplification effect of soils on seismic wave, and then results in smaller seismic shear force and larger seismic shear strain. Thus, the structure buried in soft soils suffers smaller axial force and larger shear force and bending moment than that in medium-compactness sands. However, the above-mentioned studies, based on the one-layer isotropic soil model, mainly focused on the effect of changing soil types, and the uncertainty of soil dynamic properties have not been considered.

To study the uncertainty of soil dynamic properties, some researchers [9-11] used the one-dimensional equivalent linearization method by adopting a specific variable coefficient to simplify the soil models. Obviously, this method has certain limitations, such as the virtual resonance effect [12], which is an inherent error. At layered sites, considering the uncertainty of soil properties, the calculations are complicated because different kinds of soil properties increase or decrease in different soil layers [13]. An alternative method based on the random vibration theory has been used to simulate dynamic soil properties [14-15]. However, this method is complex and unsuitable for widespread engineering applications in evaluating the seismic performances of underground structures.

The present paper assumes that the elastic modulus of the concerned soil layer obeys the normal distribution with the variation coefficient of 0.2, and this hypothesis is well adopted in previous studies [16-19]. Taking a typical underground station in Shanghai as an engineering reference, the influences of uncertainty of elastic modulus at layered soil site on structural seismic responses are studied by using the statistic method. To avoid the calculation contingency of using only one input ground motion, eight input ground motions are used in the present paper.

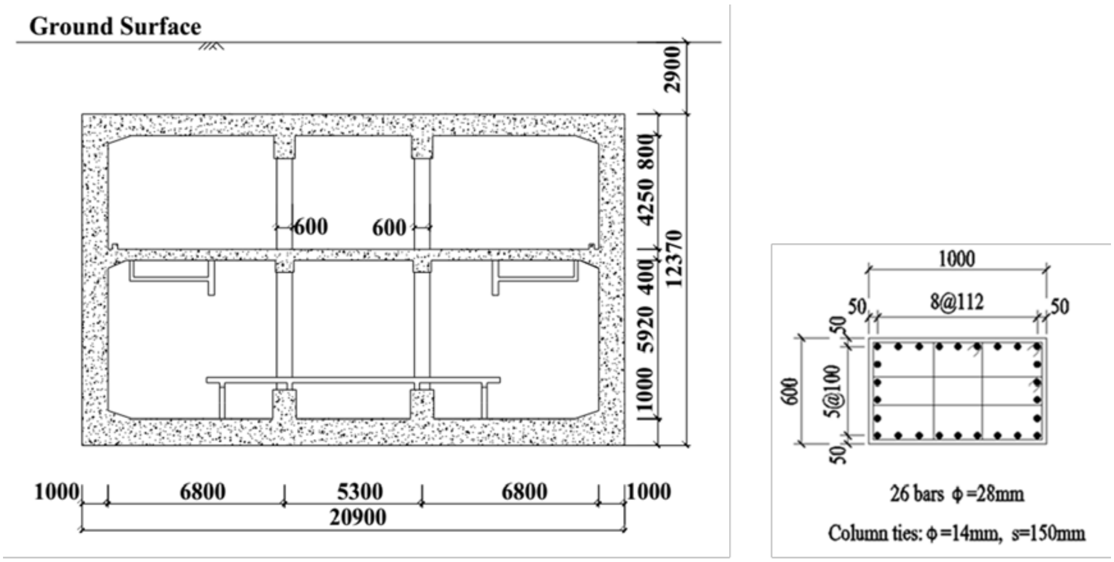
2. Finite element modeling

2.1 Numerical model

The finite element code ABAQUS [20] is used to perform the full-time history analyses of underground structure with surrounding soils. Fig. 1 shows the cross-section dimension of the station and its central column. The numerical analyses are performed under plane strain condition. Fig. 2 depicts the analytical model with the area of 500 m × 60.55 m. When considering the boundary effect, as recommended by the Code for Seismic Design of Buildings [21], the width of each side of soil around the structure should be at least triple of the width of the structure. In the present model, the width of each side of soil is 250 m. Further, the infinite element boundary is used as the side boundary. The infinite element (CINPE4) provided by ABAQUS is based on the static analysis [22] and the dynamic response analysis [23], and it can simulate no reflection by setting damping on the boundary. The bottom boundary is placed 45.28 m from the bottom plate of the structure, on which the X and Y displacements are fixed before the ground motion is input.

2.2 Constitutive models and material properties

Quadratic plane strain elements (CPE4R) and beam elements (B21) are used to simulate the soil and the station structure, respectively (Fig. 2). Soil behavior is modelled by Mohr-Coulomb elasto-plastic model, and the specific properties are shown in Table 1. There are three soil layers, which are artificial fill, silty clay and gray clay from top to bottom. And the station structure is cased in the silty clay.



(a) (b)

Fig. 1. Cross-section dimension of the station and central column

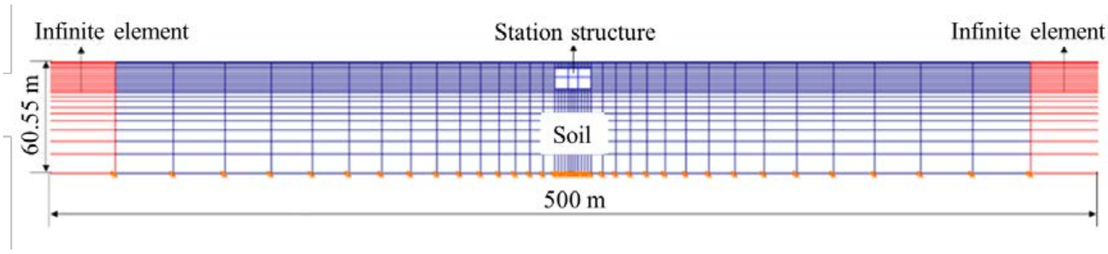


Fig. 2. Numerical analytical model

Table 1. Soil properties of station site

Layer num.	Soil type	Depth (m)	Unit weight (kN/m^3)	Elastic modulus (MPa)	Poisson's ratio υ	Internal friction angle (°)	Cohesion (kPa)
1	Artificial fill	0-1.32	19.00	20.34	0.32	15.0	20.0
2	Silty clay	1.32-19.8	17.72	13.32	0.34	27.7	13.0
3	Gray clay	19.8-60.55	18.10	24.13	0.32	30.3	7.0

The concrete of Grade C45 and Grade C35 [24] are used to build the central columns and the other parts. For concrete C45, its elastic modulus, Poisson's ratio, tensile, and compression strength are 33.5 GPa, 0.2, 2.51 MPa, and 29.6 MPa, respectively. And for concrete C35, its parameters are 31.5 GPa, 0.2, 2.20 MPa, and 23.4 MPa, respectively. To better simulate the dynamic response of the elastic-plastic stage, the concrete damaged plasticity model is used. And the detailed information of this model and its calculation of damage parameters have been stated in the previous studies [25-26]. Since the longitudinal spacing between columns is 8 m in practical engineering, the reduced stiffness is adopted to consider the spacing [27].

Bilinear isotropic model (idealized elastic-plastic model), following the kinematic hardening rule, is selected to simulate the rebar. Fig. 1(b) shows the reinforcement details of the central column. Rebar HRB400 [24] is used in the present structure with the elastic modulus and yield strength of 200 GPa and 400GPa, respectively.

To simplify the analyses, no-slip condition is assumed for the soil-structure interaction. Although the interface behavior is quite crucial for the dynamic response of underground structures [28-29], this assumption is quite common in engineering practice, as it can be treated as the upper limit for the developed shear stresses around the tunnel [30].

3. Calculation cases and input ground motions

3.1 Calculation cases

Layered homogeneous soil model is adopted in the present paper. The soil properties of Layers 1 and 3 are set as listed in Table 1. There are five calculation cases classified by the elastic modulus of Layer 2, in which the station structure is cased. Table 2 depicts these five calculation cases with details of the elastic modulus of Layer 2. Based on the practical experience and some previous studies [16-19], the elastic modulus of Layer 2 obeys the normal distribution, and the variation coefficient of the mean elastic modulus is set as 0.2. The standard deviation is the product of the mean elastic modulus and the variation coefficient.

Table 2. Calculation cases and corresponding elastic modulus of Layer 2

Case number	Standard deviation (MPa) *	Elastic modulus (MPa)
Case1		7.99 (μ-2σ)
Case2		10.66 (μ-σ)
Case3	2.67 (σ)	13.32 (μ)
Case4		15.98 (μ+σ)
Case5		18.65 (μ+2σ)

*Standard deviation (σ) = Variation coefficient × Mean elastic modulus (μ)

3.2 Input ground motions

There are eight ground motions used as base excitation. The time history data of the input ground motions are from the Pacific Earthquake Engineering Research Center (PEER) in the United States. The detailed information of input ground motions is shown in Table 3. The predominant frequency of the input ground motions can be classified into three categories as low-, medium-, and high-frequency. Due to space limitation, only two acceleration time histories of Landers and Hector Mine are depicted as in Fig. 3. The peak ground acceleration of the input ground motions is set as 0.1 g. According to the Code for Seismic Design of Buildings [21], a PGA of 0.1 g would correspond to a probability of exceedance of 10% in 50 years for the underground station.

Table 3. Information of input ground motions

Ground motion	Earthquake	Date	Recording stations	Direction	Predominant period (s)	Duration (s)
EQ-1	Landers	28 Jun 92	NO. 11628	90	0.18	134.96
EQ-2	Chichi	20 Sep 99	CHY042	NS	0.22	89.995
EQ-3	Chichi	22 Sep 99	CHY035	EW	0.32	89.995
EQ-4	SMART1	14 Nov 86	SMART1012	EW	0.34	40
EQ-5	Chichi	25 Sep 99	CHY027	EW	0.36	89.995
EQ-6	Northridge	17 Jan 94	NO.14560	90	0.42	60
EQ-7	Hector Mine	16 Oct 99	NO.11628	90	0.42	100
EQ-8	Chichi	20 Sep 99	CHY042	EW	0.8	89.995

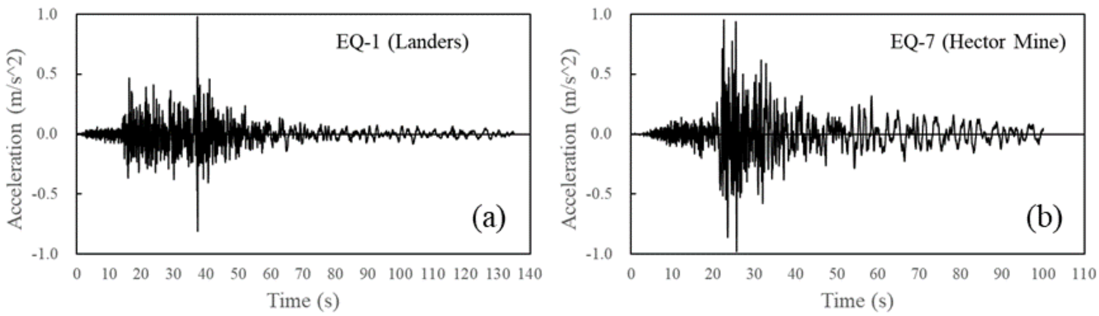


Fig. 3. Time histories of input ground motions, such as (a) Landers; (b) Hector Mine

4. Results and discussion

In engineering practice, the primary indexes, used to conduct seismic performance evaluation on underground stations, include the peak shear force and bending moment of columns and story drift [27, 31]. Tables 4, 5 and 6 show the peak shear force and bending moment of columns and story drift, respectively. And the corresponding numerical characteristics, such as mean value and variation coefficient are also calculated as shown in Tables 4-6. Due to space limitation, only the seismic responses of upper floor are shown herein since the maximum values basically occurs in this floor. And it should be noted that the findings of dynamic behavior of the lower floor are the same as the upper one.

Seen from Tables 4 and 5, it can be easy to find that the changing of soil elastic modulus has various influences on structural internal forces with different input ground motions. For example, in condition EQ-3, the maximum differentials of peak shear force and bending moment of upper column can reach 56% and 57%, respectively. In conditions EQ-4 – EQ-8, the variation coefficient of internal force ranges within 0.01-0.06, which implies the changing of soil elastic modulus barely influences the internal force. And the detailed explanations will be illustrated in the following.

Table 4. Peak shear force of upper column

Ground motion	Peak shear force of upper column (kN)						
	Case1	Case2	Case3	Caes4	Case5	Mean value	Variation coefficient*
EQ-1	567.8	546.6	491.9	651.6	517.8	555.1	0.11
EQ-2	862.9	1060.0	1044.0	848.8	836.2	930.4	0.12
EQ-3	305.2	344.2	374.2	428.8	475.5	385.6	0.17
EQ-4	1136.5	1121.2	1148.2	1146.8	1146.8	1139.9	0.01
EQ-5	1143.0	1128.2	1128.2	1159.0	1103.4	1132.4	0.02
EQ-6	1058.9	1050.2	1078.7	1102.4	1060.3	1070.1	0.02
EQ-7	924.14	1095.3	1025.6	1053.6	1068.9	1033.5	0.06
EQ-8	1085.6	1059.0	1055.9	1078.1	1052.4	1066.9	0.01

*The variation coefficient is a dimensionless value (the same below).

Table 5. Peak bending moment of upper column

Ground motion	Peak bending moment of upper column (kN•m)						
	Case1	Case2	Case3	Caes4	Case5	Mean value	Variation coefficient
EQ-1	1082.7	1046.2	941.5	1226.6	989.9	1057.4	0.10
EQ-2	1648.3	2047.1	1981.8	1629.8	1620.0	1785.4	0.12
EQ-3	577.8	656.6	711.8	821.6	908.6	735.3	0.18
EQ-4	2044.4	2014.5	2086.5	2089.9	2110.2	2069.1	0.02
EQ-5	2141.1	2160.3	2153.3	2106.4	2140.6	2140.4	0.01
EQ-6	2039.4	2026.4	2055.7	2120.2	2047.5	2057.8	0.02
EQ-7	1759.2	2022.4	1954.3	2023.8	2031.2	1958.2	0.06
EQ-8	2021.7	2029.8	2011.8	2062.5	2004.0	2026.0	0.01

Table 6 shows the peak upper story drift and the corresponding numerical characteristics.

Seen from Table 6, it can be concluded that changing the elastic modulus has obvious influence on story drift. And the variation coefficient is basically about 0.2 under all kinds of input excitations, which is the variation coefficient of the elastic modulus of the concerned soil layer. This phenomenon can be explained through Fig. 4. As illustrated in Fig. 4, the deformation of the surrounding soil, rather than the vibration characteristics of the structure, dominates the seismic response of an underground structure embedded in soft soils. Thus, the story drift obeys quite similar normal distribution to that of the elastic modulus of the concerned soil layer, which the structure is cased in.

Table 6. Peak upper story drift

Ground motion	Peak upper story drift (‰)						
	Case1	Case2	Case3	Caes4	Case5	Mean value	Variation coefficient
EQ-1	2.14	1.92	1.42	2.06	1.25	1.76	0.23
EQ-2	2.54	3.94	3.47	2.72	2.53	3.04	0.21
EQ-3	1.09	1.31	1.61	1.50	1.20	1.34	0.16
EQ-4	8.66	7.29	6.24	5.66	4.74	6.52	0.23
EQ-5	18.47	19.16	14.09	9.05	7.40	13.64	0.39
EQ-6	5.29	3.52	5.19	3.53	3.16	4.14	0.25
EQ-7	3.48	4.94	4.40	4.57	2.94	4.07	0.20
EQ-8	6.34	6.59	5.04	2.89	3.29	4.83	0.35

Note: The upper limit value recommended by Code is 4‰ [21].

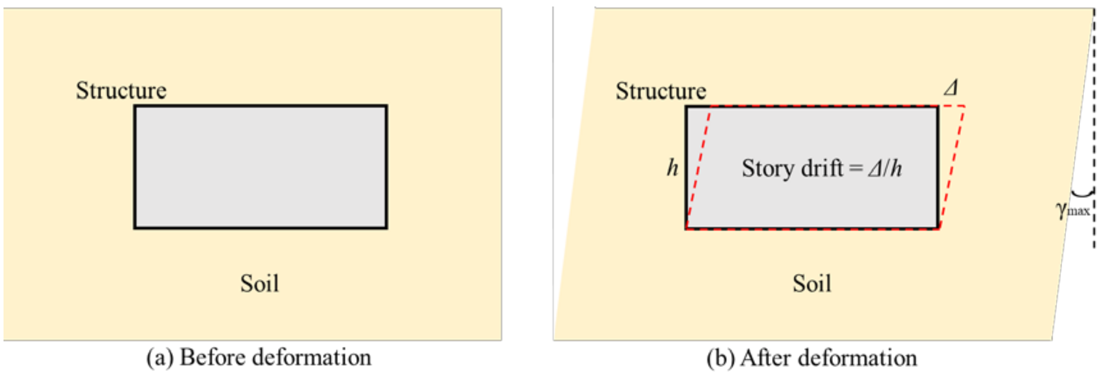


Fig. 4. Racking deformation mode of underground structure

According to the Code [21], the upper limit value recommended is 4‰. As shown in Table 6, the drift story could exceed the upper limit under several cases, when using input ground motions like EQ-4 – EQ-8. And under these excitations, the values of story drift vary significantly (see Table 6), whereas the values of internal forces are very close (see Tables 4 and 5). It implies that the structure is in the plastic state. And this could explain that the internal forces under these conditions barely change with the changing of soil elastic modulus, whose variation coefficient of internal force ranges within 0.01-0.06. From the above-discussion, it also can be concluded that the index, like internal forces, cannot comprehensively reflect the dynamic behavior state and seismic performance of underground structures when entering severe plastic stage. Thus, the performance-based seismic design of underground structure should be paid well attention in engineering practice.

5. Conclusion

In this paper, a numerical study is conducted to explore the influences of uncertainty of elastic modulus at layered soil site on structural seismic responses through the statistic method. And there are eight input ground motions for avoiding the calculation contingency. Some conclusions can be drawn as follows:

1. The changing of soil elastic modulus has various influences on structural internal forces with different input ground motions. Under EQ-4 – EQ-8 conditions, the changing of soil elastic modulus has little influences on the internal force since the structure enters plastic stage.
2. The story drift obeys quite similar normal distribution to that of the elastic modulus of the concerned soil layer, which the structure is cased in. Because The deformation of the surrounding soil dominates the seismic response of an underground structure embedded in soft soils.
3. Internal forces cannot comprehensively reflect the dynamic behavior state and seismic performance of underground structures when entering severe plastic stage. The performance-based seismic design of underground structure should be paid well attention in engineering practice.

Acknowledgments

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