Seismic vulnerability assessment of multi-storey subway station structure

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Abstract. The safety of underground structure under seismic load is an important basis of the normal operation of underground rail transit system. Structural seismic vulnerability assessment based on incremental dynamic analysis method can evaluate the probability of the structure exceeding a certain limit state under a specific seismic intensity in terms of probability. In this paper, the seismic vulnerability of a multi-storey subway station structure is evaluated using this method, and a two-dimensional finite element model of both soil and structure is established by finite element software ABAQUS. The vulnerability curve is obtained through incremental dynamic analysis and mathematical statistics. Based on this curve, the probabilities of the structure exceeding four seismic limit states are obtained under the design seismic intensity and the rarely occurred seismic intensity at 7 degree. Results show that this station may attain slight damage under design seismic intensity of 7 degree, and may attain life safety at the rarely occurred seismic intensity at 7 degree.

1 Introduction

In earlier years, the researchers generally agree that the seismic performance of underground structure is better than that of the surface structure. However, the Daikai subway station encountered M type failure mode during the Kobe earthquake at Japan in 1995[1,2]. Therefore, seismic performance of underground structure should obtain enough attention. With the continuous development of science and technology, underground space is fully exploited and the layer of underground subway station structure increases. Consequently , it is necessary to do research on the seismic performance of multi-storey underground subway station.

Among the approaches of evaluating seismic performance, seismic vulnerability assessment based on incremental dynamic analysis(IDA) can evaluate the probability of the structure exceeding a certain limit state under a specific seismic intensity in terms of probability[3,4]. At the same time, the method can fully take the randomness of seismic ground motion and structural dynamic response characteristics under strong earthquake into consideration. This method has been applied to the seismic vulnerability assessment of conventional underground structures[5,6].

Considered the advantages of seismic vulnerability assessment, in this study, the seismic vulnerability of multi-storey subway station is carried out. A two-dimensional numerical model of a four-storey three-span structure and the surrounding soil is developed

Table1. Soil parameters of the example structure.

Sequence	Name	Depth (m)	Unit Weight (kN/m^3)	Elastic Modulus (MPa)	Poisson's Ratio	Friction Angle (°)	Cohesion (kPa)
1	Man-made fill	0~0.5	1820	14	0.32	14.5	21
2	Man-made fill	0.5~1.3	820	14	0.32	14.5	21
3	Brownish yellow to grayish yellow silty clay	1.3~3.2	820	14	0.32	14.5	21
4	Grey silty silty clay	3.2~8.4	760	10	0.33	12.5	14
5	Grey silty clay	8.35~14.8	680	7	0.37	9.5	14

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6	Gray clay	14.8~18.2	760	11	0.34	13.5	15
7	Gray silty clay	18.2~22.4	790	13	0.31	16.5	17
8	Gray silty clay interbedded with silt	22.4~29.2	800	17	0.29	18	16
9	Gray silty clay	29.15~32.3	840	16	0.31	16	24
10	Gray-green silty clay	32.3~33.4	980	26	0.26	19	34
11	Grass yellow to cyan sandy clay	33.4~39.1	900	33	0.26	29	5
12	Grass yellow to gray silt	39.05~66.6	870	43	0.24	31.5	3
13	Gray silty clay	66.6~71.6	820	17	0.23	14.5	26
14	Gray fine silty sand	71.55~85	890	45	0.25	34.5	0

using the finite element software ABAQUS. Through incremental dynamic analysis, the vulnerability curves at four limit states are obtained, based on which the exceeding probabilities corresponding to four limit states at specific seismic intensity are ensured.

2 Numerical modeling

2.1 Typical multi-storey subway station structure

As shown in Figure 1, a four-storey three-span subway station is considered as a typical example of multi-storey subway station. The first underground floor is the stereo garage, the second underground floor is the lobby floor, the third underground floor is the device floor, and the bottom floor is the island platform floor. The section width of the station is 23.6m, and the height is 29.11m. The size of central column at the first and second underground floors is 0.7m by 1.1m, while the size of central column at the third underground floor and the bottom floor is 0.7m by 1.4m, and the longitudinal space of the central column along the station is 8m. The buried depth of the station is 2.9m and the soil properties are shown in Table 1.

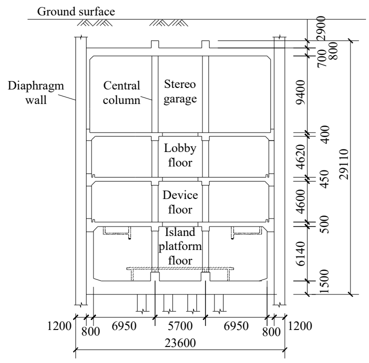

Figure 1. Cross section of the multi-storey subway station structure.

2.2 Numerical model

According to the general profile , a two-dimensional finite element model of soil and structure is established using finite element software ABAQUS[7], the dimension of which is 1000 m long and 85 m high, as shown in Figure 2. The structure members are simulated through beam element (B21) and the material properties of concrete and steel are illustrated in Table 2. The layered soil is simulated through 4-nodes plane strain element (CPE4R) and the quadrilateral plane strain infinite element (CINPE4). The interface between the soil and the structure is modeled as a frictional surface, among which coefficient of friction μ is equal to 0.4 and friction angle is 22°. Moreover, no cohesion exists between structure and soil and the ground motion is imposed at the bottom of the model.

Table2. Material Parameters of multi-storey subway station.

Component	Material					
	Concrete				Steel	
	Elastic Modulus (GPa)	Axial Tensile Strength (MPa)	Axial Compression Strength (MPa)	Possion's Ratio	Elastic Modulus (GPa)	Yield strength (MPa)
Central column	33.5	2.51	29.6	0.2	200	400
Others	31.5	2.20	23.4	0.2	200	335

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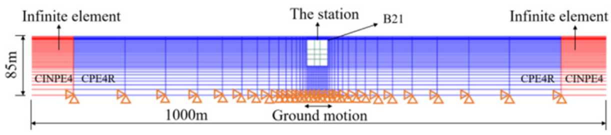

Figure 2. Finite element model

3 Seismic vulnerability assessment process

3.1 Incremental dynamic analysis

Based on the procedure of IDA[4], the ground motion records are selected according to the site type, as shown in Table 3. Peak acceleration at the bottom of structure (PBA) is selected as intensity measure(IM) and the maximum inter-story drift angle(θ_{max}) is chosen as the damage measure(DM). Besides, the ground motion records are scaled with Peak Velocity as 3, 5, 10, 20, 30,

40, 50, 60, 70, 80cm/s, and with nonlinear dynamic time-history analysis under each ground motion intensity,

the IDA curves can be obtained, as shown in Figure 3. The range of θ_{max} is 0 to 0.045. θ_{max} increases gradually with the increasing of ground motion intensity and apparent discrepancy exists among each IDA curve. To better statistic IDA data, the IDA curves are arranged into 16%, 50% and 84% fractile curves to analyze the IDA calculation results in the mean sense, as illustrated in Figure 4.

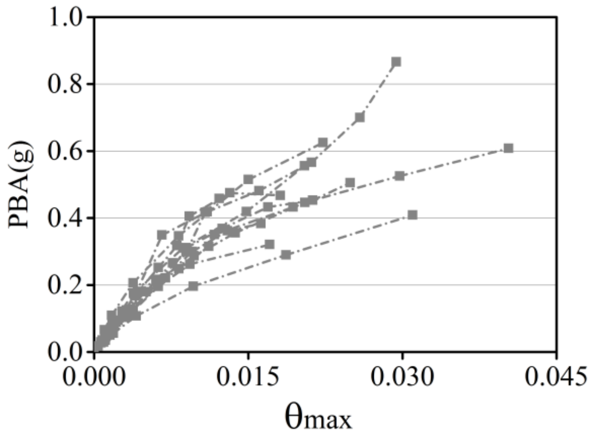

Figure 3. IDA curves

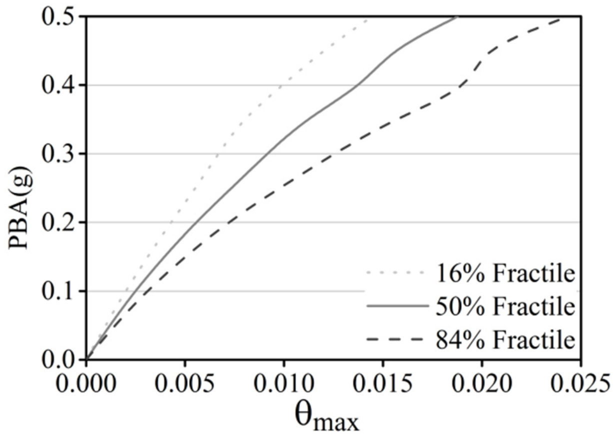

Figure 4. Fractile curves

Table3. Twelve ground motion records selected.

No.	Event	Station	Component	PGA(g)	PGV(cm/s)
M1	Imperial Valley-06, 1979	El Centro Array #3	E03140	0.267	47.97
M2	Imperial Valley-06, 1979	El Centro Array #3	E03230	0.223	43.29
M3	Loma Prieta, 1989	APEEL 2 - Redwood City	A02043	0.274	53.65
M4	Loma Prieta, 1989	APEEL 2 - Redwood City	A02133	0.220	34.12
M5	Loma Prieta, 1989	Foster City - Menhaden Court	MEN270	0.110	21.98
M6	Loma Prieta, 1989	Foster City - Menhaden Court	MEN360	0.119	20.93
M7	Loma Prieta, 1989	Treasure Island	TRI000	0.100	15.59
M8	Loma Prieta, 1989	Treasure Island	TRI090	0.160	33.20
M9	Superstition Hills-02, 1987	Imperial Valley Wildlife Liquefaction Array	IVW090	0.179	31.67
M10	Superstition Hills-02, 1987	Imperial Valley Wildlife Liquefaction Array	IVW360	0.208	36.21
M11	Northridge-01, 1994	Carson - Water St	WAT180	0.091	6.33
M12	Northridge-01, 1994	Carson - Water St	WAT270	0.088	8.32

3.2 Results of structural seismic vulnerability assessment

Seismic vulnerability assessment means calculate the probability of structural dynamic response exceeding a certain limit state *LSi* with different ground motion intensity levels, i.e $P(LSi\,|IM=im)$. Usually, we assume that DM for IM's condition distribution follows the lognormal cumulative distribution function. Then,

$$P(LS_i|IM=im)=P(DM>dm_i|IM=im)=1-\Phi\left(\frac{ln\,dm_i-\mu_{ln\,DM|IM=im}}{\sigma_{ln\,DM|IM=im}}\right) \quad (1)$$

In formula (1), $\mu_{ln\,DM|IM=im}$ is the mean of $ln(DM)$ and $\sigma_{ln\,DM|IM=im}$ is the standard deviation of $ln(DM)$. Φ is the standard cumulative normal distribution function.

Based on the formula, we can obtain the seismic vulnerability curve with IM as horizontal axis, exceeding probability as vertical axis and the seismic vulnerability under specific ground motion intensity can be investigated. Based on the procedure mentioned above, the limit states of this station should be ensured firstly, which can refer to Liu et al.[5], as illustrated in Table 4.

Then, the vulnerability curve can be obtained using formula (1) and nonlinear regression analysis of MATLAB, as shown in Figure 5.

In this study, we mainly investigate structural seismic vulnerability under the design seismic intensity and the rarely occurred seismic intensity at 7 degree[8]. For design seismic intensity of 7 degree, PGA is equal to 0.1g with the exceeding probability in 50 years of 10%.

Table4. Thresholds at each limit state.

Limit state (LS)	Operational (OP)	Slight Damage (SD)	Life Safety (LY)	Collapse Prevention (CP)
θ_{max}	0.0011	0.0024	0.0065	0.0116

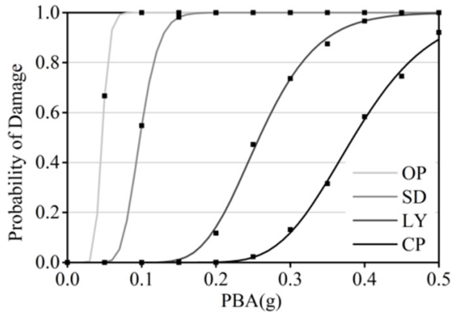

Figure 5. Seismic vulnerability curves

Table5. Exceeding probability at each limit state.

Seismic intensity	PGA(g)	PBA(g)	Limit state			
			Operational	Slight Damage	Life Safety	Collapse Prevention
Design seismic intensity at 7 degree	0.1	0.074	99.9%	11%	0%	0%
Rarely occurred seismic intensity at 7 degree	0.22	0.160	100%	99.2%	2.2%	0%

For rarely occurred seismic intensity of 7 degree, PGA is equal to 0.22g with the exceeding probability in 50 years of 2%. Then, we can calculate the corresponding mean value of PBA under specific seismic intensity and the exceeding probability of each limit state can be found through vulnerability curve in Figure 5, and the results are shown in Table 5.

It can be seen that the subway station structure may attain slight damage under design seismic intensity of 7 degree and the probability is 11%. When it comes to the rarely occurred seismic intensity at 7 degree, the subway station may attain life safety limit state with the probability of 2.2%. What's more, from the seismic vulnerability assessment result, the multi-storey subway station basically meets the design concept for underground structure that not damaged in medium earthquake and repairable in large earthquake.

4 Conclusion

In this study, seismic vulnerability assessment of multi-storey subway station is conducted based on incremental dynamic analysis. The results are as follows.

(1) There's apparent discrepancy of IDA curves with different ground motion input.

(2) The multi-storey subway station structure investigated may attain slight damage under design seismic intensity of 7 degree and the probability is 11%.

(3) When it comes to the rarely occurred seismic intensity at 7 degree, the subway station may attain life safety limit state with the probability of 2.2%.

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