APPLICATION OF INCREMENTAL DYNAMIC ANALYSIS TO SEISMIC EVALUATION OF UNDERGROUND STRUCTURE

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Abstract. *Based on the IDA method for seismic evaluation of superstructure, an IDA method for seismic evaluation of underground structure was proposed in this paper. The feature of IDA and its implementation procedures were introduced in detail. Combined with an engineering project, a two-dimensional finite element numerical model was proposed to analyze structural seismic response through finite element analysis software ABAQUS. 10 ground motion records were selected to provide sufficient accuracy in the estimation of seismic demands. Analysis result shows that IDA method can be applied successfully to underground structure and the difference between superstructure and underground structure using IDA method was also presented. Furthermore, the efficiency of different intensity measures was investigated. Two intensity measures were used, namely, Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and θ_{max} was selected as the damage measure. The analytical progress and results are helpful for the performance-based seismic design of underground structure and a wide application of IDA in other complex underground structures.*

1 INTRODUCTION

With the rapid development of science and technology, underground structure becomes more and more important in our daily life. Therefore, the security of underground structure under seismic loads should be ensured. In early years, many researchers believed that because of the restraint of surrounding soil, the seismic performance of underground structure could be better than that of superstructure. However, from the damage phenomenon in the earthquakes happened in recent years, we know that the existing underground structures are not security enough, which can also cause great earthquake damage sometimes. Especially in the Kobe earthquake at Japan in 1995, the Daikai subway station was suffered from serious earthquake damage, and more than 30 columns of the central section of the station completely collapsed over a total length of about 110m [1]. This event also aroused many researchers' awareness to do research on seismic performance of underground structure.

Nowadays, the concept of performance-based earthquake engineering is the most popular seismic design theory in recent years. This concept is also considered as the major guiding ideology for seismic design in the future. The aim of this concept is to make sure the structures designed can have the anticipative functions [2]. During the design life of architectural structure, specific performance levels should be provided when it endures different earthquake levels, which should also make the costs lower enough over the structures' life cycle.

There are several methodologies proposed to fulfill this aim, but undoubtedly, the most promising method is incremental dynamic analysis (IDA) or dynamic pushover, which can estimate the seismic performance of structures accurately and is of great contribution in performance-based earthquake engineering. It takes the old concept of scaling ground motion records and develops it into a way to accurately describe the full range of structural behavior, from elasticity to collapse [3]. In the concrete, IDA is a parametric analysis method, which involves performing a series of nonlinear dynamic analyses of a suite of ground motion records, each scaled to multiple levels of intensity, thus producing dynamic capacity curves of response parameterized versus intensity level. The concept has been provided as early as 1977 by Bertero [4], and has been used by several authors, such as Luco and Cornell [5, 6], Bazurro and Cornell [7, 8], Mehanny and Deierlin[9], Nassar and Krawinkler[10]. The method was well documented and introduced by Vamvatsikos and Cornell in 2000[11]. With the rapid spread of IDA among researchers all over the world, this method has already been used to many different kinds of structures in recent years, including the use to high-rise towers by Behrouz and Mahmood et al [3], the use to hybrid structure by Zhou Ying et al [12], the use to steel moment resisting frames by Behrouz and Hamideh et al [13] and the use to multi-column bridge bents by A.H.M and M. Shahria [14]. From the content mentioned above, we can find that IDA is mostly used to evaluate the performance of superstructure.

In this paper, IDA is applied to the underground structure. An introduction of the method of IDA is presented specifically and its available application to underground structure is shown through the representative example of Daikai subway station. The analytical process and results are helpful for the performance-based seismic design of underground structure and capacity estimation of underground structure.

2 INCREMENTAL DYNAMIC ANALYSIS

2.1 Basic concepts [11]

1. Original ground motion records:

The original ground motion records a_1 are selected from the ground motion database, which can represent the structure's site conditions.

2. Scale factor (SF)

The scale factor λ is a nonnegative number, which can produce ground motion a_λ with different intensity levels ranging from structure's elasticity to collapse by multiplying original acceleration time history a_1 . A value of $\lambda=1$ signifies the original record, $\lambda<1$ means a scaled-down record, while $\lambda>1$ is a scaled-up one. A common method is to determine one intensity level, which can be used for initial elastic analysis, and then enhance the intensity level one-to-one through multiplying the SF.

3. Intensity measure (IM)

Intensity Measure is a parameter that can signify the ground motion intensity and should be scalable. There are many quantities proposed to characterize the intensity of a ground motion record. Common examples of scalable IMs are the Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), the $\xi=5\%$ damped Spectral Acceleration at the structure's first-mode period ($S_a(T_1, 5\%)$), and the yield reduction R-factor, et al.

4. Damage Measure (DM)

Damage Measure or Structural State Variable is a parameter that can deduced from the output of the corresponding non-linear dynamic analysis. It can characterize the additional response of the structural model due to a prescribed seismic loading. Common examples of DMs are maximum base shear, node rotations, peak story ductility, various proposed damage indices (e.g. a global cumulative hysteretic energy), peak roof drift, the floor peak inter story drift angles, the maximum peak inter story drift angle.

The selection of a suitable DM depends on the application and the structure itself. For structural damage of frame buildings, $\theta_{\max}$ relates well to joint rotations and both global and local story collapse, thus becoming a strong DM candidate.

2.2 Basic steps

The basic steps of IDA described in FEMA-350/351 are [15, 16]:

1. Establish the calculation model which can be used for both elastic analysis and elastic-plastic analysis of the structure.
2. Choose the ground motion records which can be representative of events likely to cause severe ground motions in the site on which structures are located. Around 10 to 20 records are usually enough to provide sufficient accuracy in the estimation of seismic demands for mid-rise building [17]. Choose suitable IM and DM.
3. Get a series of ground motion records through monotonously scaling the original ground motion records.
4. A single-record IDA study, as shown in Figure 1(a). Choose a little scaled record for elastic time history analysis, getting the first point of IM-DM, which is denoted as Δ_1 ; the elastic slope of the ligature between the origin and Δ_1 is denoted as K_e ; continue dynamic analysis for the next scaled ground motion record to get the second point of IM-DM, which is denoted as Δ_2 ; if the slope of the ligature between Δ_1 and Δ_2 is larger than $0.2K_e$, continue elastic-plastic dynamic analysis for the next scaled ground motion record until the slope of the ligature between Δ_i and Δ_{i+1} is lower than $0.2K_e$, at which point the structure is considered being collapse. Δ_{i+1} is the ultimate value of DM; if Δ_{i+1} is larger than 0.1, the ultimate value of DM is considered as 0.10; the ligature of all points is the IDA curve.
5. Exchange the original ground motion record and repeat step3 and step4 to get an IDA curve set, which is a collection of IDA curves of the same structural model under different ground motion records, as shown in Figure 1(b). Conduct statistic according to a specific method and get the statistical IDA curves.

Figure 1: IDA curves.

3 THE APPLICATION OF IDA TO UNDERGROUND STRUCTURE

In order to show the available application of IDA to the underground structure, the Daikai subway station at Japan which suffered from strong seismic loads in 1995 is taken as a typical example according to the steps introduced above.

3.1 General profile [1]

The Daikai subway station was built between 1962 and 1964 by cut-and-cover which belongs to the privately owned Kobe Rapid Transit System. The distance between the station and the epicenter of the earthquake is about 15 km. The Daikai station can be divided into three sections as follows: (1) the main section of the station that collapsed; (2) the subway tunnels section with no severe damage occurred; and (3) the access station section that had two underground levels, where no severe damage occurred. The main structure considered in this paper is the first section, as shown in Figure 2. The rectangular reinforced concrete box is of 17m wide and 7.17m high, and the space of central columns is 3.5m in the longitudinal direction. The columns which are about 5m high had a rectangular reinforced concrete cross section of 0.4m by 1.0m. The soil condition applied in this paper can be got from the reference [19], which is shown in Table 1.

Figure 2: Section one that collapsed [1].

Soil layer	Depth(m)	Unit weight(t/m^3)	Shear wave velocity(m/s)	Poisson ratio
1	0~2.04	1.9	140	0.333
2	2.04~5.10	1.9	140	0.488
3	5.10~8.21	1.9	170	0.493
4	8.21~11.45	1.9	190	0.494
5	11.45~17.20	1.9	240	0.490
6	17.20~39.20	2.0	330	0.487
7	-	2.1	500	0.470

Table 1: Soil condition of the site where Daikai subway station is located.

3.2 Analytical modeling

The two dimensional finite element model with both soil and subway station is established according to the general profile mentioned above through the finite element software ABAQUS, as shown in Figure 3. To model the behavior of reinforced concrete accurately, both concrete damage plasticity model and steel model are all considered in this detailed numerical model. With the help of SHAKE, soil's equivalent linearization is considered. The boundary of soil in this model is considered through infinite element.

Figure 3: Finite element model.

3.3 Selection of ground motion records

The ground motion records selected from the ground motion database should be able to represent the structure's site conditions. According to the United States Geological Survey, USGS, the site condition can be divided into four groups, denoted as S_1 , S_2 , S_3 , S_4 respectively. The shear wave velocity of each group is greater than 750m/s, 360~750m/s, 180~360m/s and less than 180m/s in turn. The character of the site where Daikai subway station is located is similar to S_3 group. Therefore, the ground motions selected all come from S_3 group. As mentioned above in 2.2, ten to twenty records are usually enough to provide sufficient accuracy in the estimation of seismic demands [17]. Consequently, a set of ten ground motion records that belong to a bin of relatively large magnitudes of 7.5-8.0 and near-fault, all recorded on soil type S_3 are selected from the Pacific Earthquake Engineering Research Center [20], as shown in Table 2. The selected ground motions are effectively presumed to be able to cause severe ground motions in the site where structure is located.

No	Event	Station	Φ^{01}	Soil ²	M^3	PGA(g)	PGV(cm/s)
1	Kocaeli Turkey, 1999	ERD 99999 Duzce	DZC180	S_3	7.51	0.312	58.86
2	Kocaeli Turkey, 1999	ERD 99999 Duzce	DZC270	S_3	7.51	0.358	46.40
3	Kocaeli Turkey, 1999	KOERI 99999 Yarimca	YPT060	S_3	7.51	0.268	65.75
4	Kocaeli Turkey, 1999	KOERI 99999 Yarimca	YPT330	S_3	7.51	0.349	62.18
5	Chi-Chi, Taiwan, 1999	CWB 99999 CHY101	CHY101-E	S_3	7.62	0.353	70.64
6	Chi-Chi, Taiwan, 1999	CWB 99999 CHY101	CHY101-N	S_3	7.62	0.439	115.0
7	Chi-Chi, Taiwan, 1999	CWB 99999 TCU050	TCU050-E	S_3	7.62	0.147	36.91
8	Chi-Chi, Taiwan, 1999	CWB 99999 TCU050	TCU050-N	S_3	7.62	0.130	42.36
9	Denali, Alaska, 2002	TAPS Pump Station #10	PS10047	S_3	7.9	0.138	134.8
10	Denali, Alaska, 2002	TAPS Pump Station #10	PS10317	S_3	7.9	0.318	76.99

¹ Component

² USGS

³ Magnitude

Table 2: Set of ten ground motion records.

3.4 Selection of IM and DM

The most important issues to perform an IDA are selecting a suitable IM and DM. The basic principle of IM selection is to truly reflect the potential damage effect under seismic loads in the future and make the discrepancy of DM under different ground motions as small as possible. In this paper, Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), which are common examples of scalable IMs are selected. The spectral acceleration at the

structure's first-mode period $S_a(T_1, 5\%)$ may not be suitable for underground structure, which will not be discussed in this paper.

The basic principle of DM selection is to truly reflect the damage of structures, including the structural components, non-structural components and in-house facilities. This progress also depends on the application and the structure itself. As mentioned above, $\theta_{\max}$ relates well to joint rotations and both global and local story collapse, thus $\theta_{\max}$ is selected as DM in this paper.

In order to cover the entire range of the structural response from elasticity to global dynamic instability, the original ground motion records are scaled with the value of PGV as 10, 30, 50, 60, 70, 80, 90, 100 cm/s in turn. The model is conducted with one-way ground motion input of X axis along the structural plane. When it comes to PGA as IM, there is no need to do another large number of calculations, but just replace the value of PGV with the corresponding PGA and then get the IM versus DM curves.

3.5 IDA analysis results

IDA analysis of Daikai subway station subjected to ground motion is performed using ABAQUS software. IDA result of studied structure in terms of IM and DM is presented in Figure 4. The figures present the IDA curves for 10 ground motion records shown in Table 2.

Figure 4: The 10 IDA curves analysed.

As can be seen, for a specific numerical model, the IDA curves under different ground motion records have significant differences, especially the variation of slope. For example, the slope of curve (1-3) is decreasing gradually while the slope of curve (4) presents the trend of decreasing firstly, increasing secondly, and then decreasing. The latter phenomenon is due to period elongation or the so-called structural resurrection [11]. The slopes of the straight lines from the origin of the axes to the first IM-DM points on the graphs are referred to as the elastic slope. These trends mentioned above are nearly the same as IDA analysis results for the superstructure.

What is more, the IDA graphs also bring a fresh perspective to an important question of the effective IM choice for the underground structure. As mentioned above, IM selection is to make the discrepancy of DM under different ground motions as small as possible. Smaller dispersion of DM given IM implies that fewer nonlinear runs and a smaller sample of ground motion records are enough to estimate structure's performance. Therefore, a desirable property of a candidate IM is small dispersion. From the graphs in Figure 4, it is obvious that the latter produces a lower dispersion over the full range of DM values. PGV appears preferable to PGA for the subway station.

4 CONCLUSIONS

- IDA can be applied successfully to underground structure, especially the Daikai subway station. The trend of IDA curves for the underground structure is nearly the same as the superstructure.
- For the IM selection of underground structure, PGV is better than PGA for its smaller dispersion, which may also be the difference between underground structure and superstructure.

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