Energy response characteristics of a subway station structure based on probability density evolution method

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Abstract

Energy-based seismic design has been widely used in ground building structures. The vibration characteristics of underground structures are quite different from those of ground structures due to the constraints of surrounding soils. When energy-based seismic design is applied to underground structures, the energy response characteristics of underground structures should be defined first. Based on the probability density evolution method (PDEM), this paper studies energy responses (including plastic energy dissipation, elastic strain energy, and structural kinetic energy) of a multi-story subway station structure from the perspective of stochastic analysis. It is found that the change of kinetic energy, elastic deformation energy, and plastic energy dissipation is consistent with the trend of the intensity change of the earthquake motion. The distribution range of PDF of kinetic energy, elastic deformation energy and plastic energy dissipation becomes wider when the earthquake intensity is larger. Plastic energy does not dissipate all the input energy of the station structure, and the proportion of plastic energy dissipation is less than 1/3.

Keywords: Probability density evolution method, Subway station structure, Energy response, Stochastic earthquake

1 Introduction

In the 1995 Kobe earthquake, the subway station structure represented by Daikai Subway Station suffered serious damage [1][2], which gives rise to the seismic performance study of subway station structures [3][4].

Since Housner [5] put forward the energy analysis method of structural seismic response, the energy-based seismic design method has gradually been accepted and developed rapidly [6-11]. The response of structures to earthquakes is a process of energy input and dissipation. However, due to the constraints of surrounding soils around, the vibration characteristics of underground structures are not obvious, and the energy input and dissipation characteristics need to be further studied. Considering the randomness of ground motions, the energy input and dissipation characteristics of underground structures can be obtained more comprehensively by using the stochastic analysis method.

Based on the probability density evolution method (PDEM) and the idea of equivalent extreme value events, this paper studies the energy response of a multi-story subway station structure under stochastic earthquake from the perspective of stochastic analysis.

2 Numerical model

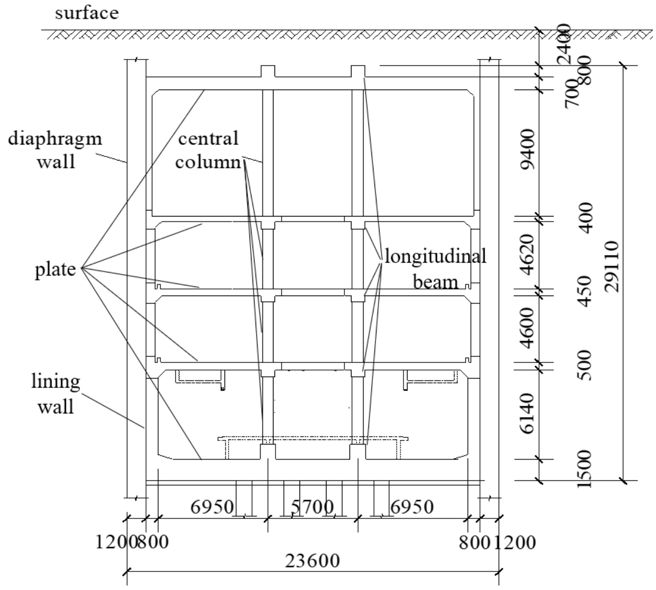

Figure 1. Standard cross section of the subway station, dimensions in mm

Figure 1 gives the standard cross section size of the multi-story subway station structure analyzed in this paper, which located in Shanghai, China. The width and height of the standard section of the our-story three-span island station is 23.6m and 29.1m, respectively, with buried depth of the roof of 3.2m. The inner lining wall is connected to the diaphragm wall through the embedded parts, thus both of them bear forces together and form the side wall. The longitudinal distance between columns is 8 m. According to "Chinese Code for Seismic Design of Urban Rail Transit Structures" [12], the shear wave velocity of the soil is 150m/s.

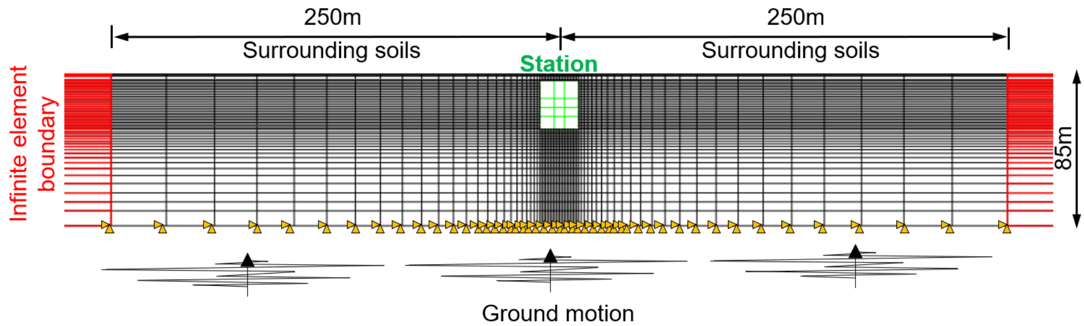

Figure 2. Numerical model of the underground subway station with surrounding soils

The plane-strain dynamic analysis model is established in the finite element code ABAQUS [13], which is shown in Fig. 2. Mohr-Coulomb constitutive model with Rayleigh damping is applied to the soil. The Poisson's ratio, internal friction angle, and cohesion is 0.3, 15˚, and 20kPa, respectively. Beam element, B21, is chosen for the structure. Central columns are made of C45 concrete and other parts of the structure are made of C35 concrete [14]. The concrete damaged plasticity model is adopted to better simulate the dynamic response of the structure, and the calculation of damage parameters has been done in previous studies [15][16]. Idealized elastic-plastic model was selected for rebar. Rebar used in central columns and other parts were HRB400 and HRB335, respectively, whose yield strength is 400MPa and 335MPa, respectively. The soil-structure interaction is defined by the Coulomb friction law, and the coefficient of friction is assumed to be 0.4.

In this paper, the depth of soil is 85m, and the single side width of the soil mass is 250 m, which is more than 3 times the structural width specified in "Chinese Code for Seismic Design of Buildings" [17]. To reduce the boundary effect, infinite element boundary is adopted as the lateral soil boundary [13], as shown in Fig. 2.

3 Process of PDEM

4.1 Numerical analysis process of PDEM

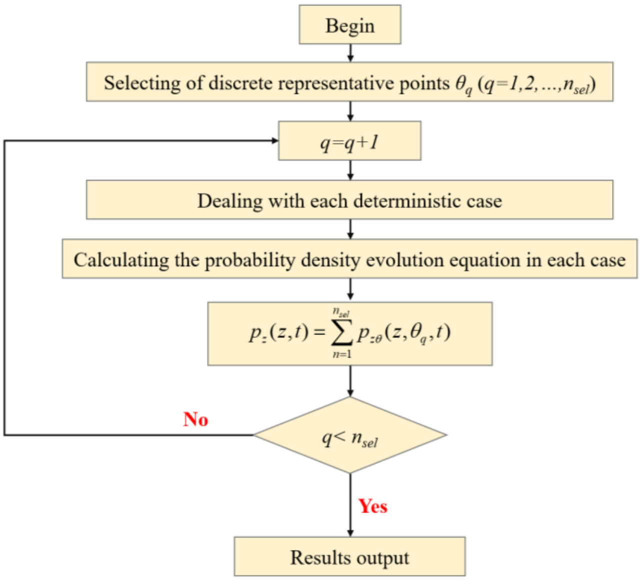

Figure 3. Basic steps of PDEM

Based on the principle of probability conservation, the PDEM is proposed by Li and Chen [14], and a relatively complete system of PDEM has been formed After more than ten years of development. The basic steps of stochastic response analysis of structures using PDEM are shown in Fig. 3. For more detailed contents of the method, please refer to the references [18] [19] and previous study [20].

In the numerical solution process of PDEM, the stochastic process of earthquake motion should be discrete in the probability space, then a certain number of stochastic earthquake motion samples are obtained. In this paper, Spectral representation - Random function method, which is proposed by Liu et al. [21], is used to simulate the random process of ground motion. 254 representative points are selected in the probability space, after that 254 earthquake motion samples are generated for the dynamic time history analysis. Relevant parameters are determined according to "Chinese Code for Seismic Design of Buildings" [17] for generating the ground motion samples. Figure 4 gives 3 typical ground motion samples.

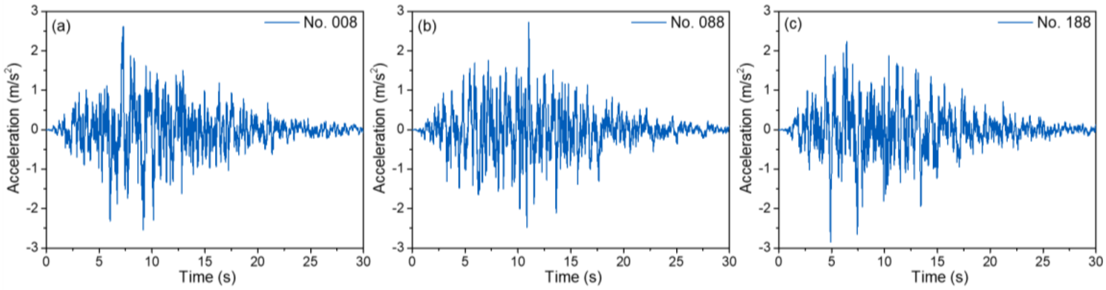

Figure 4. Typical acceleration time history samples

5 Results and analysis

The total input energy of the structure consists of three parts [6], as shown in the energy balance equation given by Eq. (1):

$$W_e + W_p + W_h = E \quad (1)$$

where, W_e is elastic vibration energy, W_p is cumulative plastic energy dissipation and W_h is damping energy dissipation. Elastic vibration energy can be divided into kinetic energy W_{ek} and elastic deformation energy W_{es}, as shown in Eq. (2):

$$W_e = W_{ek} + W_{es} \quad (2)$$

Damping of underground structures during earthquake is not clear, so this paper does not consider the damping of subway station structure at present. The kinetic energy, elastic deformation energy, and cumulative plastic energy of the structure are mainly studied.

4.1 Stochastic response analysis of energy response

Figure 5 (a-c) shows the probability density function (PDF) evolution contours of kinetic energy, elastic deformation energy and plastic energy dissipation of the structure, respectively, during earthquake.

The PDF evolution of kinetic energy with time is shown in Fig. 5 (a). From Fig. 5 (a), it can be seen that the PDF distribution of kinetic energy is highly concentrated near 0 kJ in the initial stage of the stochastic process (i.e. 0 < T < 2 s). This is because the amplitude of ground motion is very small at the beginning, which leads to the weak motion of structure. As time goes on, the amplitude of ground motion increases gradually, and the distribution range of PDF of structural kinetic energy is also increased. The PDF with the widest distribution range of structural kinetic energy is in the period of 7 < T < 17 s, which is within the period of strong amplitude of ground motion (i.e. 3 < T < 17 s). After 17 s, the amplitude of ground motion decreases gradually, and the distribution range of PDF of structural kinetic energy becomes narrower, which indicates that the magnitude of ground motion amplitude is closely related to structural kinetic energy. It is noteworthy that the distribution of PDF is not completely reduced to zero after the earthquake, which indicates that the structure is still in motion.

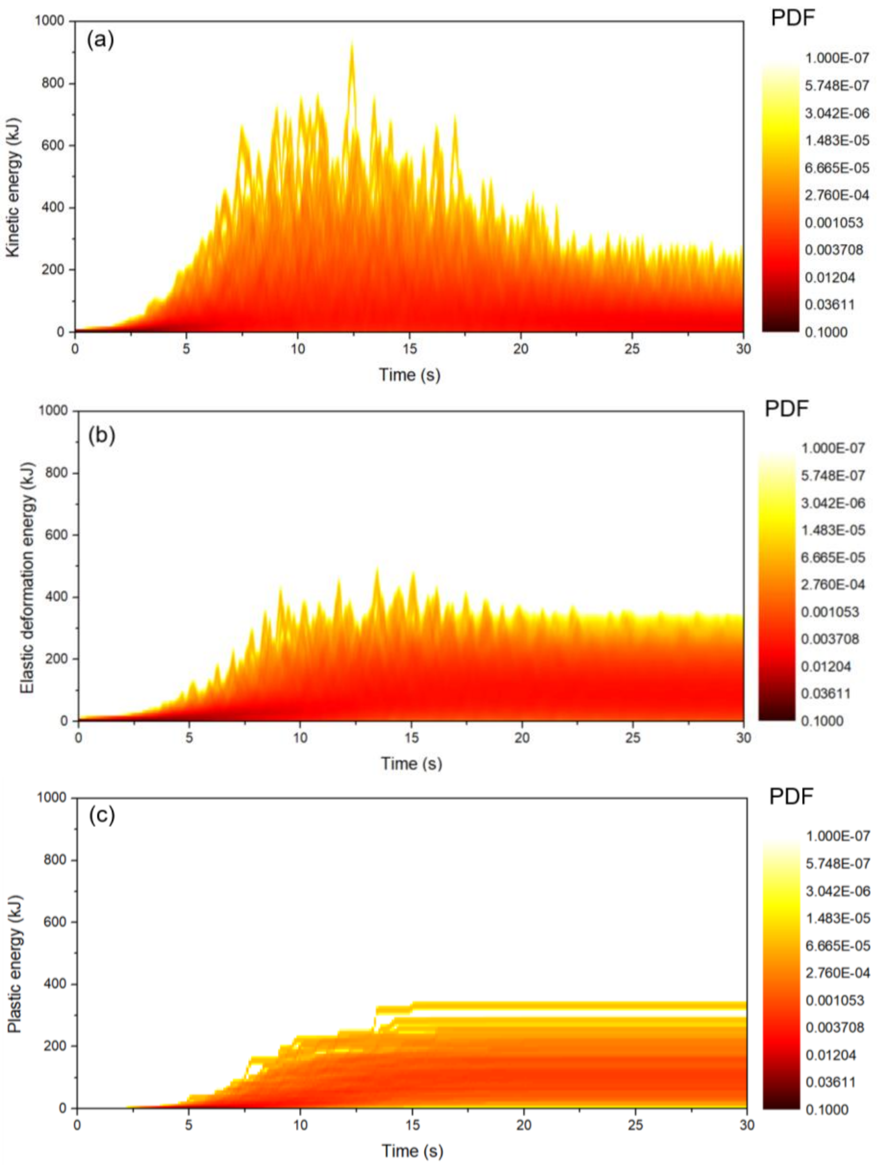

Figure 5. PDF evolution contours of (a) kinetic energy; (b) elastic deformation energy and (c) plastic energy dissipation of the structure

The PDF evolution of elastic deformation energy with time is shown in Fig. 5 (b). Similar to PDF of structural kinetic energy, it can be seen from Fig. 5 (b) that PDF of structural elastic deformation energy is highly concentrated in the vicinity of 0 kJ at the initial stage of ground motion, indicating that the elastic deformation of the structure is very small at this time. With the increase of ground motion amplitude, the distribution range of elastic deformation energy PDF becomes wider. In the period of large amplitude of ground motion ($3 < T < 17$ s), the PDF distribution range of elastic deformation energy is obviously narrower than that of kinetic energy at the same time. In the later period of earthquake ($T > 17$ s), the PDF distribution range of elastic deformation energy is narrower, but it basically changes little. This is because the structural deformation is controlled by the deformation of surrounding soil. The surrounding soil appears obvious deformation in the earthquake, which makes the structure store higher elastic deformation energy.

The PDF evolution of plastic energy dissipation with time is shown in Fig. 5 (c). The plastic energy dissipation increases monotonously with time. From Fig. 5 (c), it can be seen that the time period when the PDF distribution range of plastic energy dissipation of the structure changes is mainly in the range of 3 < T < 17 s, which is consistent with the time period when the earthquake amplitude is large. When T < 3 s and T > 17 s, the PDF distribution of plastic energy dissipation hardly changed. This indicates that plastic energy dissipation mainly occurs in the period of large earthquake amplitude.

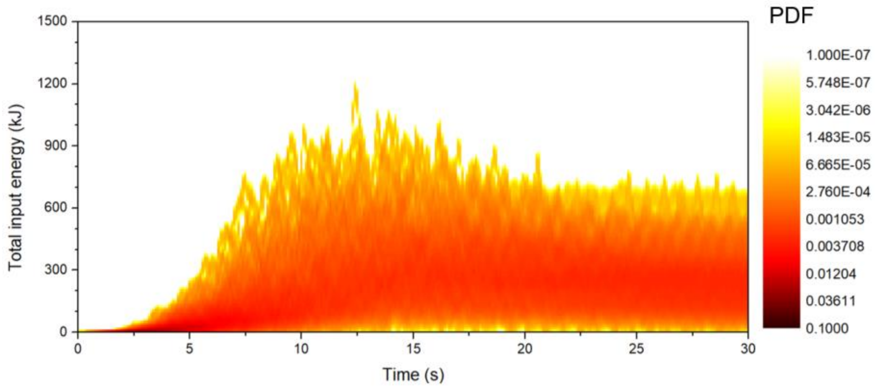

Figure 6. PDF evolution contours of total input energy of the structure

Figure 6 shows the PDF evolution contours of total input energy of the structure during earthquake. The total input energy is the sum of kinetic energy, elastic strain energy and plastic energy dissipation at the moment. From Fig. 6, it can be seen that the PDF distribution range of total input energy experienced a process of broadening (T < 15 s) and narrowing (T > 15 s). This indicates that plastic energy dissipation does not dissipate all the input energy of the station structure, and the rest of the energy probably dissipates into the soil through soil-structure interaction.

4.2 Extreme value analysis of energy response

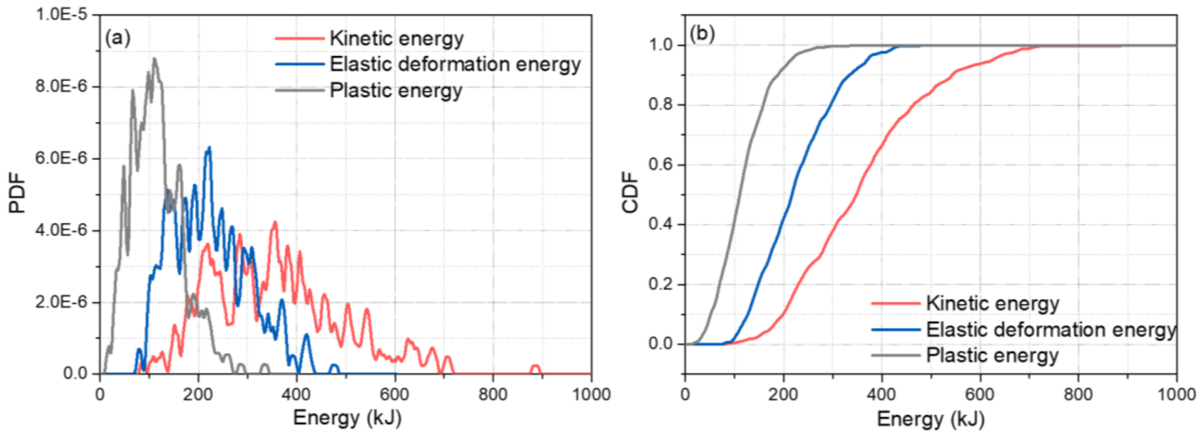

Figure 7. PDF and CDF curves of maximum energy during earthquake

Based on PDEM and the equivalent extreme event thought, the corresponding equivalent extremum events are constructed to calculate the distribution of extreme energy value of the structure under stochastic earthquake motion. Figure 10 gives the probability density function (PDF) and the cumulative probability function (CDF) of the maximum energy during earthquake. The extreme energy value corresponding to 50% CDF in Fig. 10 (b) is taken as representative value, and the corresponding representative extreme values of kinetic energy, elastic deformation energy and plastic energy dissipation are 348 kJ, 216 kJ, 110 kJ, respectively. It is indicated that plastic energy dissipation does not dissipate all the input energy of the station structure, and the proportion of plastic energy dissipation is less than 1/3. The rest of the energy probably dissipates into the soil through soil-structure interaction.

In terms of energy balance, two aspects can be considered to give advices to the seismic design of subway station structure. On the one hand, the total input energy of the structure should be controlled by improve surrounding soils. On the other hand, the proportion of plastic energy dissipation of structural components should be reduced by means of increasing the energy dissipated to the soil and reasonably arranging the energy dissipation components such as shear plate dampers (SPDs).

6 Conclusions

Based on PDEM and finite element elastoplastic dynamic time history analysis, the energy response characteristics of a multi-story subway station structure under stochastic earthquake motion are studied in the presented paper. The main conclusions are as follows:
(1) In a seismic process, the change of kinetic energy, elastic deformation energy, and plastic energy dissipation of subway station structure is closely related to earthquake intensity. The distribution range of PDF of kinetic energy, elastic deformation energy and plastic energy dissipation becomes wider when the earthquake intensity is larger.
(2) Plastic energy dissipation does not dissipate all the input energy of the station structure, and the proportion of plastic energy dissipation is less than 1/3. The rest of the energy probably dissipates into the soil through soil-structure interaction.

Acknowledgements

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