IOP Conf. Series: Materials Science and Engineering **452** (2018) 022109 doi:10.1088/1757-899X/452/2/022109

Influences of random phases of artificially synthesized earthquake waves on peak ground acceleration in soil-layer seismic response analysis

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Abstract. Application of artificially synthesized earthquake waves (ASEWs) is one of the main methods for determining the input ground motion in seismic response analysis at present. The research fit 3,000 earthquake waves of different random phases as the input ground motion at bedrocks. Based on the actual data about the type II sites in Beijing, the influences of random phases of the ASEWs on the peak ground acceleration (PGA) in soil-layer seismic response analysis were analyzed. The results indicated that 1) the PGAs in the soil-layer seismic response analysis of ASEWs were basically normally distributed under ground-motion input of different intensities; 2) as the intensity of ground-motion input increased, the discreteness of PGA caused by random phase of ASEWs became greater; 3) the influences of random phase on the PGA cannot be eliminated until there are more than 6 ASEWs. Moreover, the number of ASEWs needs to be increased at the same time as the intensity of the ground-motion input grows.

1. Introduction

The time-history input of ground motion is an inevitable requirement in the development of seismic design of structures. Due to the limited quantity of records of strong earthquakes, which cannot meet the requirement of many aspects, the application of artificially synthesized earthquake waves (ASEWs) has become the major approach for determining the input time history [1].

With the accumulation of records of strong earthquakes and engineering experience, the input ground motion for seismic design of structures has developed from the initial static loads, to response spectrum theory, and finally to the time-history input considering the whole earthquake process of ground motion.

Numerous scholars have studied the simulation of ground motion from various aspects including filtering of white noise, focal mechanism, and wave propagation approaches. Among them, the superposition method of trigonometric series method is the most widely used in actual engineering. The method follows the basic concept of constructing an approximately stationary Gaussian process using the sum of a group of trigonometric series which is then multiplied by the strength envelope function to obtain the non-stationary acceleration time history at bedrocks [2, 3].

According to the fitting technology of response spectrum proposed by Scanlan and Sachs and the research of Ohsaki on phase characteristics, Hu Lvxian *et al.* modified the fitting precision and principle of response spectrum. They not only considered the signs of contributions of each component of the Fourier spectra to the maximum response, but also proposed the phase correction theory for points not converging. The modification accelerates the convergence speed and makes the fitting technology more reasonable, so it has been widely used in the engineering field.

Although ASEWs supplement for the deficiency of actual ground motion data to some extent, their application probably leads to uncertainty to the final ground motion parameters owing to the randomness of the ASEWs. At present, it is stipulated in the *Evaluation of Seismic Safety for Engineering Sites* (GB17741-2005) that no less than 3 artificially fit earthquake waves are needed for engineering work in type II sites and micro-zones, so as to guarantee the reliability of the final ground motion parameters. However, it is found in real work that the ground motion parameters (such as peak ground acceleration (PGA)) determined by any several groups of three ASEWs differ greatly. Considering that the application of ASEWs is an irreplaceable method for determining input time history at present, it is necessary to research the uncertainty of ground motion parameters resulting from the random phase of ASEWs.

In the research, 3,000 earthquake waves were artificially synthesized. Then, by carrying out seismic response analysis using the non-dimensional equivalent linear method, the influences of random phases of ASEWs on the PGA in soil-layer seismic response analysis were analysed.

2. Calculation methods and research schemes

2.1. ASEWs

In the research, response spectra similar to those stipulated in the *Code for Seismic Design of Buildings* (GB50011-2010) were used as the standard target spectra to artificially synthesize 1,000 time histories of ground-motion acceleration individually with input seismic intensities of 50 gal, 100 gal, and 200 gal. That is, totally 3,000 earthquake waves were synthesized.

The normalized target response spectra fit using the synthesized ground motion were calculated using Formula (1) with the characteristic parameters listed in Table 1. Then, they were multiplied by the PGA Amax (50, 100, and 200 gal) at bedrocks to obtain the target response spectra of the fit time histories of ground-motion acceleration.

During the fitting, 66 cycles were selected from the target response spectra as control points of the fit target response spectra. The control points were in the period of 0.04–6.00 s, distributed roughly with equal intervals on a logarithmic scale. The relative error between the target response spectra and the response spectra of the synthesized time histories of ground motion should be smaller than 5%.

Some of the calculated target response spectra of ground-motion acceleration and the time-history curves of horizontal ground-motion acceleration are illustrated in Figure 1.

Table 1. Characteristic parameters of normalized target response spectra

Amax/gal	β_m	T_0	T_1	T_g	C
50	2.25	0.04	0.1	0.45	0.9
100	2.25	0.04	0.1	0.45	0.9
200	2.25	0.04	0.1	0.45	0.9

$$\beta(T) = \begin{cases} 1 & T \le T_0 \\ 1 + (\beta_m - 1)\dfrac{T - T_0}{T_1 - T_0} & T_0 < T \le T_1 \\ \beta_m & T_1 < T \le T_g \\ \beta_m (\dfrac{T_g}{T})^c & T > T_g \end{cases} \tag{1}$$

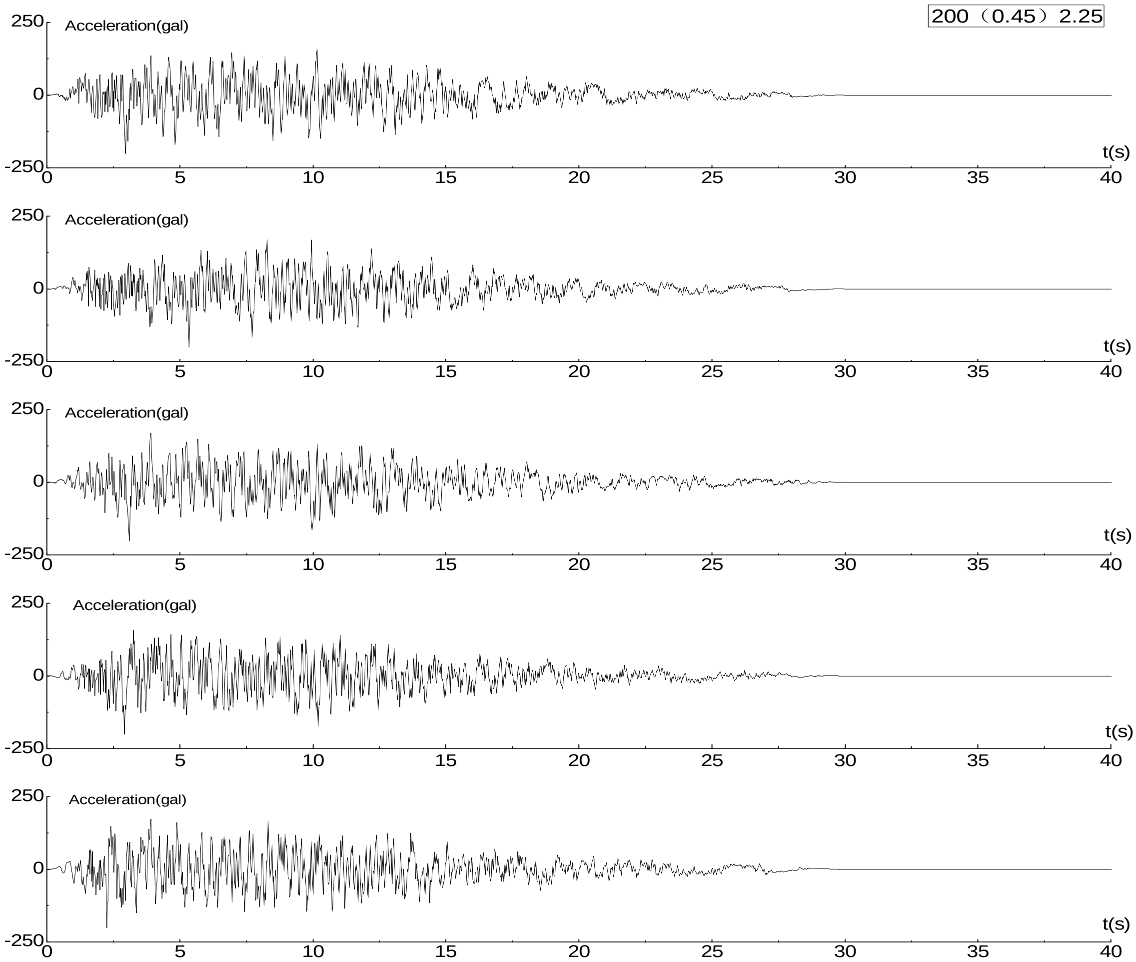

Figure 1a. Input time histories of horizontal acceleration (200 gal gal)

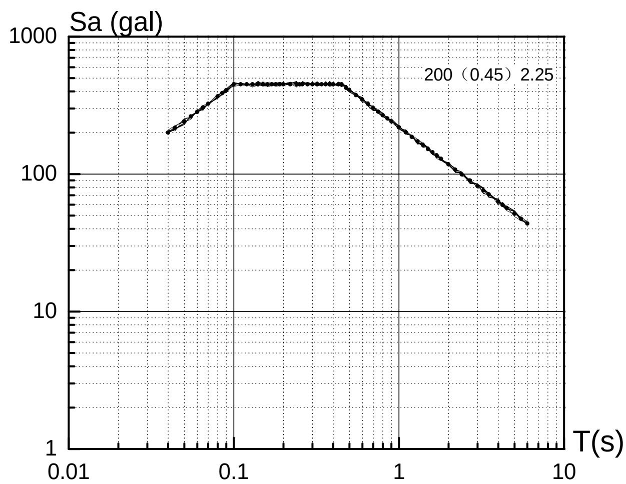

Figure 1b. Response spectrum of horizontal acceleration (200 gal)

2.2. Soil-layer seismic response analysis

To endow the statistical results with more practical meaning, the type II sites in Beijing were selected. Then, the seismic response analysis model of the sites was established based on the actual borehole data and the measured soil dynamics parameters. The selection of the sites follows the principle that the sites should have complete lithology description, complete test data of shear wave velocity and soil dynamics, and uniformly distributed thickness of soil layers at the boreholes. This is to ensure that the selected computation section is universally representative.

All soil densities on the selected section referred to the results of indoor soil test. The dynamics nonlinear parameters of soils, that is, dynamic shear modulus ratio and damping ratio, were taken from the results of soil dynamics test, with a small amount from the values recommended by the China Earthquake Administration and Yuan Xiaoping *et al.*

2.3. Research schemes

The amplitudes of the 3,000 artificially synthesized time histories of ground-motion acceleration at bedrocks were halved to serve as the ground-motion input at bedrocks of the soil-layer seismic response to carry out the seismic response analysis individually. On this basis, PGAs in the seismic response analysis of any 1,000 ASEWs under seismic impacts of different intensities were calculated and analysed, as well as the mean values of PGAs in the seismic response analysis of any 3, 6, and 9 ASEWs.

3. Calculation results and analysis

According to the numerous calculation results of seismic response, the influences of random phases of ASEWs on the PGA in soil-layer seismic response analysis under the ground-motion input of different intensities were analysed at first. Furthermore, the impacts of random phases of ASEWs on PGA in soil-layer seismic response analysis under the ground-motion input of same intensity were explored. On this basis, some suggestions were proposed for ASEWs in actual work.

3.1. Influences of random phase of ASEWs on PGA in seismic response analysis under the ground-motion input of different intensities

Figures 2 and 3 and Table 2 provide the statistical results of seismic response analysis for the sites with 3,000 ASEWs under the ground-motion inputs of different intensities. It can be seen that 1) the PGAs in seismic response analysis of any 1,000 ASEWs were basically normally distributed under the ground-motion input of different intensities; 2) the discreteness of the PGAs caused by random phase of the ASEWs became greater with the rising intensity of the ground-motion input.

Table 2. Statistical results of PGAs in seismic response analysis

Input Ground motion (gal)	Peak acceleration average (gal)	Peak acceleration deviation	Max	Min
50	59	3.34	71	49
100	112	6.82	134	90
200	210	13.83	247	171

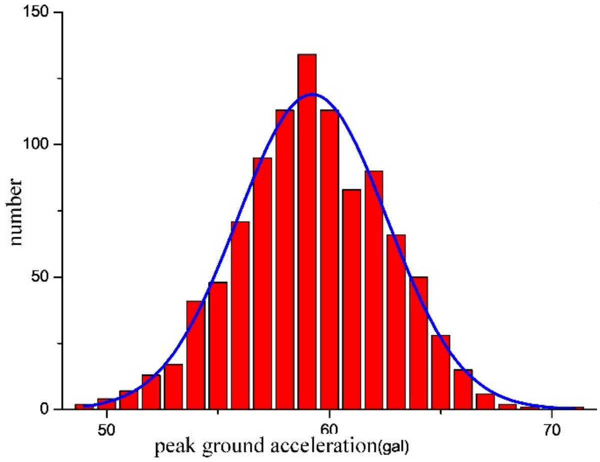

Figure 2a. Distribution of PGA values in seismic response analysis of ASEWs (input intensity: 50)

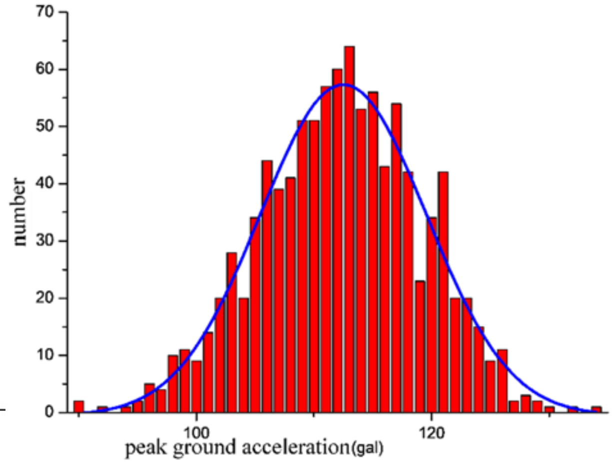

Figure 2b. Distribution of PGA values in seismic response analysis of ASEWs (input intensity: 100)

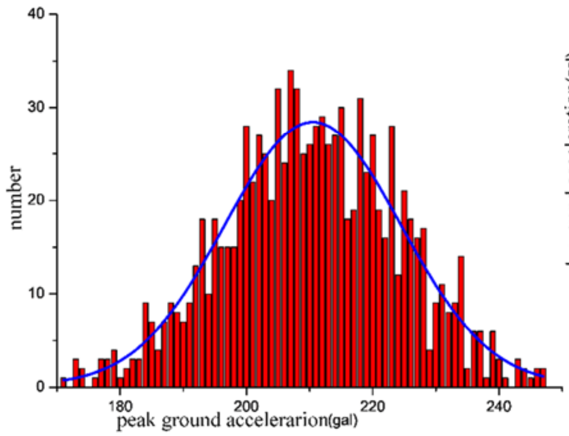

Figure 2c. Distribution of PGA values in seismic Response of analysis ASEWs (input intensity: 200)

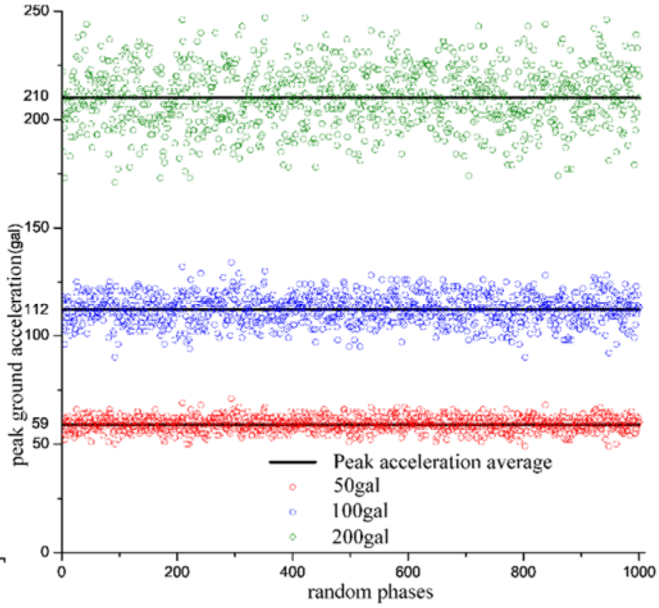

Figure 3. PGAs in seismic response analysis of ASEWs under the ground-motion inputs of different intensities

Table 3 lists the statistical results of the mean PGAs in the seismic response analysis of 3, 6, and 9 ASEWs, respectively under the ground-motion inputs of different intensities. It can be seen that 1) as the intensity of ground-motion input increased, the random phase of ASEWs led to more discrete PGAs; 2) with the increasing number of ASEWs, the discreteness of PGAs gradually reduced. Especially under weak ground-motion input, the discreteness can basically be ignored.

Table 3a. Statistical results of mean PGAs in seismic response analysis of any 3 ASEWs

Input intensity (gal)	Mean PGA (gal)	Standard deviation of PGA	Maximum	Minimum
50	59	1.96	64	53
100	112	4.03	124	99
200	210	8.27	235	189

Table 3b. Statistical results of mean PGAs in seismic response analysis of any 6 ASEWs

Input intensity (gal)	Mean PGA (gal)	Standard deviation of PGA	Maximum	Minimum
50	59	1.38	64	56
100	112	2.87	120	106
200	210	6.13	225	191

Table 3c. Statistical results of mean PGAs in seismic response analysis of any 9 ASEWs

Input intensity (gal)	Mean PGA (gal)	Standard deviation of PGA	Maximum	Minimum
50	59	1.05	62	57
100	112	2.20	117	107
200	210	4.68	220	199

3.2. Influences of random phase of ASEWs on the PGA in seismic response analysis under the ground-motion input of same intensity

Figure 4 compares the mean PGAs in seismic response analysis of any 3, 6, and 9 ASEWs under the ground-motion inputs of three intensities (50, 100, and 200 gal). By combining Table 3 and Figure 4, it can be seen that

1) The mean PGAs in the seismic response analysis of any 3, 6, and 9 ASEWs all showed certain discreteness, while the more the ASEWs, the lower the discreteness was.

2) As the intensity of ground-motion input grew, the difference in the discreteness also increased gradually.

3) Under the ground-motion input of medium intensity, the application of 6 ASEWs can basically guarantee the stability of PGA results in soil-layer seismic response analysis.

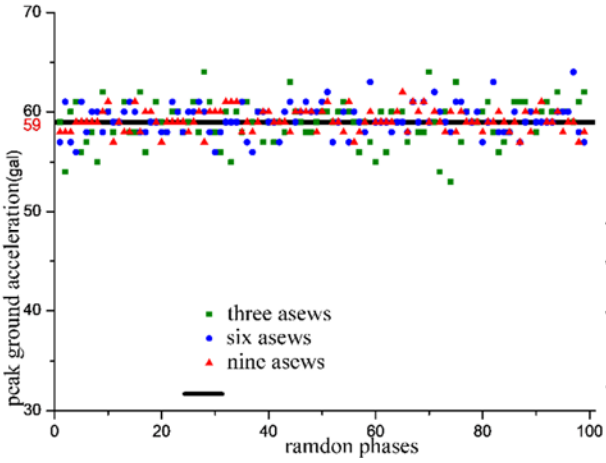

Figure 4a. Comparison of mean PGAs in the soil-layer seismic response analysis of any 3, 6, and 9 ASEWs (50 gal)

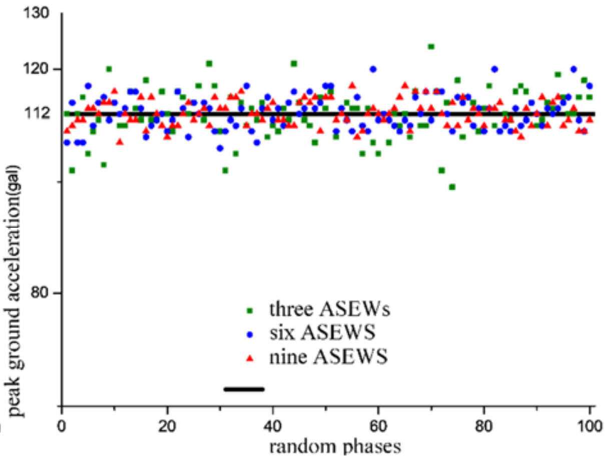

Figure 4b. Comparison of mean PGAs in the soil-layer seismic response analysis of any 3, 6, and 9 ASEWs (100 gal)

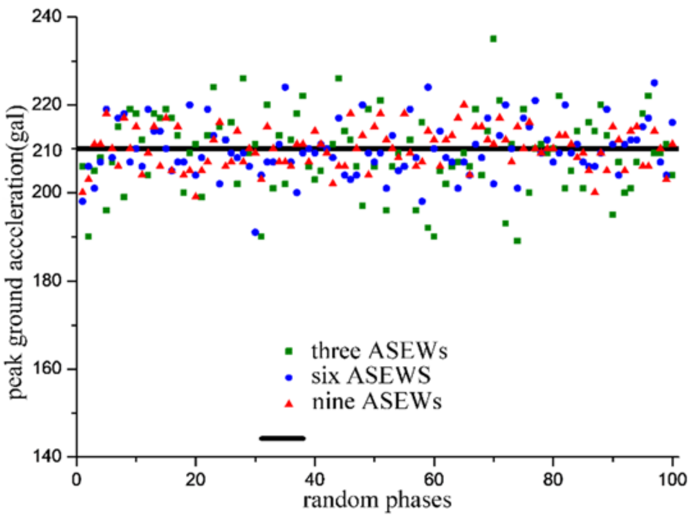

Figure 4c. Comparison of mean PGAs in the soil-layer seismic response analysis of any 3, 6, and 9 ASEWs (200 gal)

4. Conclusion

Based on the data about type II sites in Beijing, the research conducted seismic response analysis using the one-dimensional equivalent linear method with 3,000 ASEWs as the input ground motion at bedrocks. Then, the PGAs in the seismic response analysis of any 1,000 ASEWs under the ground motion of different intensities were calculated and analysed, as well as the mean PGAs in the seismic response analysis of any 3, 6, and 9 ASEWs.

According to the research results, it is suggested to use more than 6 ASEWs in actual work to guarantee the reliability of the final results of seismic response analysis. Moreover, with the rising intensity of the input ground motion, it is necessary to increase the number of ASEWs at the same time.

Acknowledgements

In this paper, the research was sponsored by research grant from Institute of Crustal Dynamics, China Earthquake Administration (No. ZDJ2018-11).

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