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SEISMIC RESPONSES OF STRUCTURES SUBJECTED TO ARTIFICIAL GROUND MOTIONS GENERATED USING 1D AND 2D GROUND MODEL

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SUMMARY

In this study ten spectrum-compatible artificial earthquakes with different seed numbers for random number generator subroutine are generated and used as the input for a two-dimensional soil stratum with a region of soil improvement. Both 1D and 2D ground motion analyses are performed and their differences in the ground motions on the surface of improved ground are investigated. The dynamic analysis of a ten-story building is then performed using the computed surface motions as input and the seismic responses of the building are compared. The surface ground motions of 2D analysis are larger than those of 1D analysis and the seed number has significant effects on the maximum story drift ratio. In the dynamic analysis of a building located on top of an improved soil zone, if the input ground motion is computed using 1D analysis, then the structural response will be underestimated. Thus, for such a case, the surface ground motion must be obtained using 2D analysis if the design ground motion is specified at the engineering bedrock. Also, the results of currently adopted averaging process given in the code are affected by how the samples are chosen and a clear guideline should be developed.

INTRODUCTION

In implementing a performance based design, it is required to select one or more performance objectives associated with different severities of earthquake. To ensure that the designed structure can meet these performance objectives, analytical techniques, which allow one to predict degrees of damage in the various elements based on the inelastic demands predicted for these elements, must be adopted. One method is the so-called pushover approach which consists of performing a series of incremental nonlinear static analyses on the structural model. It has been reported that if the response of the structure is dominated by first mode, this approach can give a reasonable estimate of inelastic demand distributions and damages in the structure; however, for long period structures, the estimate of damages made using this approach is poor [1]. The other method is the nonlinear dynamic time-history analysis which is more complex to perform and time-consuming and is deemed to be able to give accurate predictions if assumed constitutive relation for structural elements reflects their true behavior.

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However, in the nonlinear dynamic analysis a time history of earthquake motion must be selected to serve as the input for the analysis. As stated in FEMA368 [2], the earthquake motion actually recorded at the site can be used as the input motion for the analysis; however, if there is no recorded earthquake motion, the artificial earthquake motion generated by enveloping the design spectrum can also be adopted. In Japan, the newly developed performance-based seismic design code for buildings, instead of providing the design forces, gives two design spectra at engineering bedrock [3]. Thus, due to the lack of strong ground motion records at sites, in most nonlinear dynamic time-history analyses, the spectrum-compatible artificial earthquake ground motion has to be generated.

Pappin et. al [4] investigated the effects of site response on performance based design for 2 levels of input seismic ground motion and 3 different actual soil profiles using nonlinear 1D ground model. They found that regardless of the soil type of the site, the performance based design will cause the ‘no collapse’ requirement to dominate the seismic design in the regions of low to moderate seismicity, while in the regions of high seismicity, the ‘immediate occupancy’ requirement will dominate the seismic design for low period structures located on soft or loose soil sites. The performance-based seismic design code for buildings in Japan, in addition to giving the design spectra at engineering bedrock, it also provides the design spectrum at ground surface which is also derived using 1D soil profile [3]. Although using 1D model to compute the surface ground motions is easy to implement, it has long been recognized both from theoretical analyses and field observations that the surface topography, subsurface topography, lateral inhomogeneities in the properties of the site can alter the motions significantly, as compared with that of 1D model which assumes the soil layers to be horizontal [5,6,7,8], and their effects on the seismic responses should be examined, since in the performance based design the input motion plays an important role in verifying the design for different performance objectives. Thus, in this study a ground with a zone of soil improvement is selected which is modeled as a 2D finite element model and a 1D finite element model, respectively. The spectrum-compatible artificial earthquake motion is then generated to serve as the input motion for the finite element model to obtain the surface ground motions which are subsequently used as the input motions for the seismic response analyses of the buildings. The differences between the ground motions generated using 1D and 2D ground models and their effects of the seismic responses of a ten-story building are then explored.

METHODOLGY

The methodology adopted in this study consists of three stages: (1) the design spectrum specified at the engineering bedrock is selected and the artificial earthquake motions compatible with this spectrum is generated, (2) the ground motion generated in step (1) is then used as the input for surface ground motion calculation, and (3) nonlinear dynamic time-history analysis is subsequently performed using the surface motion computed in step (2) as input. Each step is described in the followings.

Generation of artificial earthquakes

Many methods have been proposed for generating artificial earthquakes. In this study the one adopted is to express the acceleration in terms of complex exponentials as

$$a(t) = f(t)\sum_{k=0}^{n} A_k \exp(i\omega_k t + \phi_k) \tag{1}$$

where a(t) is the acceleration, A_k the kth Fourier amplitude, ϕ_k the kth Fourier phase angle, ω_k the selected frequency and f(t) the envelope function which approximately envelops the time history of the entire earthquake record and represents the nonstationary property of earthquake motion. Conventionally, in applying this equation to generate spectrum-compatible artificial earthquake, the ω_k is chosen arbitrarily to cover the entire frequency range of the design spectrum and ϕ_k is obtained by using the random number uniformly distributed over the range $(0,2\pi)$. During the iterative process, the quantities $\omega_{k,}$ ϕ_k and f(t) remain unchanged, while only the A_k is adjusted so that the response spectrum of the generated artificial earthquake motion can envelop the design spectrum. However, Ohsaki [9] pointed out that for a given earthquake record, close correlation can be found between shape of the distribution of the difference of Fourier phase angles for any two consecutive frequencies and the wave-shape of an earthquake motion; in other words, the shape of the distribution of the difference of Fourier phase angles for any two consecutive frequencies has the same shape as f(t). Therefore, in his so-called "phrase difference method", the independent random numbers are assigned for the desired numbers of phase difference and assuming ϕ_1=0, the kth Fourier phase angle is then computed using

$$\phi_{k+1} = \phi_k + \Delta\phi_k \qquad k=0,1,.2,\ldots..n-1 \qquad (2)$$

Shown in Fig. 1 is the shape of the distribution of the difference of Fourier phase angles adopted in this study; in the figure, T_R is the rise time to reach the full amplitude, T_L is the time to decrease the amplitude, T_D is the duration of the motion and NDIF is the number of the intervals used to obtain the corresponding accumulated function. This approach do not need to multiply f(t) as shown in equation (1) and is shown to have the uniform convergence. In this study, a program NCUARTEQ [10] based on the "phase difference method" is developed and used for generating the spectrum-compatible earthquake motions. It is also noted that we adopt the criterion listed in [11] where the calculated response spectrum of the artificial earthquake is considered to envelop the design spectrum when no more than five points below, and no more than 10% below the design spectrum.

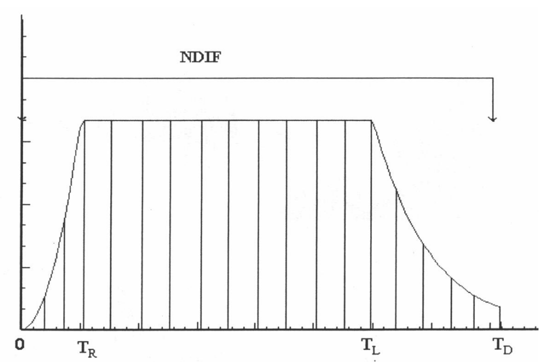


Figure 1 Distribution of phase difference

Seismic ground response analysis

In this study the seismic ground response is computed using the program NCULIQUID2 [12] which is a two-dimensional nonlinear effective stress finite element program based on Biot's equations. In this program the soil displacement and the pore pressure can be obtained directly from the solutions of equations. The constitutive relation for soil is the cap model [13] and the pore pressure model is the one proposed by Pacheco et. al [14], which is developed based on cap model. In addition, viscous boundary accounting for two-phase nature of soil is used to model the lateral infinite extent of soil stratum [15].

Dynamic analysis of building

The nonlinear dynamic analysis of building in this study is performed using the program Raumoko 2D which is developed by Prof. Carr of University of Canterbury [16]. This program is versatile and can perform the static analysis, linear and nonlinear dynamic time-history analysis, modal analysis and static push-over analysis.

DESIGN SPECTRUM AND ANALYTICAL MODEL

The Level 2 design spectrum at engineering bedrock given in the performance-based seismic design code for buildings in Japan is adopted. This spectrum is defined as follows.

$$0.64 \le T < 5.0 \qquad S_0 = 512/T \tag{3a}$$

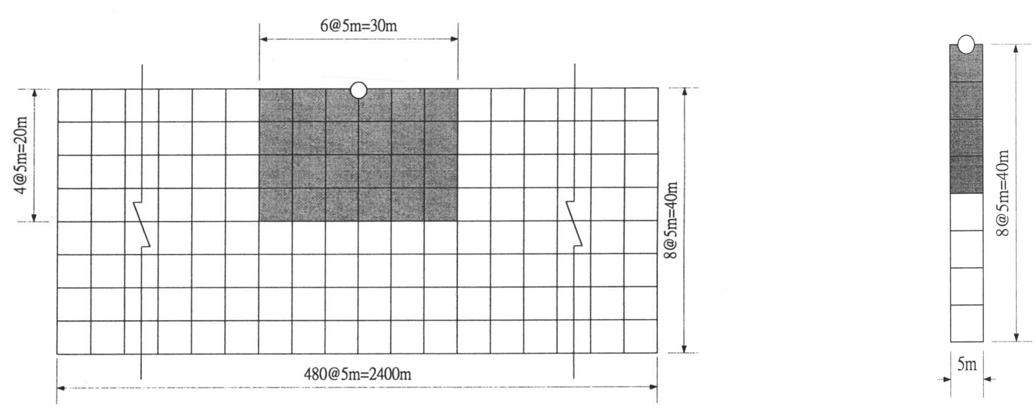
$$0.16 \le T < 0.64 \qquad S_0 = 800 \tag{3b}$$

$$T < 0.16 \qquad S_0 = 320 + 3000T \tag{3c}$$

Shown in Fig. 2a is the hypothetical two-dimensional ground model employed in this study. The shaded region is the improved construction site and the improvement is made such that its shear wave velocity changes from 170m/sec to 300m/sec. The depth of soil stratum is 40m and the width of improvement region is 30m. In the analysis the width of the entire model is taken as 2400m. Also shown in Fig. 2b is the one-dimensional finite element ground model. In this analysis the one-dimensional ground is represented by one column of plane strain elements with the same equation number being assigned to each degree-of-freedom on the same horizontal planes [17]. The circle in the figure is the location where the ground motion is used as the input for the dynamic analysis of building. Table 1 describes the parametric values of the ground model.

Table 1 Parametric values for soil stratum

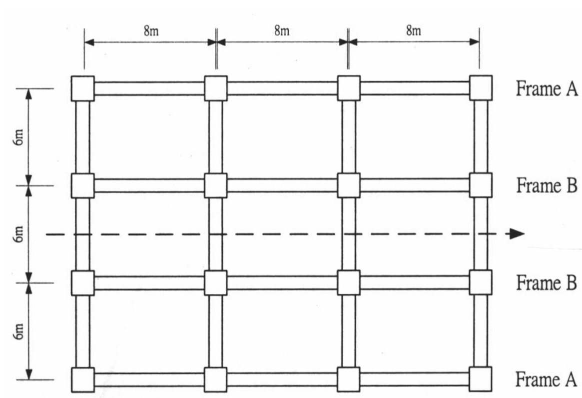
parameter	Original soil	Improved soil
Shear-wave velocity (m/sec)	170	300
Poisson ratio	0.44	0.46
Mass density (t/m^3)	1.9	2.1
Cohesion (kN/m^2)	12	100.5
Friction angle (degree)	10	26.7
Cap model parameter R	4.0	1.6
Cap model parameter W	0.18	0.18
Cap model parameter D (1/kN)	$5x10^{-6}$	$5x10^{-6}$



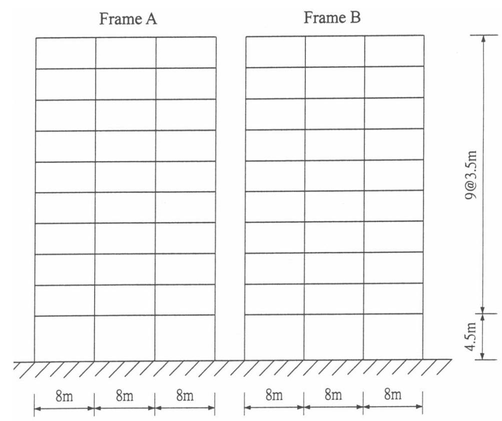
(a) 2D ground model **(b) 1D ground model**

Figure 2 Finite element model of ground

The building investigated is a 10-story building which has 3 bays on each side. Except the first-story which has a height of 4.5m, all other stories have the same height of 3.5m. This story is designed according the seismic design code in Taiwan and has been used in other study [18]. Figure 3 shows its plane view and side view. Only the dynamic analysis of the fames in the long direction is conducted. In the analysis the frames A and B are connected together in the same plane and all the joints on the same horizontal planes are declared to have the same degrees of freedom to simulate the rigid diaphragm and 3 dimensional behavior of the building. The bi-linear behavior is assumed for the nonlinear behavior of the members and the joints are taken as rigid. The periods of the first two modes are 1.582 seconds and 0.5651 seconds, respectively. The Rayleigh damping with 5% damping for the first two modes are used.



(a) top view



(b) side view

Figure 3. Building model

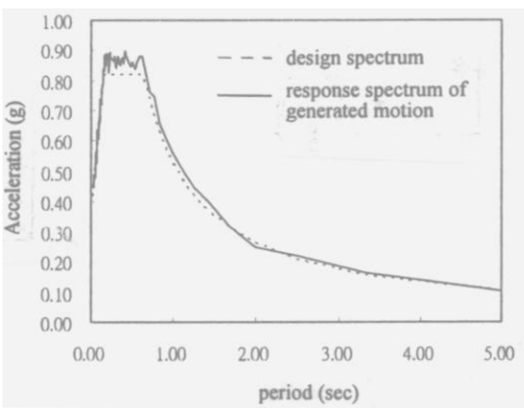
RESULTS AND DISCUSSIONS

It is known that there are infinite number of artificial earthquakes which can be generated to envelop the same design spectrum. In order to investigate effect of these earthquakes on the seismic responses of buildings, we generate ten artificial earthquakes using the following number as the seed numbers for the random number generator subroutine: 10579, 123, 130579, 2223, 2459, 290197, 5791, 6079, 7983 and 8953. The T_R, T_L , T_D and NDIF as shown in Fig. 1 are 5.0 seconds, 15.0 seconds, 20.48 seconds and 100, respectively. Shown in Table 2 are the maximum accelerations and their corresponding time for the ten earthquakes. It can be seen that the time to reach the maximum acceleration varies significantly with the seed number, indicating that the seed number plays an important role in generating the spectrum-compatible artificial earthquakes. Figure 4 shows the response spectrum computed by the artificial earthquakes using seed number 10579 and 123, which envelop the design spectrum denoted as dash line.

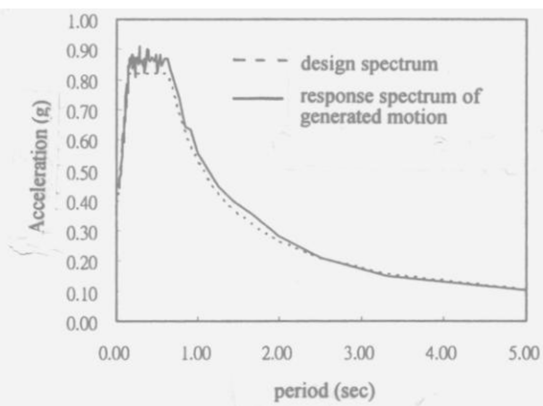
In the seismic ground analysis the 1D analysis is frequently performed because of its easy implementation. However, in the case where a portion of ground is improved, the 1D condition is violated and whether the 1D analysis is still applicable needs further investigation. Shown in Fig. 5 are the response spectra computed from the surface motions on the surface of improved soil zone, as described in the previous section, which are obtained using 1D and 2D analysis. It can be seen that the response spectra computed using ground motion from 2D analysis are influenced by the seed numbers. For the case using seed number 123, the peak value is at period of 1 second, while for the case using seed number 130579 its peak value is at period about 0.4 seconds; in addition, the significant difference can also be observed for the peak values. On the other hand, the response spectra of 1D analysis are very different from those of 2D analysis with the spectral values of 2D analysis being much greater than those of 1D analysis for period below about 3 seconds. The reason for such a difference is that in 1D analysis the improved soil zone is assumed to extend laterally to infinity and during the strong earthquake most of the wave energy is trapped at the bottom soft soil region and dissipated by the nonlinear soil behavior; for 2D analysis the improved soil zone is surrounded by soft soil region and “floats” on top of the soil stratum during strong earthquake, resulting in larger ground motions. Thus, this indicates that for the case of soil stratum with an improved zone and the surface ground motion is desired over that zone, it will be inappropriate to perform the 1D ground motion analysis.

Table 2 Maximum acceleration and time of occurrence for different seed numbers

Seed number	Maximum acceleration(gal)	Time (sec)
10579	-339.97	13.80
123	381.19	9.05
130579	-387.32	10.12
2223	-345.84	11.45
2459	391.29	9.66
290197	-364.75	10.01
5791	-357.89	12.35
6079	-369.72	4.89
7983	338.99	11.70
8953	-371.79	14.12



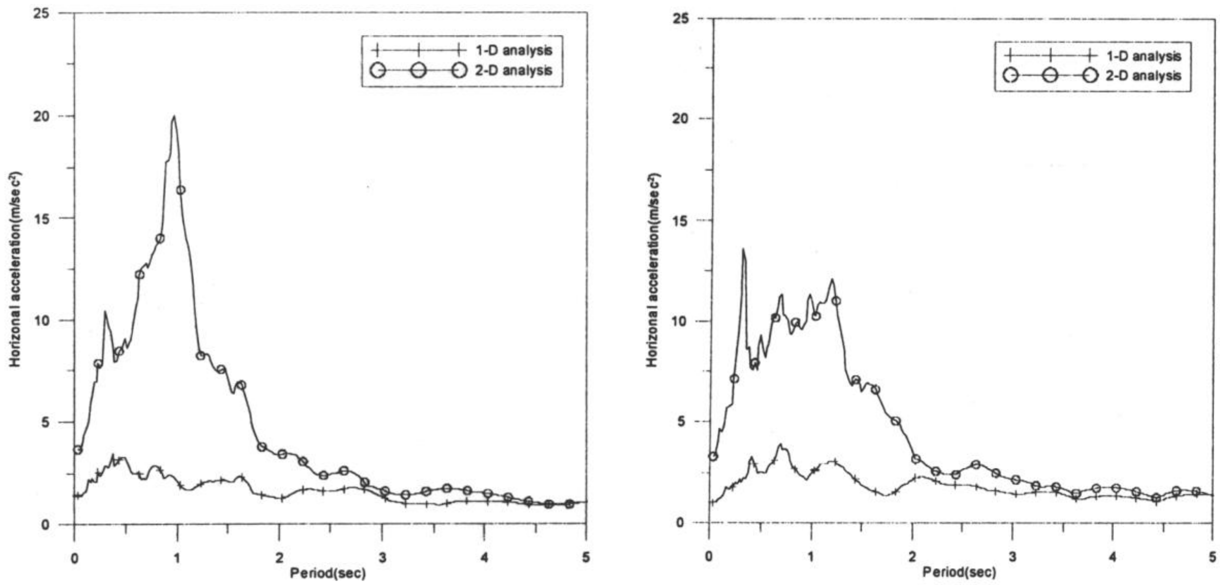
(a) seed number 10579



(b) seed number 123

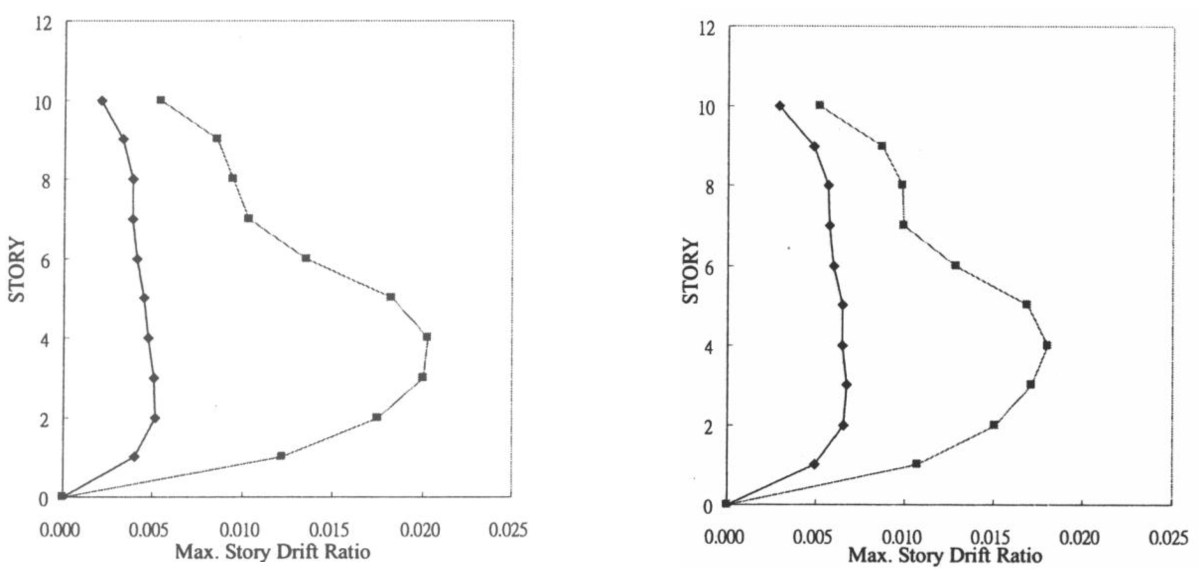
Figure 4 Design spectrum enveloped by generated artificial earthquakes

Figure 6 depicts the maximum story drift ratio for the ten-story building described in the previous section using the surface ground motions computed from 1D and 2D analysis as the input motions. In the figure the dash line in the figure is the result using the ground motion from 1D analysis and the solid line is the result using the ground motion from 2D analysis. Again it can be seen that the seed number affects the seismic responses significantly. In addition, larger response is obtained using the ground motion computed from 2D analysis, the difference being about 3 times. This clearly indicates that in the dynamic analysis of a building located on top of an improved soil zone, if the input ground motion is computed using 1D analysis, then the response will be underestimated. Thus, for such a case, the surface ground motion must be obtained using 2D analysis if the design ground motion is specified at the engineering bedrock.



(a) seed number 123 (b) seed number 130579

Figure 5 Response spectra of surface ground motion from 1D and 2D analyses

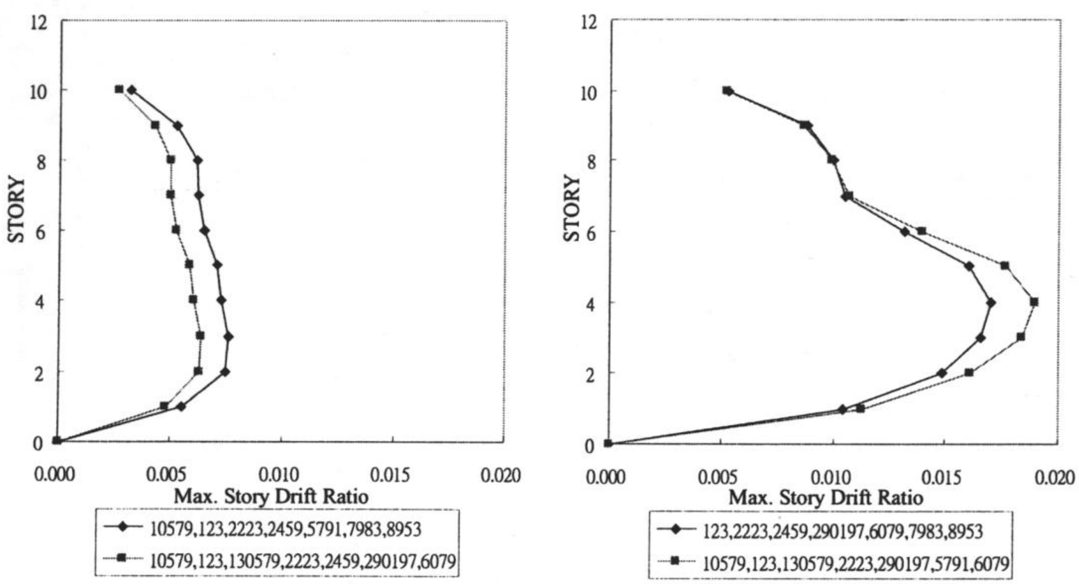


(a) seed number 123 (b) seed number 130579

Figure 6 Maximum story drift ratio using motions computed from 1D and 2D analysis

As discussed previously, the seismic responses of building are influenced by the seed numbers. That is, although the response spectra of different artificial earthquakes envelop the design spectrum, the seismic response of building will be different. In order to overcome such discrepancies, it has been suggested that the seismic responses from analyses using several artificial earthquakes be averaged. In this study, since we have generated ten artificial earthquakes, we arbitrarily choose seven responses and average them.

Shown in Fig. 7 are the average values of maximum drift ratio subjected to 1D and 2D ground motion, respectively. In the figure the solid line is the average result using the seed numbers 10579, 123, 2223, 2459, 5791, 7983 and 8953, and the dash line is the average result using the seed numbers 10579, 123, 130579, 2223, 2459, 290197 and 6079. It can be observed that the differences are larger for case subjected to 1D ground motion than that subjected to 2D ground motion. This implies that the results of currently suggested averaging process are affected by how the samples are chosen and thus a clear guideline should be developed.



(a) 1D ground motion (b) 2D ground motions

Figure 7 Average values of maximum drift ratio using 1D and 2D ground motion

CONCLUSIONS

In this study ten spectrum-compatible artificial earthquakes with different seed numbers for random number generator subroutine are generated and used as the input for a two-dimensional soil stratum with a region of soil improvement. Both 1D and 2D ground motion analyses are performed and their differences in the ground motions on the surface of improved ground are investigated. The dynamic analysis of a ten-story building is then performed using the computed surface motions as input and the seismic responses of the building are compared. The surface ground motions of 2D analysis are larger than those of 1D analysis and the seed number has significant effects on the maximum story drift ratio. In the dynamic analysis of a building located on top of an improved soil zone, if the input ground motion is computed using 1D analysis, then the structural response will be underestimated. Thus, for such a case, the surface ground motion must be obtained using 2D analysis if the design ground motion is specified at the engineering bedrock. Also, the results of currently adopted averaging process given in the code are affected by how the samples are chosen and a clear guideline should be developed.

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