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Seismic response of a continuous foundation structure supported on partially improved foundation soil

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ABSTRACT

The response of a continuous foundation structure supported on partially improved foundation soil was recorded during an earthquake. The measured results show that partially improved foundation soil can induce torsional response of the foundation due to the irregular soil-foundation system. A numerical model considering soil-structure interaction was then established, and the numerical results were compared with the observation data. Using the validated numerical model a parametric study was carried out to investigate the torsional response of a continuous foundation structure with irregular soil foundation system. It can be concluded from the study that eccentricities in the soil foundation system would result in a torsional response. Particularly with different lengths of soil-cement piles in the partially improved foundation soil, the generated torsional response can not be ignored during the seismic excitation.

1. Introduction

Continuous foundation structures, such as mat or raft foundation, are frequently employed together with subsoil improvement to support medium-rise buildings. In recent years, seismic reports have pointed out that structure failures due to torsional response are common during seismic excitation [1] and that torsional motion can aggravate building failures [2]. Consequently, extensive studies have been performed to understand the torsional behavior of structures. Chandler [3] presented a detailed parametric study of the coupled lateral and torsional response of a partially symmetric single storey building model subjected to both steady state and earthquake base excitations. It was concluded that torsional coupling induces a significant amplification of earthquake forces which should be accounted for in their design. De-La-Llera and Chopra [4–6] calculated the value of the accidental eccentricity with the equivalent lateral force procedure by investigating the dynamic response of single and multistory buildings subjected to torsional ground motion. Nagarajaiah et al. [7,8], using multi-story models, concluded that the isolation system eccentricity as well as superstructure asymmetry both contributed to the torsional response. Similarly Jangid and Datta [9,10] found that significant eccentricity of the superstructure could reduce the effectiveness of the base isolation system. In Ten-Colunga et al. [11–13], parametric studies where the torsional response of base-isolated structures when eccentricities are set in the isolation system or in the superstructure were presented. Nonlinear dynamic analyses were used to study peak responses for different static eccentricity ratios between the center of mass and the center of rigidity, due to asymmetries in the stiffness of the isolators or in the superstructure. It can be concluded from the study that eccentricities in the isolation system or in the superstructure lead to a torsional response that adversely affects the design of the isolation system. In general, the amplification factors for the maximum isolator displacement of the un-symmetric system with respect to the symmetric system increase as the eccentricity increases. Most of these studies assumed base fixity in the structural models, neglecting the soil structure interaction (SSI).

Some studies show that soil structure interaction may considerably influence the dynamic response of the structures subjected to earthquake loading [14–16]. Dynamic response of a structure was carried out in the frequency domain [14] by using the fast Fourier transform to obtain the structural response of torsionally asymmetric buildings, including soil structure interaction effects. The results indicated that the earthquake response of a soil-torsionally coupled structure interaction can be significantly different from that calculated with a fixed base model. Mohasseb and Abdollahi [15] employed the cone models in two actual projects including soil structure interaction, it was observed that the equivalent damping of the superstructure increase of 32% in

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comparison to the fixed base structure. Further, the period of the superstructure, including soil, increased from 0.3 s to 0.32 s. Lin et al. [16] presented an input/output (I/O) selection concept to extract the dynamic parameters of an irregular building superstructure considering both torsional coupling (TC) and soil-structure interaction (SSI) effects. This approach was applied to assess the change of dynamic properties of the superstructure of two instrumented buildings using measurements recorded before and after the 1999 Chi-Chi, Taiwan earthquake. It was shown that the decrease in value of the modal frequencies will be overestimated if the soil structure interaction effects were neglected. However, SSI analyses are rarely carried out for the seismic design of building structures due to the direct numerical analysis requires a high computational effort, performing an analysis considering SSI is computationally uneconomical for regular design applications [17].

Neglecting SSI in the seismic response analysis of building structures may result in a false torsional response of the structure. In many cases, fixed-base analyses cannot predict accurately the torsional response of building structures, particularly when the buildings are constructed with irregular soil foundation systems. Previous studies on the torsional responses of structures did not take into account the possible contribution from irregular foundation-soil system. In this study, accelerometers were installed in the free field and on the continuous foundation structure supported on foundation soil that was partially improved by cement-soil piles. The dynamic response of the soil-structure system was recorded during an actual earthquake. Results of the observation data combined with the simulation results from a numerical parametric study were employed to evaluate the behavior of irregular foundation soil systems.

2. Description of the structure and foundation

The subject structure is a base isolated four-story reinforced concrete frame structure. The superstructure is supported on rubber base isolators that rest on spread footings. The spread footings are connected to one another by reinforced concrete beams. Isolators are bolted firmly to the superstructure and spread footings. The isolation system and superstructure are regular in elevation and symmetric with respect to two main orthogonal axes. The superstructure is 99 m long and 50 m wide, represented herein as the x and y directions, respectively. Fig. 1a shows the side view of the superstructure. Stiffness of the structure in the x, y and torsional directions are depicted in Table 1.

The connected spread footings are embedded 4.5 m below grade, and its plan dimensions are 52 × 104 m. Subsoil investigation before structure construction showed that 75% of the area under the foundation (shadow area in Fig. 1b) may liquefy during strong ground motions. Soil liquefaction, which results from a build-up of excess pore water pressures in loose saturated soils, leads to an almost complete loss of strength and stiffness of soil. In order to reduce the potential hazards posed by soil liquefaction, cement-treated ground improvement technique was employed in the shadow area. The ground improvement consists of 2203 cement-soil piles with diameter D = 1.0 m, length L = 7 m, and center-to-center pile spacing S = 1.3 m. Parallel-Seismic (PS) test and boring investigation were carried out in the improved-area and the non-improved-area, the results of which are depicted in Table 2.

3. Field instrumentation

Immediately after construction, the foundation structure and the free field were permanently instrumented with accelerometers.

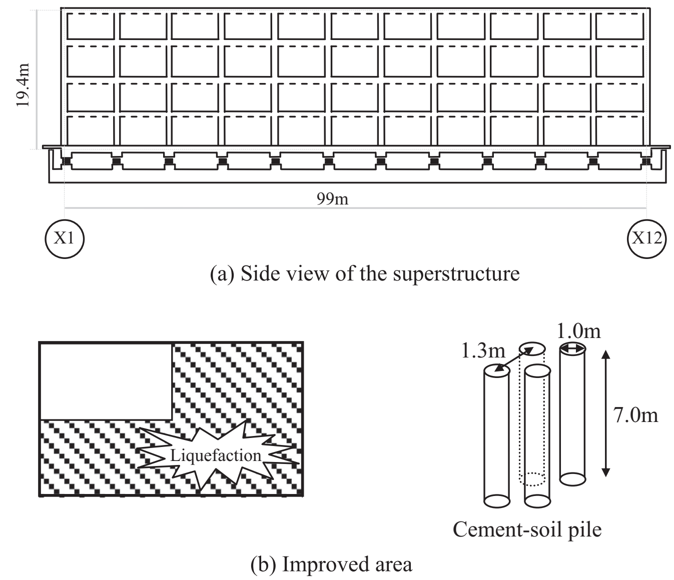


Fig. 1. Sketch of the ground improvement.

Table 1
Stiffness values of the superstructure and isolation system.

	x (10^{10}N/m)	y (10^{10}N/m)	Torsion (10^{13}Nm/rad)
Isolation	0.42	0.42	0.92
First–Fourth floor	1.79	1.78	3.32

In order to capture the horizontal and torsional responses of the foundation structure, two uni-directional horizontal accelerometers were installed orthogonally at the center of the foundation, and another one uni-directional horizontal accelerometers were placed at the center of the east edge, as shown in Fig. 2. Two uni-directional horizontal accelerometers were installed in the soil adjacent to the building to observe free field response. The locations and detail information of the accelerometers are shown in Fig. 2. Symbol gr, bm indicates the freed field and the foundation, respectively. Symbol cc, ce represents the overall center and the center of the east edge.

The horizontal response of the foundation is obtained through the accelerometers located at the center of foundation, and the torsional response (U_T) of the foundation structure can be calculated as $U_T = (U_{ce} - U_{cc})/L$, where U_{ce} is the horizontal response at the center of the east edge, U_{cc} is the horizontal response at the center of the foundation structure, and L is the distance between the two instrumented locations.

4. Foundation responses in an actual earthquake

On July 21, 2010, a magnitude 5.1 earthquake occurred in Naraken province of Japan, at 34.21° North latitude and 135.69° East longitude. Focal depth of the earthquake is 58 km. This earthquake induced ground accelerations less than 7 gals at the base of the foundation. Some characteristics of the records shown in Fig. 3 are summarized in Table 3. The generated torsional response of the foundation during the earthquake is shown in Fig. 4.

Table 2
Parameters of the soil and cement-soil pile.

0.00m	Depth GL:(-m)	Vs m/s	Density 10^3kg/m^3	Poisson ration
	0.00 ～ 1.50	160	1.80	0.410
	1.50 ～ 1.95	160	1.70	0.410
	1.95 ～ 5.30	250	2.00	0.357
	5.30 ～10.00	210	1.80	0.456
	10.00～13.95	310	2.00	0.459
	13.95～16.95	270	1.90	0.486
	16.95～20.30	220	1.90	0.491
Soil	20.30～25.25	270	2.00	0.486
	25.25～32.70	300	2.10	0.483
	32.70～38.70	280	1.80	0.484
	38.70～44.55	280	1.70	0.484
	44.55～49.35	420	2.10	0.474
	49.35～58.50	710	2.10	0.448
	58.50～62.00	500	2.10	0.468
	62.00～67.00	540	2.10	0.463
	67.00～68.75	330	1.70	0.479
	68.75～71.50	330	1.90	0.479
71.50m	71.50～75.00	300	1.80	0.483
Cement-soil Pile		820	2.00	0.300

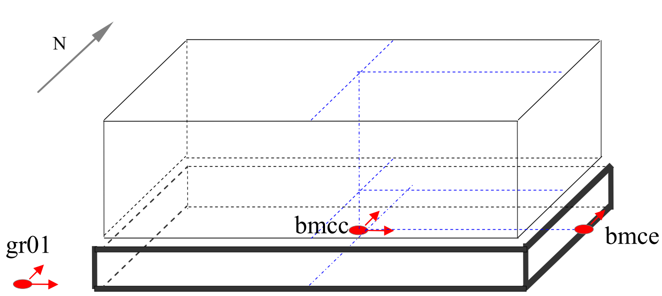


Fig. 2. Locations of accelerometers.

5. Numerical model

5.1. Methodology

A sub-structure method [18–20] with due consideration of soil structure interaction was employed in the numerical model. The equation of motion of the soil-structure system can be described as:

$$\left(\begin{bmatrix} [S_{SS}] & [S_{SB}] \\ [S_{BS}] & [S_{BB}] \end{bmatrix}\right)\begin{Bmatrix} \{u_S\} \\ \{u_B\} \end{Bmatrix} = \begin{Bmatrix} \{F_S\} \\ \{F_B\} \end{Bmatrix} \tag{1}$$

where, $[S] = [K] - \omega^2[M]$, $[K]$, $[M]$, $[u]$ and $[F]$ are the stiffness matrix, mass matrix, displacement vector and force vector, respectively. The degrees of freedom of the super-structure and the foundation-soil system are identified with the subscript S and B. Based on the sub-structure method [18–20] as shown in Fig. 5, the $[S_{BB}]$ matrices can be decomposed as:

$$[S_{BB}] = [S_{BB}]_G - [S_{BB}]_E + [S_{BB}]_F \tag{2}$$

where, the subscript G, E and F represents the free field, the excavated soil and the foundation-pile system, respectively. $[S_{BB}]_G$ is calculated by thin layered method [21,22]; the stiffness matrices of the foundation and corresponding excavated soil are calculated by

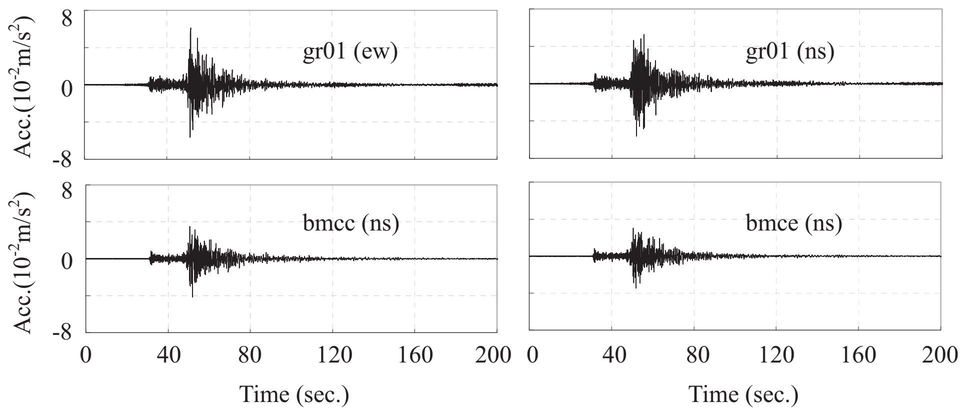


Fig. 3. Selected acceleration records.

Table 3
Amplitude of the selected acceleration records.

Direction	gr01 (10^{-2} m/s^2)	bmcc (10^{-2} m/s^2)	bmce (10^{-2} m/s^2)
ew	6.13	6.06	
ns	5.61	4.15	3.45

three dimensional solid elements; and the stiffness matrices of the cement-soil piles and the corresponding excavated soil piles are calculated by beam elements. Substitution of Eq. (2) into Eq. (1), the equation of motion of the soil- structure system based on flexible volume method can be described as:

$$\left(\begin{bmatrix}[S_{SS}] & [S_{SB}] \\ [S_{BS}] & [S_{BB}]_G - [S_{BB}]_E + [S_{BB}]_F\end{bmatrix}\right)\begin{Bmatrix}\{u_S\} \\ \{u_B\}\end{Bmatrix} = \begin{Bmatrix}\{F_S\} \\ \{F_B\}\end{Bmatrix} \tag{3}$$

Through the procedure described above, the response of the structure and foundation considering SSI can be obtained.

For the soil-foundation system shown in Fig. 5a, subscript F and O are used to denote the degrees of freedom of the footings and those of the others. Thus, the equation of motion of the soil foundation system can be written as:

$$\begin{bmatrix}[S_{FF}] & [S_{FO}] \\ [S_{OF}] & [S_{OO}]\end{bmatrix}\begin{Bmatrix}\{u_F\} \\ \{u_O\}\end{Bmatrix} = \begin{Bmatrix}\{F_F\} \\ \{F_O\}\end{Bmatrix} \tag{4}$$

Decomposing Eq. (4) leads to:

$$\{u_O\} = -[S_{OO}]^{-1}[S_{OF}]\{u_F\} + [S_{OO}]^{-1}\{F_O\} \tag{5}$$

$$\{u_F\} = -[S_{FF}]^{-1}[S_{FO}]\{u_O\} + [S_{FF}]^{-1}\{F_F\} \tag{6}$$

Substituting Eq. (5) into Eq. (6) results in:

$$([S_{FF}] - [S_{FO}][S_{OO}]^{-1}[S_{OF}])\{u_F\} = \{F_F\} - [S_{FO}][S_{OO}]^{-1}\{F_O\} \tag{7}$$

If the footings are assumed to be rigid and mass-less, vectors $\{u\}$ and $\{F\}$ can be used to denote the footing displacements and their external forces, respectively. By introducing the coordinate transformation matrix $[T]$, the following relationship can be obtained:

$$\{u_F\} = [T]\{u\} \tag{8}$$

$$\{F\} = [T]^T\left(\{F_F\} - [S_{FO}][S_{OO}]^{-1}\{F_O\}\right) \tag{9}$$

where $[T] = \left[[T]_1 \ [T]_2 \ \cdots \ [T]_i \ \cdots \ [T]_N\right]^T$ and $[T]_i$ can be expressed as:

$$[T]_i = \begin{bmatrix} 1 & 0 & 0 & 0 & z_i - z_o & -y_i + y_o \\ 0 & 1 & 0 & -z_i + z_o & 0 & x_i - x_o \\ 0 & 0 & 1 & y_i - y_o & -x_i + x_o & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

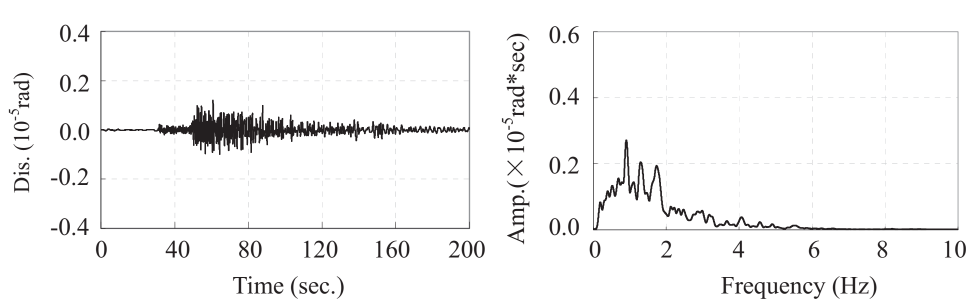
where, $(x_i \ y_i \ z_i)$ is the coordinate of node i of a footing, and $(x_o \ y_o \ z_o)$ is the coordinate of the geometrical center of the foundation.

Substituting Eqs. (8) and (9) into Eq. (6) yields:

$$[K]\{u\} = \{F\} \tag{11}$$

where, $[K] = [T]^T\left([S_{FF}] - [S_{FO}][S_{OO}]^{-1}[S_{OF}]\right)[T]$.

Through Eq. (11), the response of the footings $\{u\}$ can be described as:



(a) Time domain (b) Frequency domain

Fig. 4. Torsional response of the foundation.

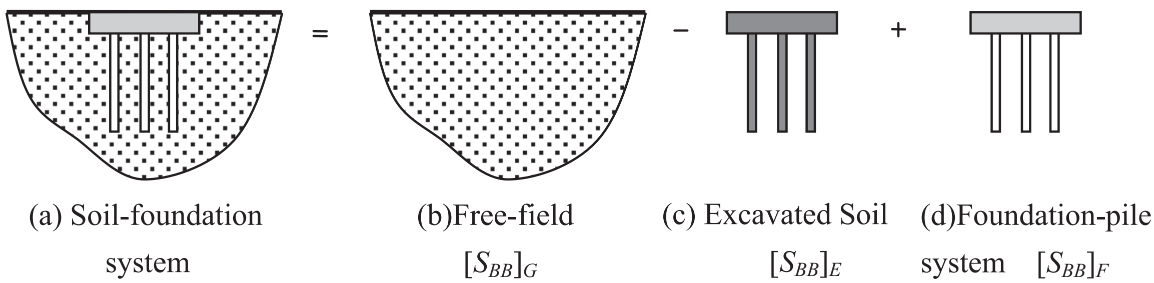


Fig. 5. Soil foundation model based on the flexible volume method.

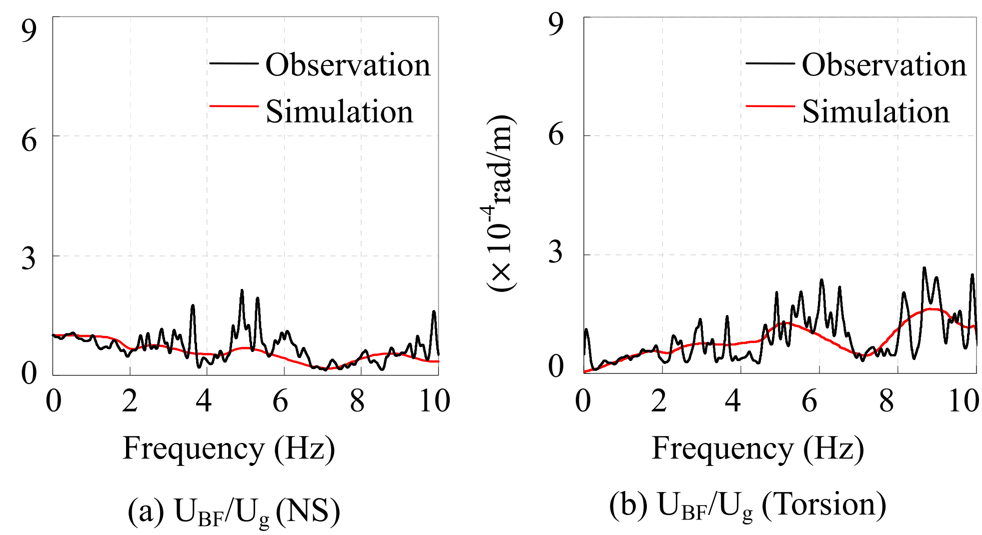


Fig. 6. The transfer function of the soil-foundation system.

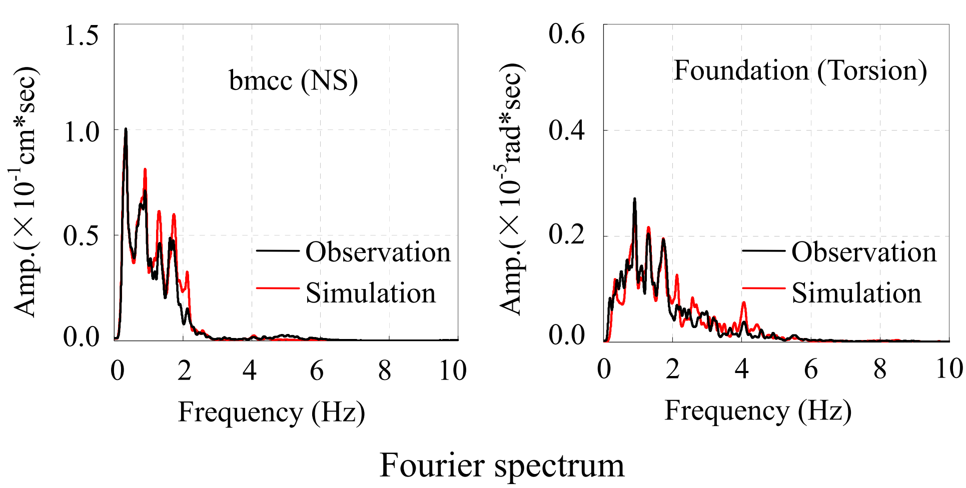


Fig. 7. The displacement response of the foundation in Frequency domain.

$$\{u\} = [K]^{-1}[T]^{T}\left(\{F_F\} - [S_{FO}][S_{OO}]^{-1}\{F_O\}\right)$$

It is assumed that the input motion to the footings is the same as the one in the free field. Therefore $\{F_F\} = \{F_F\}_G$ and $\{F_o\} = \{F_o\}_G$, thus, the foundation input motion $\{u^o\}$ can be described as:

$$\{u^o\} = [K]^{-1}[T]^{T}\left(\{F_F\}_G - [S_{FO}][S_{OO}]^{-1}\{F_O\}_G\right) \quad (12)$$

5.2. Comparison between observed and numerical responses

The recorded and simulated transfer functions in the NS and torsional directions are shown in Fig. 6. It can be seen that the numerical model was able to reproduce the observed responses satisfactorily. Figs. 7 and 8 show the comparisons between the recorded and simulated displacements of the foundation structure in both horizontal and torsional directions. A good agreement is

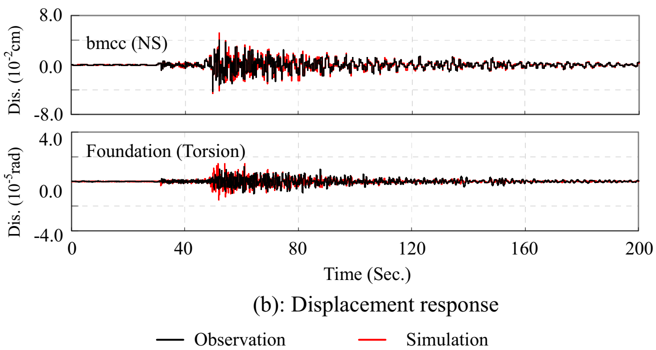


Fig. 8. The displacement response of the foundation in time domain.

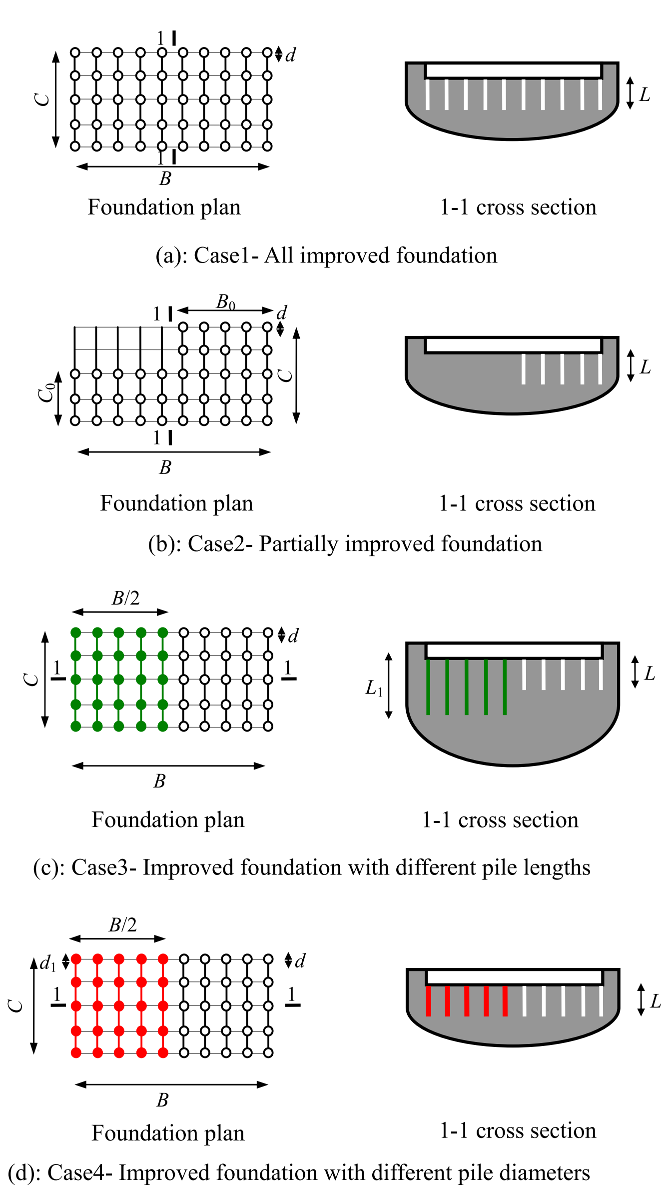


Fig. 9. Irregular soil-foundation systems.

achieved. The aforementioned sub-structure method can therefore be used to analyze the responses of a structure supported on partially-improved foundation soil under small earthquake loading.

It is observed that for a regular structure supported on partially-improved foundation soil, torsional motion can be generated in the foundation structure even with small earthquake loading. Such torsional motion may adversely affect the dynamic behavior of the superstructure. It is therefore important to understand the effect of irregular foundation soil on the torsional response of the foundation structure, which is the objective of the following parametric study.

Note: BF-the foundation of the building, g-the free field of the foundation.

Table 4
Parameters of the foundation.

Case1: All improved foundation	$B = 104$ m	$C = 52$ m
	$L = 7$ m	$d = 0.5$ m
Case2:	Case2a:	$B/B_0 = 2$
Partially improved foundation		$C/C_0 = 2$
	Case2b:	$B/B_0 = 3$
		$C/C_0 = 3$
Case3:	Case3a:	$L_1/L = 2$
Improved foundation with two different cement-soil pile lengths	Case3b:	$L_1/L = 3$
Case4:	Case3a:	$d_1/d = 2$
Improved foundation with two different cement-soil pile diameters	Case3b:	$d_1/d = 3$

6. Parametric study

The parametric study focused on the torsional response of continuous and regular foundation structure supported on partially improved foundation soil subjected to regular horizontal earthquake loading. Superstructures are not included in the numerical models. For all the cases discussed in this section, normal incident SH wave from the bottom of the foundation soil is used as an excitation source, the frequency of the excitation wave is range from 0.1 Hz to 10 Hz.

6.1. Embedded foundation supported on cement-soil piles

In order to investigate the impact of irregular soil-foundation system to the torsional response, the following cases were investigated:

(1) Case1: the soil below the embedded foundation was all improved by cement-soil piles with equal pile lengths and diameters;
(2) Case2: the soil below the embedded foundation was partially improved by cement-soil piles with equal pile lengths and diameters;
(3) Case3: the soil below the embedded foundation was all improved by cement-soil piles with different pile lengths but same pile diameters;
(4) Case4: the soil below the embedded foundation was all improved by the cement-soil piles with different pile diameters but same pile lengths.

Fig. 9 shows the illustrations of these cases and Table 4 presents their parameters of soil improvement. To better understand the lateral and torsional response, the following ratios were investigated: U_1/U_g, U_6B_1/U_g. Here U_1 is the lateral foundation displacement, U_6 is the torsional foundation displacement, U_g is the lateral free field displacement, $B_1 = B/2$.

The embedded foundation with embedded depth 4.5 m is used, and its plan dimensions are 52 × 104 m. The shear velocity of the soil around the foundation was assumed to be 160 m/s, its density was 1.8 t/m^3, and its poison ratio was 0.40. All of the numerical models are excited through the horizontal direction. The shear velocity, density and Poisson ratio of the cement-soil piles were

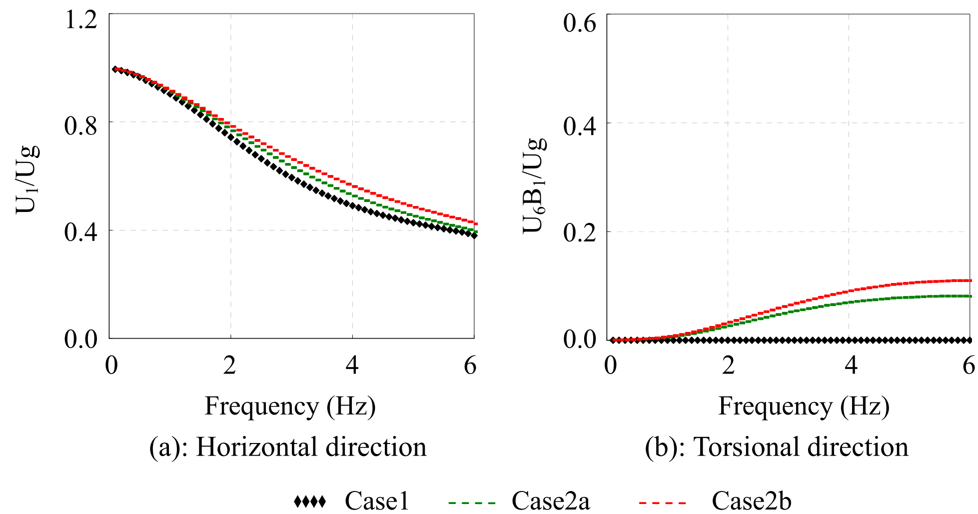


Fig. 10. Comparison result of the foundation input motion between the Case1 and Case2.

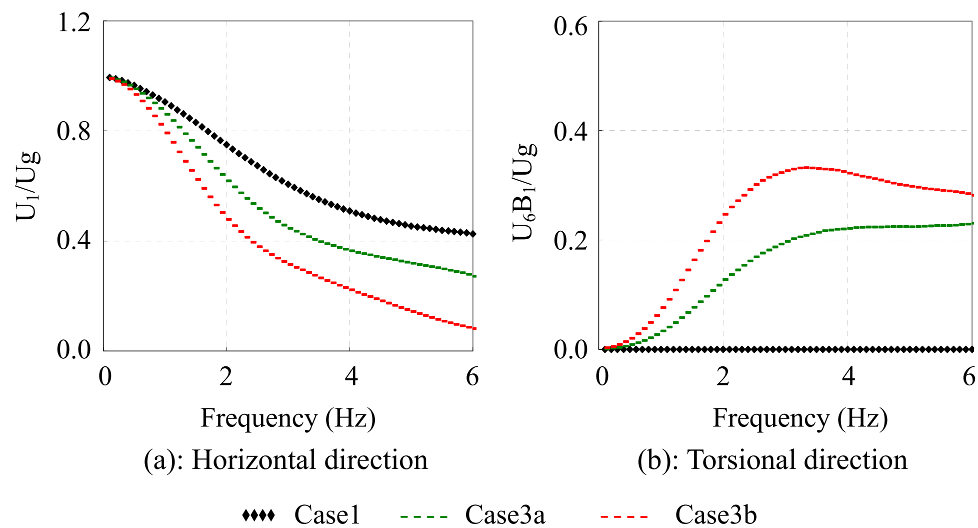


Fig. 11. Comparison result of the foundation input motion between Case1 and Case3.

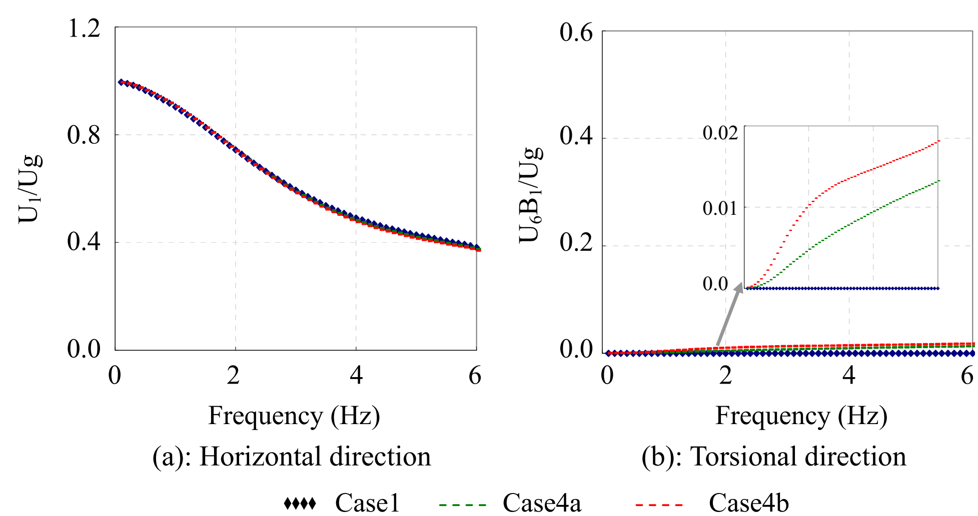


Fig. 12. Comparison result of the foundation input motion between Case1 and Case4.

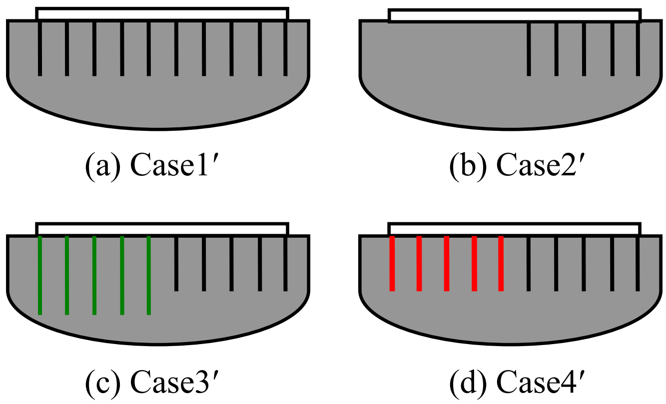


Fig. 13. Diagrammatic sketch of the raft foundation supported on the cement-soil piles.

the same as those described in Section 2. The center-to-center spacing of cement-soil piles was 2.0 m.

The comparison between Case1 and Case2 is shown in Fig. 10. It can be seen that during the horizontal seismic excitation, there is no torsional foundation motion in Case1 in which the foundation soil was equally improved, while in Case2 with partially improved subsoil, torsion motion was generated, and it increased with an increase of the ratios B/B_0 and C/C_0 as well as the input frequency.

Fig. 11 compares Case1 and Case3. The results show that different lengths of cement soil piles also led to torsional motion in the foundation. The torsional motion increased with an increase in the difference of pile length. Meanwhile with high frequency of input motion, the torsional motion amounted to about 30% of the free field motion.

Fig. 12 shows the comparison of Case1 and Case4. It can be seen that at least for the investigated range, the difference of pile diameter only resulted in very small torsional foundation motion.

6.2. Raft foundation supported on cement-soil piles

In this section, the torsional motion of a raft foundation supported on cement-soil piles were investigated. Unlike the foundation structure in Section 6.1, the raft foundation was not embedded in the foundation soil. Similarly four cases were analyzed (Case 1′ to Case 4′), and the plan dimension of the raft foundation is the same as the embedded foundation depicted in Section 6.1. The diagrammatic sketches of Case1′, Case2′, Case3′ and Case4′are shown in Fig. 13. The others parameters of Case1′, Case2′, Case3′ and Case4′ are the same to that of Case1, Case2, Case3 and Case4.

The comparison results between Case1′ and Case2′, Case1′ and Case3′ and Case1′ and Case4′ are depicted in Figs. 14–16, respectively. It can be observed form Figs. 14 to 16 that the torsional foundation input motion was generated under horizontal seismic excitation for the raft foundation with irregular soil-foundation system. Comparing the results shown in Figs. 14–16(b), it can be find out that: for Case3′, the generated torsional was much larger than that of Case1′.

and Case2′. The generated torsional foundation motion was about 40% of the free field motion. Hence, for the foundation type like that in Case3′, the generated torsional response of the foundation can not be neglected during the horizontal seismic excitation.

By comparing the results in Section 6.1 and Section 6.2, it can be seen that foundation embedment also slightly influenced the generated torsional motion. But both cases, improved foundation with different pile lengths resulted in the largest torsional motion.

7. Conclusions

The present study attempts to assess the impact of partially improved foundation soil on the torsional response of continuous foundation structure under horizontal seismic excitations. The results of the study may lead to the following conclusions:

1. The torsional response will be generated for the structure supported on partial improved foundation even if the seismic excitation is along the horizontal direction. The torsional foundation motion is generated due to the eccentricity that exists in the soil-foundation system.
2. For the foundation with two different cement-soil pile lengths, considerable torsional foundation motion will also be generated when the foundation is subjected to horizontal excitation.
3. The generated torsional motion will increase with an increase in the frequency of the seismic excitation.
4. The study shows that the effect of soil structure interaction may play a significant role in the seismic torsional response of a regular building structure during an earthquake. The generated torsional response due to irregular soil-foundation system should therefore be considered in the seismic analysis and design of building structures.

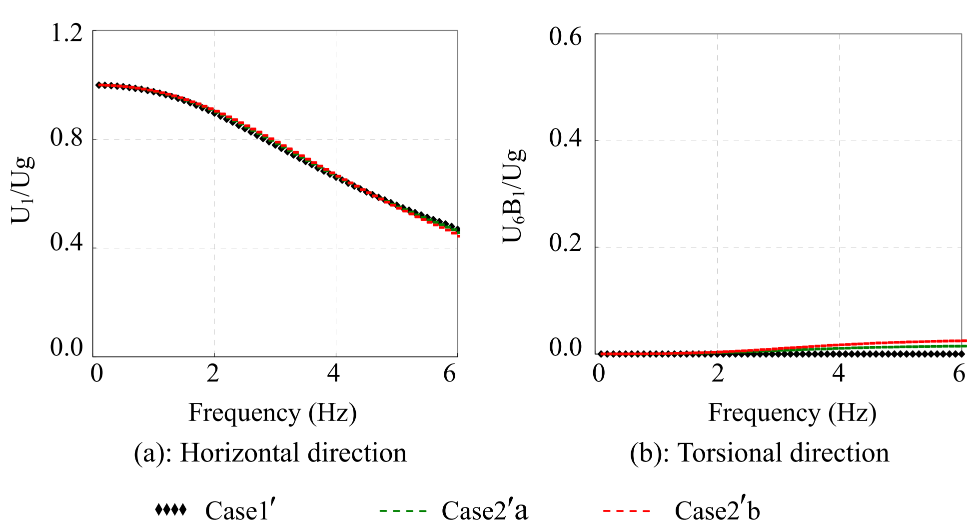


Fig. 14. Comparison result of the foundation input motion between Case1′ and Case2′.

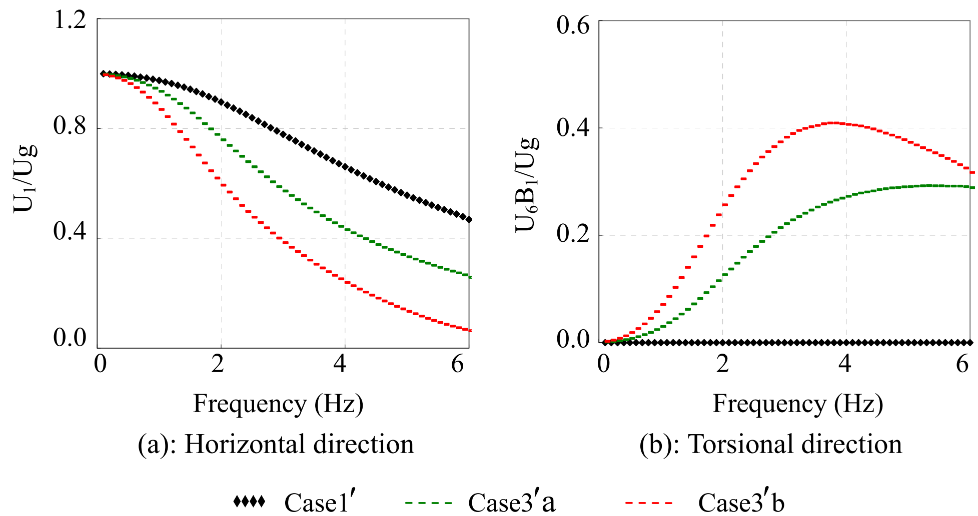


Fig. 15. Comparison result of the foundation input motion between Case1′ and Case3′.

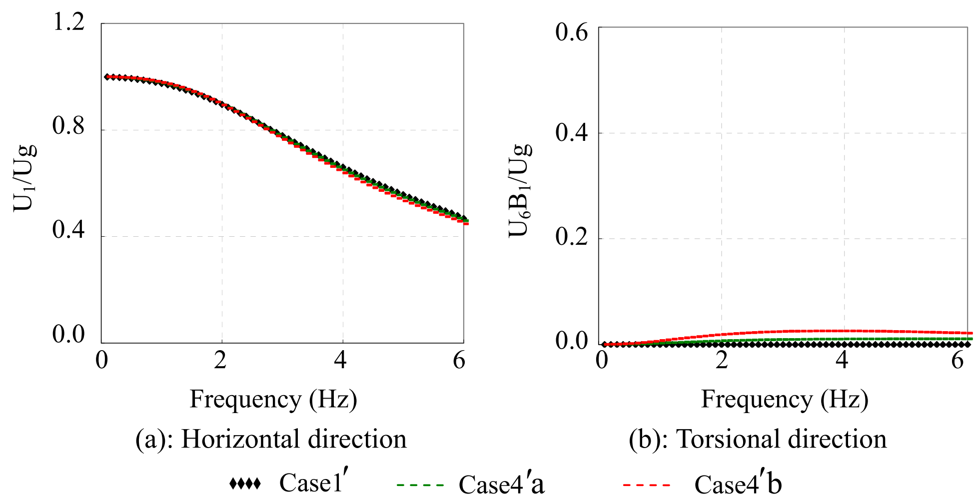


Fig. 16. Comparison result of the foundation input motion between Case1′ and Case4′.

The results of this study may help to improve the design guidelines for regular building structures supported on irregular soil-foundation system accounting for the effect of soil structure interaction. However, the foundation soil was assumed to be linear elastic in this study. This assumption limits the application of the proposed approach to the analysis of the SSI system under low seismic excitation. Nonetheless, the presented structural model and the above parametric study still provide the starting point for modeling the non-linear torsional response of a base isolated structure subjected to strong ground motions. The authors are carrying out a study to take into account the nonlinearity and softening of foundation soil under strong ground motion.

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