Open Journal of Civil Engineering, 2016, 6, 163-178
Published Online March 2016 in SciRes. http://www.scirp.org/journal/ojce
http://dx.doi.org/10.4236/ojce.2016.62015

A Study of the Effect of Soil Improvement Based on the Numerical Site Response Analysis of Natural Ground in Babol City

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Received 8 February 2016; accepted 25 March 2016; published 28 March 2016

Abstract

A series of numerical calculations have been performed to investigate the effect of soil improvement on seismic site response. Seismic site response analyses were also performed using data collected from a study area in Babol city. The improved site is a composite ground and has more or less different mechanical properties than the natural ground. In this research, the influence of the elastic modulus of the pile, the pile distance ratio, ground motion input, distance to fault rupture, and PGA of the earthquakes on seismic response characteristics are especially investigated. The results reveal that the values of the PGA and amplification factor on the surface of the natural and improved grounds depend strongly on the fundamental period of the site, the predominant period, and the intensity of the ground motion input. The acceleration response spectra also are affected by the characteristics of ground motion input and soil layers. Changing the pile distance ratio doesn't have a significant effect on the seismic response of the site.

Keywords

Seismic Site Response, Amplification Factor, Acceleration Response Spectra, Soil Improvement, Pile, Numerical Analysis, Babol

1. Introduction

The influence of local site conditions on ground motions has been investigated since the early days of earthquake engineering. Observations from as early as the 1800s exist in the literature indicating the effects of local geology on ground motions [1]. Local site effects have been studied by many researchers (e.g., [2]-[4]). Differ-

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How to cite this paper: Janalizadechoobbasti, A., Naghizaderokni, M. and Talebi, A. (2016) A Study of the Effect of Soil Improvement Based on the Numerical Site Response Analysis of Natural Ground in Babol City. *Open Journal of Civil Engineering*, **6**, 163-178. http://dx.doi.org/10.4236/ojce.2016.62015

ent site conditions are obtained in order to consider the impact of the earthquake response. The usual practice of the basis of past experiences in the field will be divided into several categories, and then classified according to site records of existing statistics of earthquake ground motion response spectrum. But regarding artificial foundation, because of its special boundary conditions and the diversity of treatment methods, it is necessary to see the relevant statistics [5].

In recent years, due to the flexibility of finite element method to deal with complex issues, people began to use numerical simulation to study this issue; Siegel *et al*. [5] investigated the site response of improved ground with stone column in the coastal eastern United States. They observed that the influence of vibrio-replacement was more dramatic in the characteristic clay profile as compared to the characteristic sand profile. Bouckovalas *et al*. [6] concentrated on seismic response of sites improved with inclusions (e.g. gravel columns). They showed that the improvement itself was not necessarily beneficial for the seismic response at ground surface; since it might lead to selective spectral amplification at periods around the fundamental period of the improved site. Ge and Liu [7] studied the effects of ground treatment on site seismic response. The study showed that foundation stabilization had an insignificant effect on frequency characteristic of the horizontal acceleration response spectrum, but the PGA might have a large diminution. Vucetic *et al*. [8] investigated the effect of soil improvement with column piles on seismic site response. In this paper, using finite element analysis [9], the influence of foundation improvement with piles is analyzed. The influence of the elastic modulus of the pile, the pile distance ratio, ground motion input, distance to fault rupture, and PGA of the earthquakes on seismic response characteristics are especially investigated.

2. Problem Definition

The soil consisted of one layer of soft soil underlain by a rock. Piles were used to increase the capacity of the soft ground. The bottom of the piles was at the top of the rock layer. A sand cushion, 0.5 m thick, was placed over the soft clay. The diameter of each pile wall was 1 m and the typical center-to-center spacing between two piles ranged from 2 to 3.0 m.

The characteristics of near-fault and far-fault earthquakes, which are used in this study, are presented in **Table 1** and **Table 2**, respectively. In order to investigate the effect of PGA, the accelerograms have been normalized to 0.2 g and 0.7 g.

Table 1. The characteristics of near-fault earthquakes [10].

Earthquake	Northridge	Loma prieta
Date	1994/01/17	1989/10/18
Station	24,207 Pacoima Dam (upper left)	47,379 Gilroy Array
Magnitude	6.7	6.9
Direction	194	090
PGA (g)	1.285	0.473
Focal depth (Km)	17.5	17.5
Closest to fault rupture (Km)	8.0	11.2

Table 2. The characteristics of far-fault earthquakes [10].

Earthquake	Northridge	Loma prieta
Earthquake	Northridge	Loma prieta
Date	1994/01/17	1989/10/18
Station	23,598 Rancho Cucama-Deer Can	58,338 Piedmont Jr. High
Magnitude	6.7	6.9
Direction	180	315
PGA (g)	0.051	0.071
Focal depth (Km)	17.5	17.5
Closest to fault	8.0	77.2

3. Finite Element Model

The use of 3d numerical analyses in geotechnical earthquake engineering is very scarce. For practitioners such analyses are considered a luxury, since they are very both time-consuming and computational effort. In addition, the commercially available 3d codes for performing numerical analysis of geotechnical earthquake engineering problems are very few and usually these codes have a smaller potential than commercial 2d codes. For example, 2d codes offer the use of advanced constitutive models or element types that are not found in the libraries of 3d codes. Hence, the numerical research in geotechnical earthquake engineering has been historically based on the use of (1d and 2d) analyses [11].

In these analyses numerical modeling was performed using the computer program PLAXIS V8, a two-dimensional finite element program developed specifically for the analysis of deformation and stability in geotechnical engineering applications. Dynamic analysis in PLAXIS can mainly be divided into two types of problems. The first one is related to single source vibrations and the second one is concerned to earthquake problems. In earthquake problems, the dynamic loading source is usually applied along the bottom of the model resulting to shear waves that propagate upwards. These types of problems are generally simulated using a plane strain model [9].

Many researchers have 2d numerical analyses for the 3d problem of the improved sites. Omine *et al*. [12] performed a series of 2d plane strain model tests on the improved ground with cement-treated soil columns. Sivakumar Babu *et al*. [13] investigated bearing capacity improvement using micropiles as plane strain problem. Papadimitriou *et al*. [11] showed how 2d numerical analyses may be accurately used for simulating the truly 3d problem of the seismic response of the improved sites. A method of converting the axisymmetric unit cell into the equivalent plane-strain model was used for two-dimensional numerical modeling of multicolumn field applications by [14]. Janalizadeh [15] evaluated the settlement of soft clay reinforced by stone columns by idealization of the stone columns in plane strain. Janalizadeh *et al*. [16] investigated the seismic response of pile foundations in liquefiable soil by using a two-dimensional plain strain finite difference program. So in these analyses Papadimitriou *et al*.'s method has been used for modeling the piles as a plane strain problem. A series of piles/columns of diameter d that are equally spaced at a center-to-center distance *D* along the y direction can be modeled as a diaphragm wall with diameter of d', while d' is given [7] by

$$d' = \left(\frac{d^3}{D}\right)^{\frac{1}{2}} \tag{1}$$

Having examined different finite element meshes, a refined mesh was introduced to decrease the effect of mesh dependency on the finite element modeling. At the interface between the piles and soft clay, interface elements have been used. Finite element analyses were carried out using 15-noded triangular elements. The bottom boundary of the mesh was set at the top of the rock with zero displacements. The vertical boundaries of the model were constrained to have vertical movement only. Next the material modeling will be discussed.

The soft soil and sand cushion were represented by an elastic plastic model with the Mohr Coulomb failure criterion, while the piles were assumed to be linearly isotropic elastic. The material properties of the piles, the sand cushion, and the soil layer are presented in **Table 3**. The young's modulus for clay and sand cushion in **Table 3** are larger than the similar numbers in other articles. This is since the dynamic stiffness of the ground is in general considerably larger than the static stiffness, since dynamic loadings are usually fast and cause very small strain [9].

4. Results

In this section, first the authors concentrate on the influence of the elastic modulus of piles and second the effect of the pile distance ratio will be discussed. In order to investigate the effect of the elastic modulus of the piles on seismic site response, this parameter is considered to be equal to 100, 500, 1000 and 5000 MPa. The fundamental period of the natural ground (T) is calculated using the familiar formula: T = 4H/VS, in which H is the soil depth and VS is the effective shear wave velocity of the soil deposit which is equal to 1.12 sec. The fundamental periods (T) of improved grounds and the predominant periods of the earthquakes are presented in **Table 4** and **Table 5**, respectively.

Table 3. Material properties used in the numerical model.

Parameter	Name	Unit	Pile [17]	Cushion [17]	Clay [18]
Material model	Model	-	Linear elastic	Mohr coulomb	Mohr coulomb
Type of material behavior	Type	-	Non-porous	Drained	Drained
Soil unit weight	Unsat	kN/m^3	22	21.3	17
Young's modulus	E	kN/m^2		260,000	50,000
Poisson' ratio	ν		0.2	0.3	0.25
Cohesion	c	kN/m^2		1.5	5
Friction angle	φ	0		30.5	21
Dilatancy angle	ψ	0		0	0
Interface strength	Rinter		0.9		0.67

Table 4. Fundamental periods of improved grounds.

Elastic modulus of the piles (MPa)	Ts (sec)
100	1.03
500	0.63
1000	0.47
5000	0,22

Table 5. Predominant periods of the earthquakes.

Earthquakes		Tp (sec)
Loma Prieta	Near-fault	0.372
	Far-fault	1.241
Northridge	Near-fault	0.65
	Far-fault	0.539

Next, the amplification factor for the near-fault earthquakes will be discussed, followed by that of the far-fault earthquakes. The amplification factor is defined as the ratio of the PGA of the improved ground to the PGA of the bedrock.

At low levels of input motion the maximum surface accelerations are greater than the maximum base accelerations. It means that the soil has a linear elastic behavior and amplifies the earthquakes [2] [3] [19]. The PGA and amplification factor on the surface of the natural ground under near-fault Loma Prieta and Northridge earthquakes with PGAs equal to 0.2 g are presented in **Table 6**. As it can be seen in these cases, both the natural ground (without stabilization regional) and the improved ground under near-fault Loma Prieta and Northridge earthquakes with the PGAs equal to 0.2 g show linear behavior (**Table 6** and **Figure 1(a)**).

It is seen from **Figure 1(a)** that under near-fault Loma Prieta earthquake, the amplification factor for the improved ground with the elastic modulus of piles equal to 100 MPa is slightly less than the amplification factor of the natural ground. The reason is that the improved ground is stiffer than the natural ground and in the case that the soils have linear behavior and bedrock is rigid, the softer site has higher amplification than the stiffer site [19] consequently, the amplification factor for the improved ground with the elastic modulus of piles equal to 500 MPa is less than the amplification factor of the improved ground with the elastic modulus of piles equal to 100 MPa. Because the fundamental period of the improved ground with Epile = 1000 MPa is approximately coincident with the predominant period of the earthquake, resonance happens and the amplification factor increases. Again the amplification factor for the improved ground with Epile = 5000 MPa decreases because of its stiffness and period.

On the other hand, under near-fault Northridge earthquake, the improved grounds act in a different way with respect to near-fault Loma Prieta earthquake. The amplification factor of the improved ground with Epile = 100 MPa is slightly less than the amplification factor of the natural ground. In Epile =500 MPa, resonance happens and the amplification factor increases. Then as the elastic modulus of the piles increases, the amplification factor decreases.

In order to investigate the effect of the PGA, the accelerograms have also been normalized to 0.7 g. The PGA and amplification factor on the surface of the natural ground under Loma Prieta and Northridge earthquakes with the PGAs equal to 0.7 g are presented in **Table 7**. Under strong ground motion, the soil exhibits non-linear behavior and instead of amplification, degradation of stiffness and strength happens [19].

From **Figure 1(b)**, it can be observed that under the near-fault Loma Prieta earthquake, the improved ground with Epile = 100 MPa also shows non-linear behavior and de-amplifies the ground motions. As the elastic modulus of piles increases, the stiffness of the improved ground increases, strains become smaller, and the improved grounds show elastic behavior and follow the same trend as that for the last section under Loma Prieta earthquake with PGA = 0.2 g. In this figure, the previously discussed trend for the improved grounds under near-fault Northridge earthquake with PGA equal to 0.2 g is repeated by the improved grounds under near-fault Northridge earthquake with PGA equal to 0.7 g.

The PGA and amplification factor on the surface of the natural ground under far-fault earthquakes with PGAs = 0.2 g are presented in **Table 8**. The natural ground in this study is composed of soft clay and has a large fundamental period. This site under far-fault Loma Prieta earthquake with PGA = 0.2 g, shows a linear behavior and due to the approximate coincident of its fundamental period with the predominant period of the earthquake, resonance happens. Improvement makes the site stiffer and brings its fundamental period far from the predominant period of the excitation. So it is seen from **Figure 2(a)** that under Loma Prieta earthquake, as the elastic

Table 6. The PGA and amplification factor on the surface of the natural ground under near-fault earthquakes with PGA_s = 0.2 g.

Earthquakes	PGA (g)	Amplification factor
Loma Prieta	0.445	2.23
Northridge	0.396	1.98

Table 7. The PGA and amplification factor on the surface of the natural ground under near-fault earthquakes with PGAS = 0.7 g.

Earthquakes	PGA (g)	Amplification factor
Loma Prieta	0.550	0.786
Northridge	0.531	0.758

Table 8. PGA and amplification factor on the surface of the natural ground under far-fault earthquakes with PGAs = 0.2 g.

Earthquakes	PGA (g)	Amplification factor
Loma Prieta	0.529	2.645
Northridge	0.380	1.900

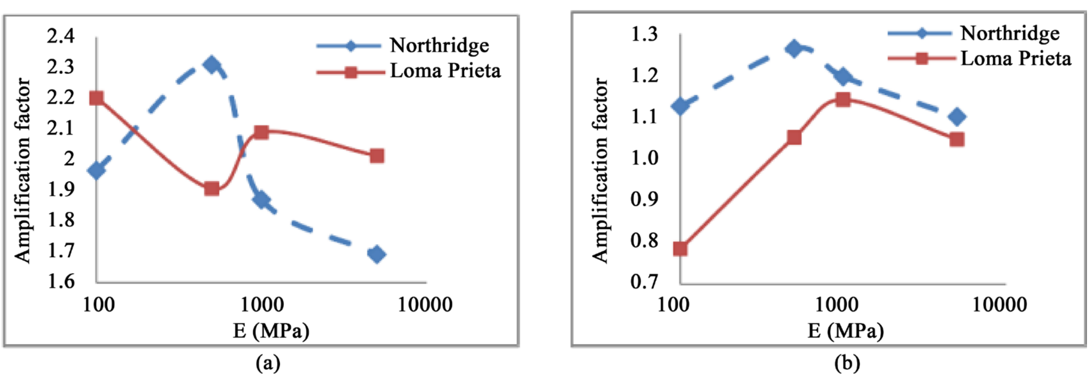


Figure 1. Amplification factor on the surface of improved grounds under near-fault earthquake with (a) PGA = 0.2 g and (b) PGA = 0.7 g.

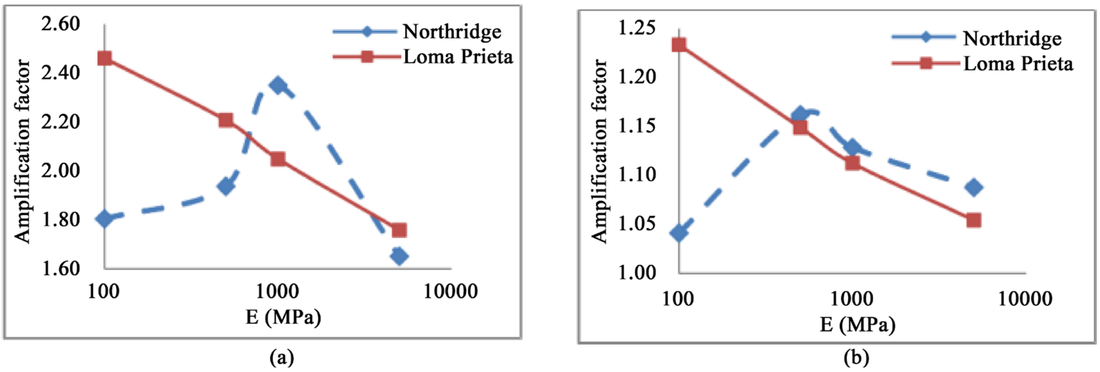


Figure 2. Amplification factor on the surface of the improved grounds under far-fault earthquake with: (a) PGA: 0.2 g and (b) PGA: 0.7 g.

Table 9. PGA and amplification factor on the surface of the natural ground under far-fault earthquakes with PGAs = 0.7 g.

Earthquakes	PGA (g)	Amplificatin factor
Loma Prieta	0.529	2.645
Northridge	0.380	1.900

modulus of piles increases, the amplification factor decreases. Under far-fault Northridge earthquake with PGA = 0.2 g, the trend of the effect of the elastic modulus of piles on the amplification factor, considering the fundamental periods of improved grounds and the predominant period of the earthquake, is acceptable.

The PGA and amplification factor on the surface of the natural ground under far-fault earthquakes with PGAs = 0.7 g are presented in **Table 9**. This site under far-fault earthquakes with PGAs = 0.7 g, shows a non-linear behavior. From **Figure 2(b)**, it can be observed that the previously discussed trends for the improved ground under far-fault Loma Prieta earthquake with PGA equal to 0.2 g is repeated by the improved ground under far-fault Loma Prieta earthquake with PGA equal to 0.7 g. Under far-fault Northridge earthquake, the amplification factor first increases and then decreases with respect to elastic modulus of the piles.

The results of this section graphically show the acceleration response spectra (Sa for 5% damping), amplification spectra and the effect of improvement on Sa for the input motion and at the ground surface for both the natural ground and improved ground. The amplification spectrum is defined as the ratio of the acceleration response spectrum of the improved ground to the pertinent spectrum of the bedrock. The effect of improvement on Sa provides insight to the effect of the improvement on the ground surface response and is defined as the ratio of the amplification spectrum of the improved ground to the pertinent spectrum of the natural ground, which is of primary interest to civil engineering works.

Figure 3(a) and **Figure 4(a)** show that the seismic response of the natural ground under near-fault Loma Prieta earthquake may be slightly different from those of the improved grounds. In particular, **Figure 5(c)** & **Figure 6(c)** show that the effect of the improvement on the spectral ordinates. It is observed that under near-fault Loma Prieta earthquake with PGA = 0.2 g, the improved ground with Epile = 5000 MPa de-amplifies the motion for intermediate periods (between 0.58 and 1.64 sec), but under Loma Prieta earthquake with PGA = 0.7 g the improvements de-amplify the motion at short periods (smaller than 0.5 sec) for approximately all of the young's modules and large periods (larger than 1.6 sec) for Epile = 1000 & 5000 MPa.

The results of the site response analysis under near-fault Northridge earthquake predict that the improved ground will respond as a stiffer profile than the original ground. As it can be seen in **Figure 5(a)** and **Figure 6(a)**, the acceleration response spectra have two peaks. The improved ground exhibits greater peak spectral accelerations at shorter periods, and the peak spectral acceleration of the improved ground at larger periods are smaller than the peak spectral acceleration of the natural ground. Also the lowest peak at larger periods belongs to the improved ground with Epile = 5000 MPa. **Figure 7(c)** shows that under Northridge earthquake with PGA = 0.2 g, the improvements de-amplify the motion for intermediate periods (between 0.64 and 1.2 sec). **Figure 8(c)** shows that under Northridge earthquake with PGA = 0.7 g, the improvements de-amplify the motion for intermediate periods (between 0.52 and 1.3 sec & between and 3.2 sec) except Epile = 500 MPa. The improved ground with Epile = 500 MPa only de-amplifies the motion for intermediate periods (between 0.52 and 1.3 sec).

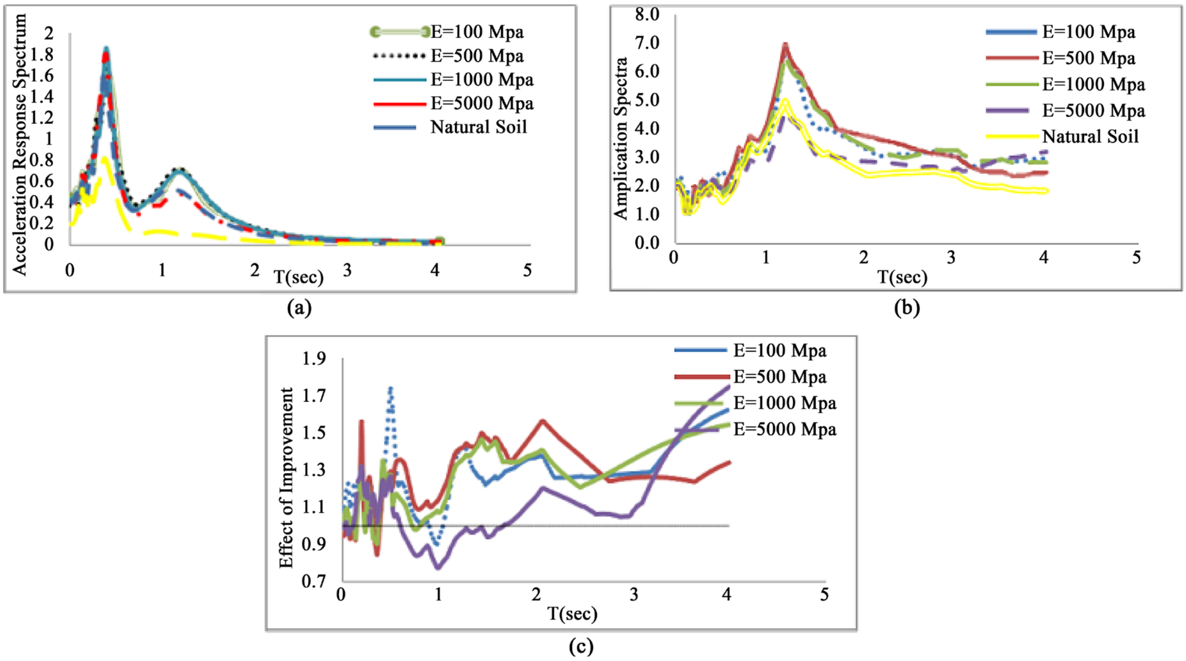


Figure 3. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Loma Prieta earthquake with PGA = 0.2 g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

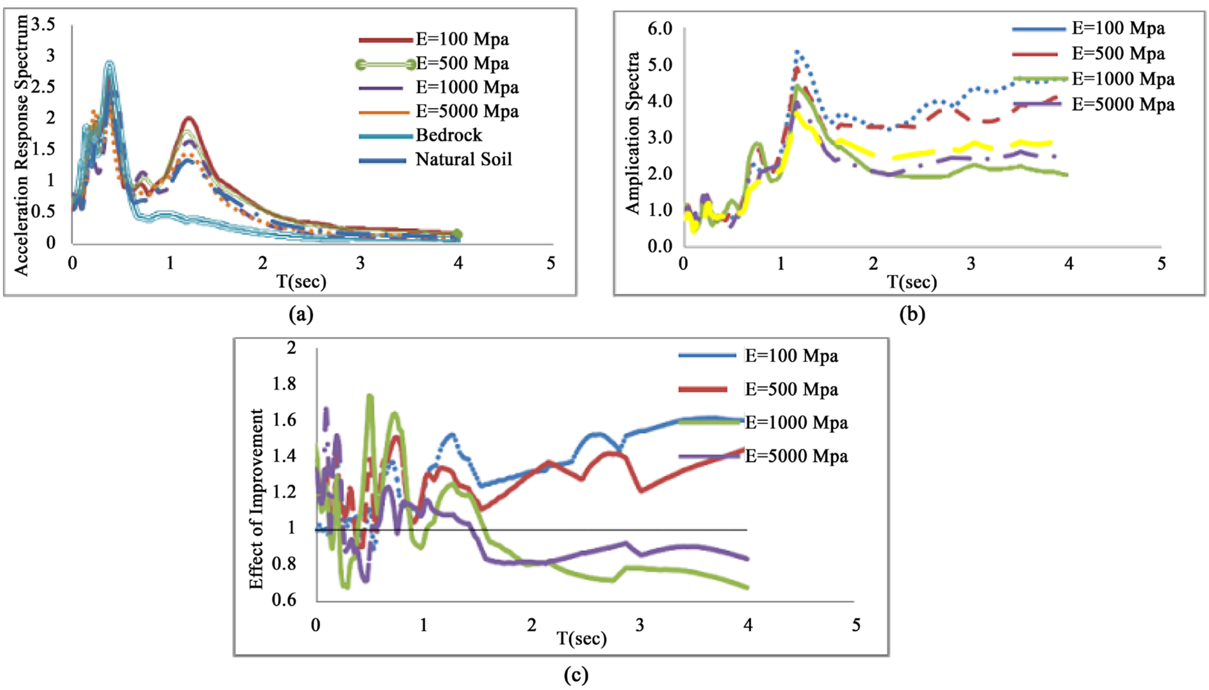


Figure 4. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Loma Prieta earthquake with PGA = 0.7 g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

Therefore, **Figures 3-6** show that the acceleration response spectra depend strongly on the ground motion input. Under Loma Prieta earthquake, the acceleration response spectra have also two peaks, but in contrast with Northridge earthquake, the acceleration response spectra of the natural ground are approximately smaller than the acceleration response spectra of the improved ground at the two peaks.

As it can be seen in **Figure 7(a)** and **Figure 8(a)**, under far-fault Loma Prieta earthquake like the near-fault ones (**Figure 3** and **Figure 4**), the acceleration response spectra for the improved ground exhibits greater spectral accelerations at the two peaks. **Figure 7(c)** shows that all of the improvements de-amplify the motion at short periods (approximately T < 0.1 sec). The improved ground with Epile = 5000 MPa also de-amplifies the motion at intermediate and large periods. The significant point that can be seen in **Figure 10(c)** is that the acceleration

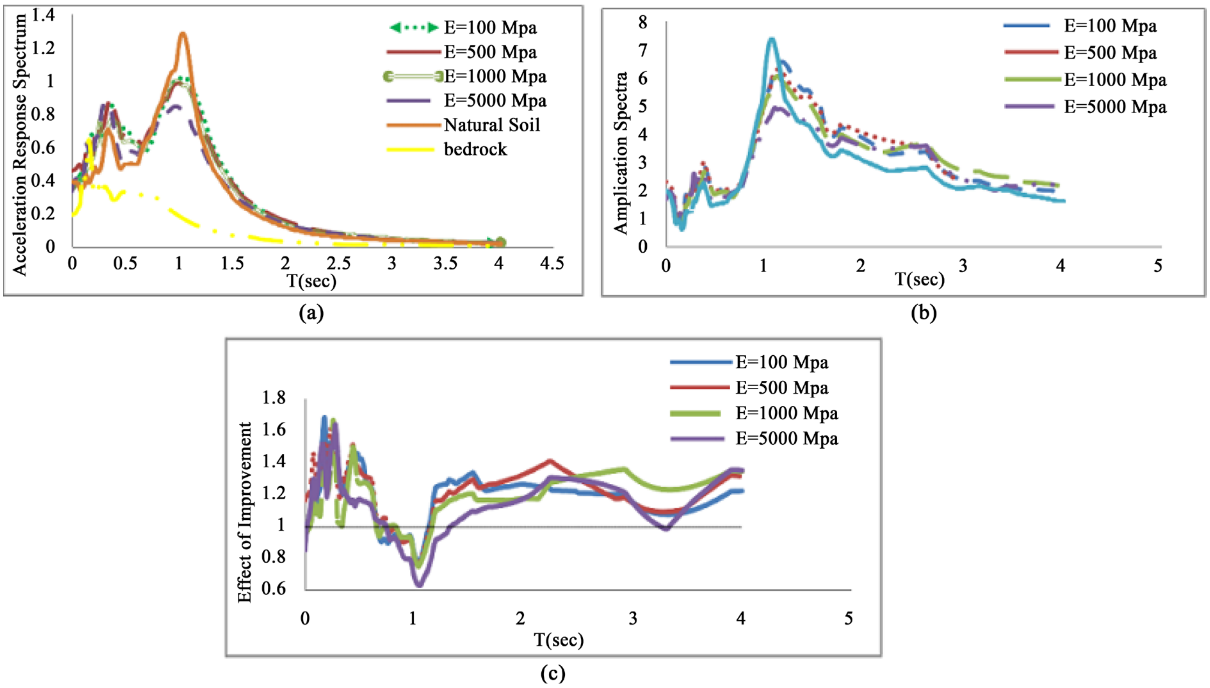


Figure 5. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Northridge earthquake with PGA = 0.2 g (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

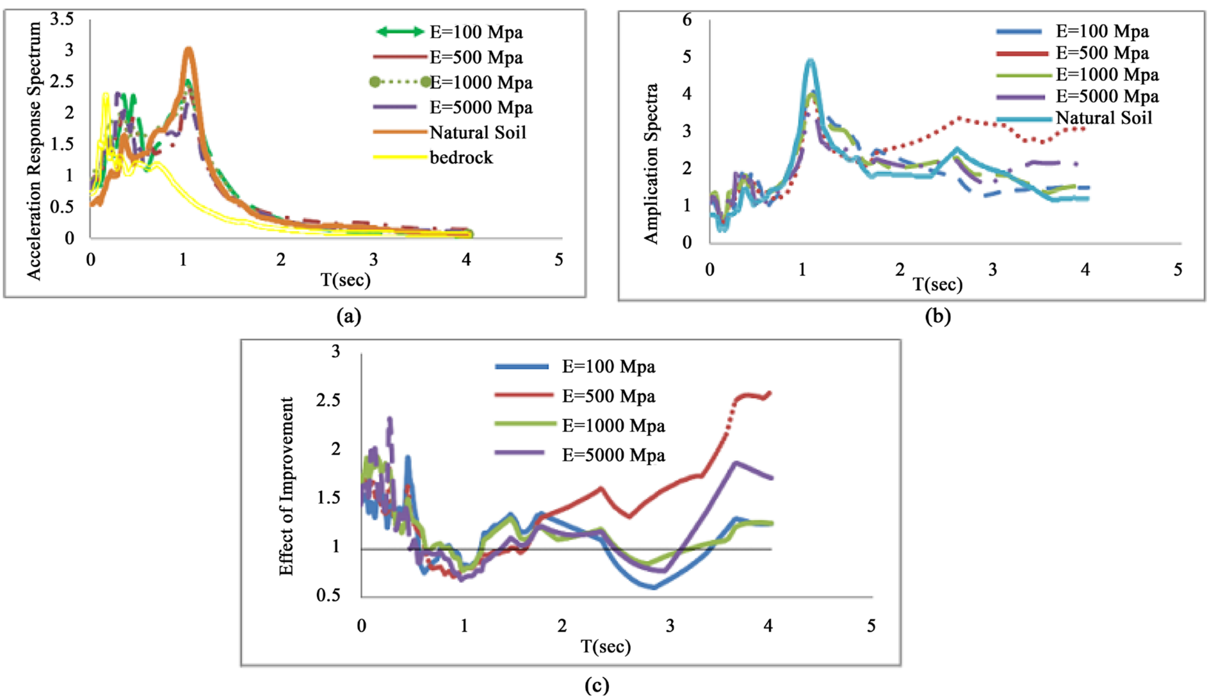


Figure 6. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Northridge earthquake with PGA = 0.7 g (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

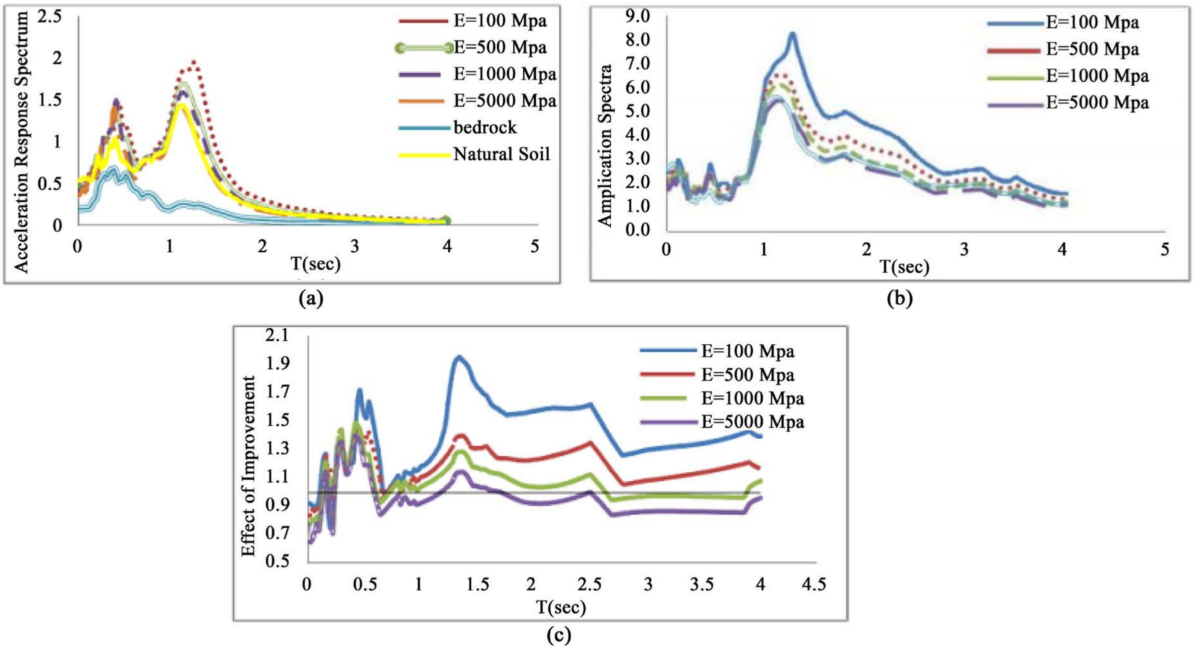


Figure 7. Comparison of seismic response on the surface of the natural ground and its improvement under far-fault Loma Prieta earthquake with PGA = 0.2 g (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

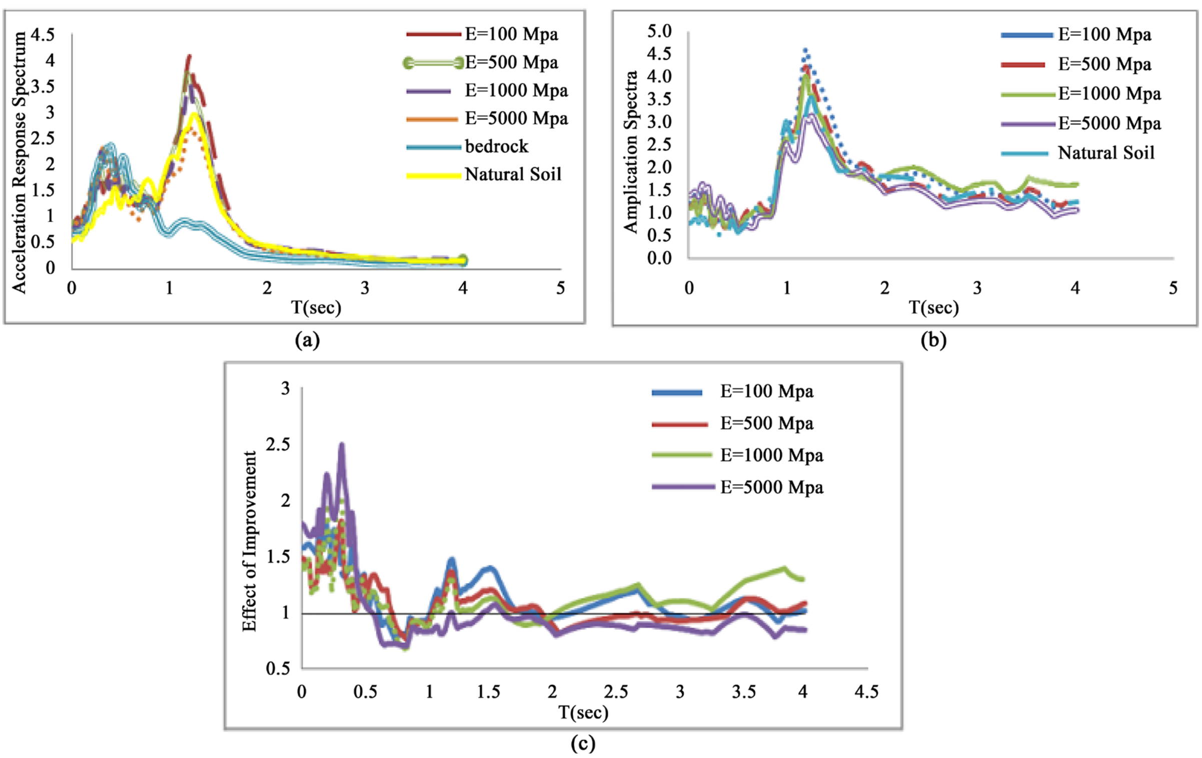


Figure 8. Comparison of seismic response on the surface of the natural ground and its improvement under far-fault Loma Prieta earthquake with PGA = 0.7 g (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

response spectra for improved ground with Epile = 5000 MPa is less than the acceleration response spectra of the natural ground for periods greater than 0.54 sec.

As it can be seen in **Figure 9(a)** and **Figure 10(a)**, under far-fault Northridge earthquake like the near-fault ones (**Figure 5** and **Figure 6**), the acceleration response spectra have two peaks, the improved ground exhibits greater peak spectral accelerations at shorter periods, and the peak spectral acceleration of the improved ground at larger periods are smaller than the peak spectral acceleration of the natural ground.

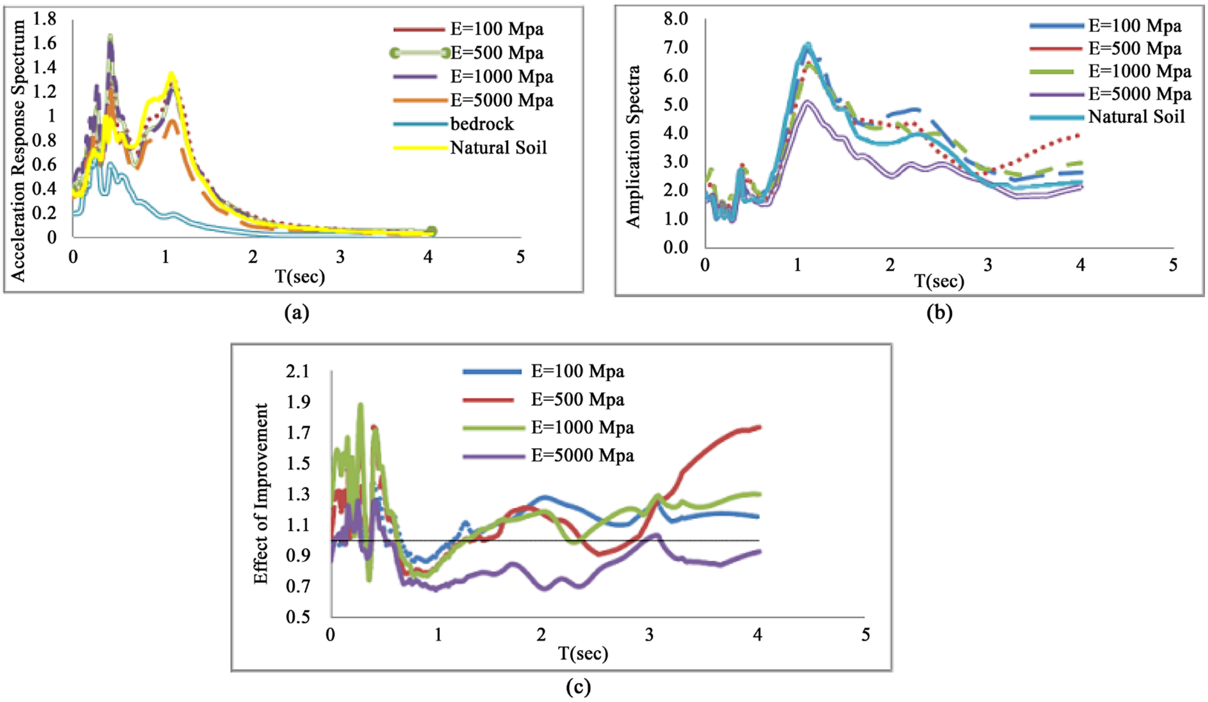


Figure 9. Comparison of seismic response on the surface of the natural ground and its improvement under far-fault Northridge earthquake with PGA = 0.2 g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

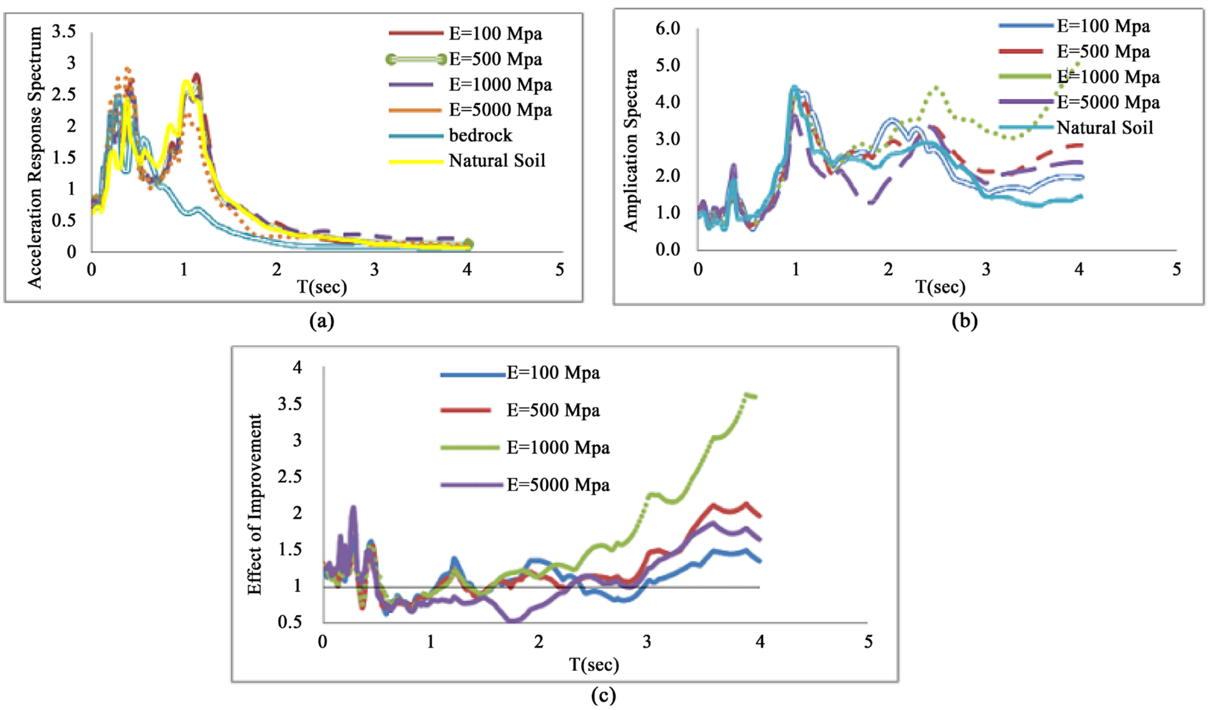


Figure 10. Comparison of seismic response on the surface of the natural ground and its improvement under far-fault Northridge earthquake with PGA = 0.7 g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

In **Figure 9(c)**, it can be observed that the improved ground with Epile = 5000 MPa de-amplifies the motion for all periods except for short periods (*i.e.* 0.5 sec < T), but other improvements de-amplify the motion just for intermediate periods (0.58 < T < 1.2 sec). **Figure 12(c)** shows that the improved ground with Epile = 5000 MPa de-amplifies the motion for intermediate periods (0.48 < T < 2.22 sec) and other improvements de-amplify the motion for 0.48 < T < 1.02 sec.

Therefore, from the figures of the effect of improvement on Sa, it can be understood that under near-fault Loma Prieta earthquake, the improved ground with Epile = 5000 MPa de-amplifies the motion at all periods except for short periods and other improvements de-amplify the motion at short periods.

But under Northridge earthquake the improved ground with Epile = 5000 MPa de-amplifies the motion at short periods and other improvements de-amplify the motion for intermediate periods (between 0.5 and 1.2 sec).

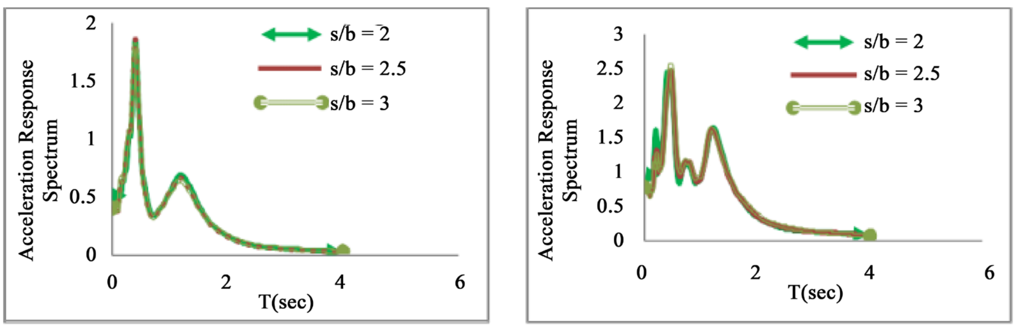
Next the effect of the pile distance ratio on seismic site response will be discussed. The pile distance ratio (s/d) is defined as the ratio of the center-to-center spacing (s) of piles to the diameter (d) of each pile. Each pile was 1 m thick and the typical center-to-center spacing between two piles ranged from 2 to 3 m. calculating the seismic response of site under Loma Prieta earthquake indicates that changing the pile distance ratio doesn't have any significant effect on seismic response of the site, so the analyses were not repeated for Northridge earthquake.

In order to investigate the effect of pile distance ratio, the parameter of elastic modulus is kept constant and equal to 1000 MPa. The amplification factors for these analyses are presented in **Table 10**.

Figure 11 and **Figure 12** graphically show the acceleration response spectra for these analyses. As it can be

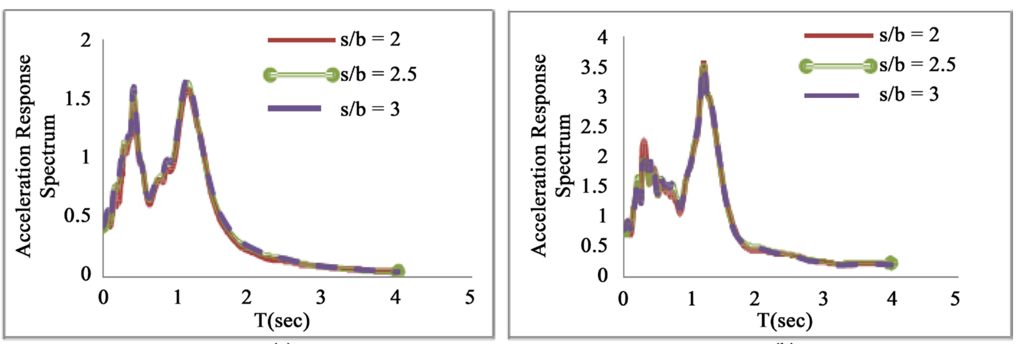
Table 10. The amplification factor for improved ground with Epile = 1000 MPa under Loma Prieta earthquake.

s/b	Near-Fault	Far-Fault	PGA = 0.2 g	PGA = 0.7 g
	PGA = 0.2 g	PGA = 0.7 g		
2	2.09	1.14	2.05	1.11
2.5	1.97	1.13	2.14	1.09
3	2.00	1.11	2.16	1.13



(a) (b)

Figure 11. Acceleration response spectra for different pile distance ratios under near-fault Loma Prieta Earthquake with: (a) PGA = 0.2 g and (b) PGA = 0.7 g.



(a) (b)

Figure 12. Acceleration response spectra for different pile distance ratios under far-fault Loma Prieta Earthquake with: (a) PGA = 0.2 g & (b) PGA = 0.7 g.

seen, changing the pile distance ratio doesn't have any significant effect on the seismic response of the site.

5. Case Study, Babol Site Effect Analysis

Babol, a city in the Mazandaran province in the northern part of Iran, is our study area. The city is located approximately 20 kilometers south of the Caspian Sea, on the west bank of Babolrood River [20]. The geological log of Babol city is presented in **Figure 13**.

The PGA and amplification factor on the surface of the ground in Babol city ground under Loma Prieta earthquake with PGAs = 0.2 g & 0.7 g are presented in **Table 11** and **Table 12**, respectively. As it can be seen from **Table 11**, in these cases the amplification factors of the improved grounds are greater than the amplification factors of the natural grounds. Under Loma Prieta earthquake with PGA = 0.7 g, the improved grounds show linear behavior but the natural grounds show non-linear behavior.

In this section, the acceleration response spectra (Sa for 5% damping), amplification spectra and the effect of improvement on Sa for the input motion at the ground surface for both natural ground and the improved ground in the Babol city are graphically shown. From **Figure 14(a)**, it can be observed that under near-fault Loma Prieta earthquake with PGA = 0.2 g, the natural ground in Babol city amplifies the motion for all periods except

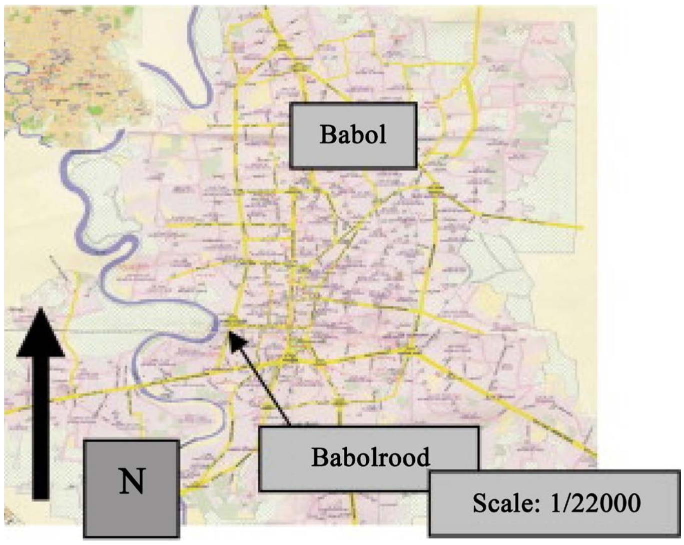


Figure 13. Position of the Babol city in the Mazandaran province.

Table 11. The PGA and amplification factor on the surface of the ground in Babol under Loma Prieta earthquake with PGA = 0.2 g.

Earthquake	Ground	PGA (g)	Amplification factor
Near-fault	Natural ground	0.28	1.4
	Improved ground	0.33	1.7
far-fault	Natural ground	0.26	1.3
	Improved ground	0.38	1.9

Table 12. The PGA and amplification factor on the surface of the ground in Babol under Loma Prieta earthquake with PGA = 0.7 g.

Earthquake	Ground	PGA (g)	Amplification factor
Near-fault	Natural ground	0.48	0.7
	Improved ground	1.11	1.6
far-fault	Natural ground	0.33	0.5
	Improved ground	1.23	1.8

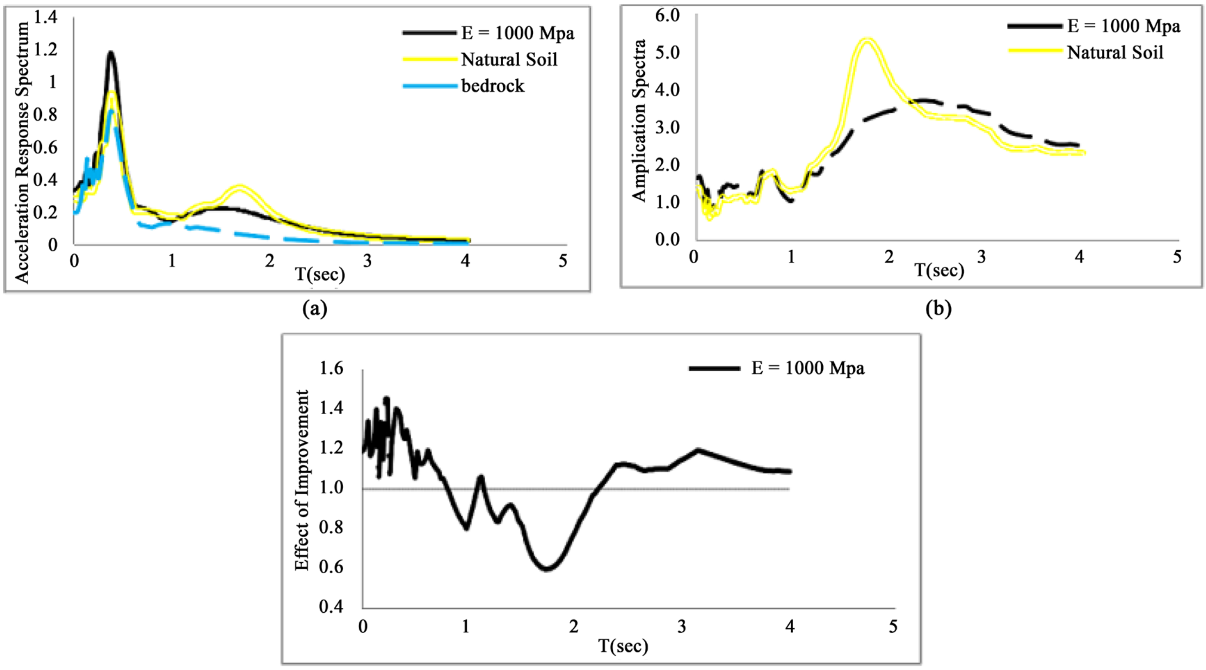


Figure 14. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Loma Prieta earthquake with PGA = 0.2 g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

for the periods between 0.06 and 0.26 sec, which can better be seen in **Figure 14(b)**. As it can be seen in **Figure 14(a)**, improvement makes the site stiffer and therefore increases the peak spectral acceleration at short periods and decreases the peak spectral acceleration at large periods**.** In contrast with **Figure 3(c)** in which improvement with Epile = 1000 MPa in a 30-m-thick clay layer approximately amplifies the motion for all periods, **Figure 14(c)** shows that the improvement de-amplifies the motion for intermediate periods (between 0.78 and 2.18 sec).

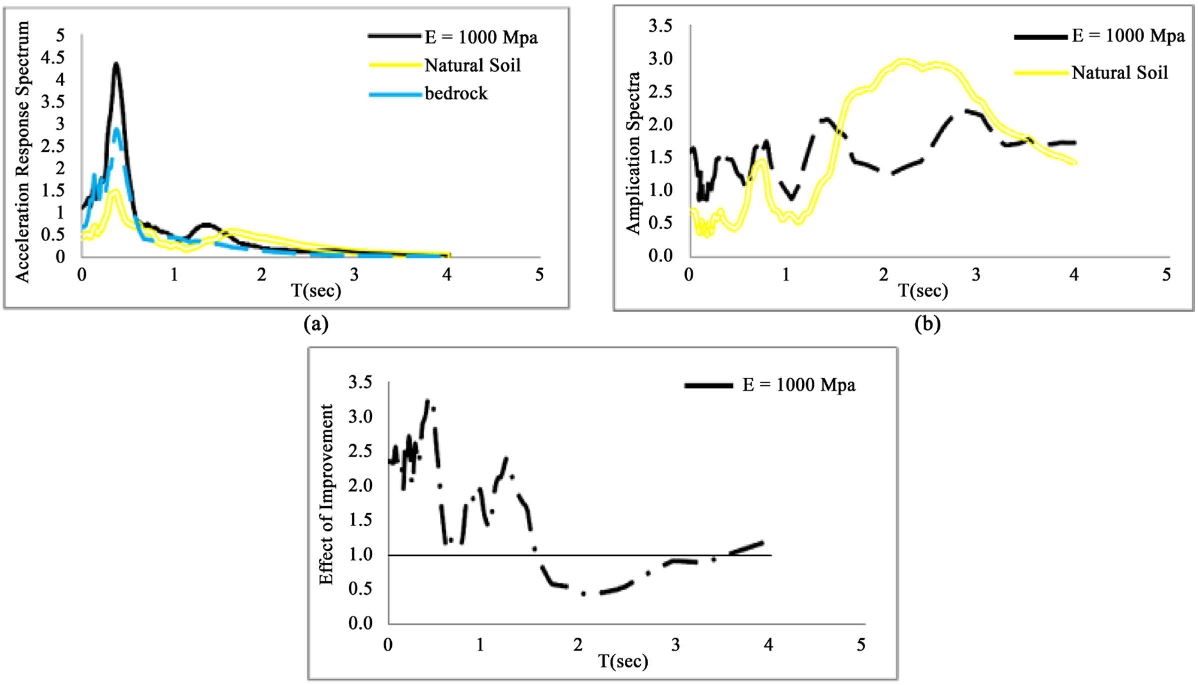
From **Figure 15(a)**, it can be observed that under near-fault Loma Prieta earthquake with PGA = 0.7 g, the natural ground in Babol city shows non-linear behavior and de-amplifies the motion. Improvement makes the site stiffer, so strains become smaller and the improved ground shows elastic behavior. These are better depicted in **Figure 14(b)**. **Figure 15(c)**, which shows that the improvement de-amplifies the motion for periods between 1.5 and 3.52 sec. Under near-fault Loma Prieta earthquake with PGA = 0.7 g, improvement with Epile = 1000 MPa in a 30-m-thick clay layer also amplifies the motion for periods larger than 1.5 sec (**Figure 4(c)**).

From **Figure 16(a)**, it can be observed that under far-fault Loma Prieta earthquake with PGA = 0.2 g, the natural ground in Babol city amplifies the motion for all periods except for the periods between 0.2 and 0.3 sec & 0.46 and 0.56 sec. In contrast with **Figure 7(c)**, in which improvement with Epile = 1000 MPa in a 30-m-thick clay layer de-amplifies the motion for short periods and large periods between 2.6 and 3.9 sec. **Figure 16(c)** shows that the improvement de-amplifies the motion for periods between 1.5 and 3 sec. Under far-fault Loma Prieta earthquake with PGA = 0.7 g, like the near-fault one with PGA = 0.7 g, the natural ground in Babol city shows non-linear behavior and the improved ground shows linear behavior (**Figure 17(a)**). The improvement de-amplifies the motion for periods larger than 1.6 sec (**Figure 17(c)**). Therefore, under Loma Prieta earthquake with PGA = 0.2 g, the natural ground in Babol city shows linear behavior and under Loma Prieta earthquake with PGA = 0.7 g, it shows non-linear behavior and de-amplifies the motion. Improvement makes the site stiffer, so strains become smaller and the improved ground shows elastic behavior. As it can be seen from this section, the seismic response of the natural ground in Babol city is different from the seismic response of a 30-m-thick clay layer. Improvements in the natural ground in Babol city de-amplify the motion for large periods. As a result, it can be concluded that the acceleration response spectra also depend on soil layers.

6. Conclusions

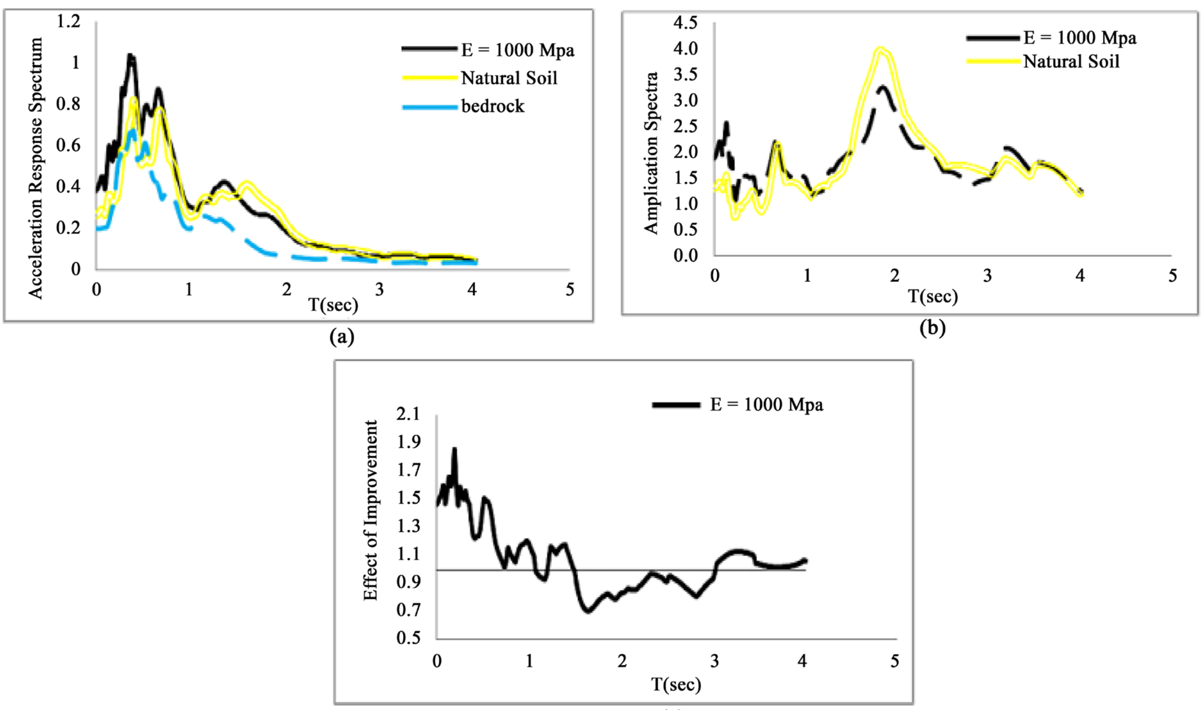
Using the finite element method to study the effect of improvement with piles on the seismic site response led to some important conclusions:

1) The values of PGA and amplification factor on the surface of the natural ground and improved grounds



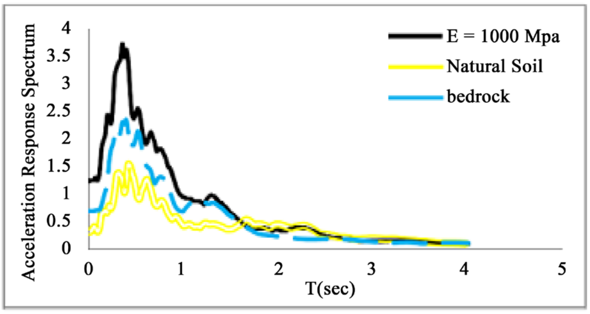
(a) (b) (c)

Figure 15. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Loma Prieta earthquake with PGA = 0.7 g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

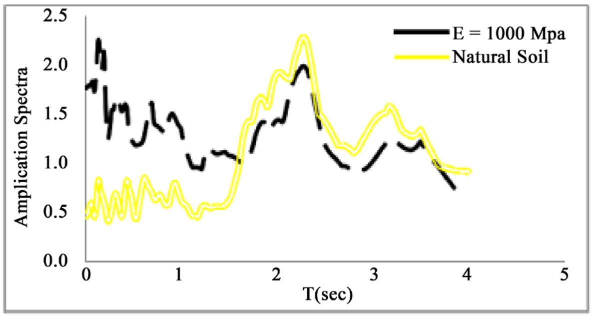


(a) (b) (c)

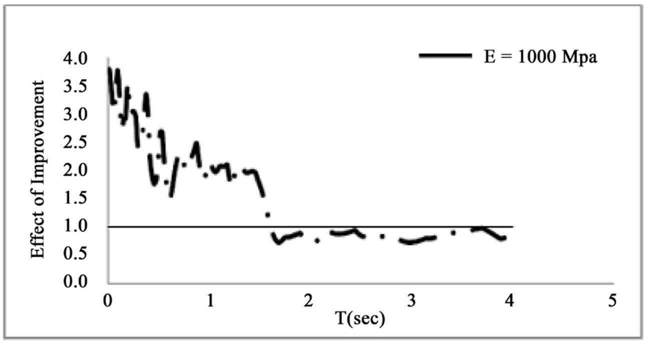
Figure 16. Comparison of seismic response on the surface of the natural ground and its improvement under far-fault Loma Prieta earthquake with PGA = 0.2 g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.



(a)



(b)



(c)

Figure 17. Comparison of seismic response on the surface of the natural ground and its improvement under far-fault Loma Prieta earthquake with PGA = 0.7 g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

depend strongly on the fundamental period of the site, the predominant period and the intensity of the ground motion input.

2) The results of the site response analysis show that the acceleration response spectra depend on the ground motion input. Under Northridge earthquake, the acceleration response spectra have two peaks and the improved grounds exhibit greater peak spectral accelerations at shorter periods and the peak spectral acceleration of the improved ground at larger periods is smaller than the peak spectral acceleration of the natural ground. Under Loma Prieta earthquake, the acceleration response spectra have also two peaks, but in contrast with Northridge earthquake; the acceleration response spectra of the natural ground are approximately smaller than the acceleration response spectra of the improved ground at two peaks.

3) From the figures of the effect of improvement on Sa, it can be understood that the improvement de-amplifies the motion for intermediate periods (between 0.5 and 1.5 sec). Moreover, under the near-fault earthquakes with PGA = 0.2 g, the improved grounds with Epile = 5000 MPa also de-amplify the motion at periods larger than 1.5 sec.

4) Calculating the seismic response of the site under the Loma Prieta earthquake indicates that changing the pile distance ratio doesn't have any significant effect on the seismic response of the site.

5) Under Loma Prieta earthquake with PGA = 0.2 g, the natural ground in Babol city shows linear behavior; and under Loma Prieta earthquake with PGA = 0.7 g, it shows non-linear behavior de-amplifying the motion. Improvement makes the site stiffer, so strains become smaller and the improved ground shows elastic behavior. As it can be seen from this section, the seismic response of the natural ground in Babol city is different from the seismic response of a 30-m-thick clay layer. The amplification factors of the improved grounds are greater than the amplification factors of the natural grounds in Babol and improvement in this area de-amplifies the motion for large periods. So it can be concluded that the acceleration response spectra also depend on soil layers and its characteristics.

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