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Open Journal of Civil Engineering, 2016, *, **
Published Online **** 2016 in SciRes. http://www.scirp.org/journal/ojce
http://dx.doi.org/10.4236/ojce.2016.*****

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 2/07/2016

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]). Different 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

How to cite this paper: Author 1, Author 2 and Author 3 (2016) Paper Title. *********, *, **-**.
http://dx.doi.org/10.4236/ojce.2016.*****

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 is 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 is not necessarily beneficial for the seismic response at ground surface; since it may lead to selective spectral amplification at periods around the fundamental period of the improved site. Gang and Jian-min [7] studied the effects of ground treatment on site seismic response. The Study showed that foundation Stabilization has an insignificant effect on frequency characteristic of the horizontal acceleration response spectrum, but the PGA may 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 typicalcenter-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 tables 1 and 2, respectively. In order to investigate the effect of PGA, the accelerograms have been normalized to 0.2g and 0.7g.

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

Earthquake	Northridge	Loma prieta
Date	1994/01/17	1989/10/18
Station	24207 Pacoima Dam (upper left)	47379 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	23598 Rancho Cucama - Deer Can	58338Piedmont 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

2.1. Se

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 andcomputational effort. In addition, the commercially available 3d codes for performing numericalanalysis of geotechnical earthquake engineering problems are very few and usually these codes have asmaller potential than commercial 2d codes. For example, 2d codes offer the use of advancedconstitutive models or element types that are not found in the libraries of 3d codes. Hence, thenumerical research in geotechnical earthquake engineering has been historically based on the use of (1 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 andstability in geotechnical engineering applications. Dynamic analysis in PLAXIS can mainly be dividedinto two types of problems. The first one is related to single source vibrations and the second one isconcerned to earthquake problems. In earthquake problems, the dynamic loading source is usuallyapplied along the bottom of the model resulting to shear waves that propagate upwards. These types ofproblems 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 analysesmay be accurately used for simulating the truly 3d problem of the seismic response of the improvedsites. 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 stonecolumns in plane strain. Janalizadeh et al. [16] investigated the seismic response of pile foundations inliquefiable 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 softclay, interface elements have been used. Finite element analyses were carried out using 15-nodedtriangular elements. The bottom boundary of the mesh was set at the top of the rock with zerodisplacements. 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 materialproperties of the piles, the sand cushion, and the soil layer are presented in Table 3. The young'smodulus 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].

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/m3	22	21.3	17
Young's modulus	E	kN/m2		260000	50000
Poisson' ratio	ν		0.2	0.3	0.25
Cohesion	c	kN/m2		1.5	5
Friction angle	φ	0		30.5	21
Dilatancy angle	ψ	0		0	0
Interface strength	R_{inter}		0.9		0.67

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 theelastic 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 thefamiliar formula: $T=4H/V_S$, in which H is the soil depth and V_S 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 tables 4 and 5, respectively.

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 thefar-fault earthquakes. The amplification factor is defined as the ratio of the PGA of the improvedground 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 and 19]. The PGA and amplification factor on the surface of the natural ground under near-faultLoma Prieta and Northridge earthquakes with PGAs equal to 0.2g are presented in table 6. As it can beseen in these cases, both the natural ground (without stabilization regional) and the improved groundunder near-fault Loma Prieta and Northridge earthquakes with the PGAs equal to 0.2g show linearbehavior (table6 and Fig.1(a)).

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

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=0.7g

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

It is seen from Fig. 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 theamplification factor of the natural ground. The reason is that the improved ground is stiffer than thenatural ground and in the case that the soils have linear behavior and bedrock is rigid, the softer sitehas higher amplification than the stiffer site [19] consequently, the amplification factor for theimproved ground with the elastic modulus of piles equal to 500 MPa is less than the amplificationfactor of the improved ground with the elastic modulus of piles equal to 100 MPa. Because thefundamental period of the improved ground with E_{pile}=1000 MPa is approximately coincident with thepredominant period of the earthquake, resonance happens and the amplification factor increases.Again the amplification factor for the improved ground with E_{pile}=5000 MPa decreases because of itsstiffness 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 theimproved ground with E_{pile}=100 MPa is slightly less than the amplification factor of the natural ground.In E_{pile}=500 MPa, resonance happens and the amplification factor increases. Then as the elasticmodulus of the piles increases, the amplification factor decreases.

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

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

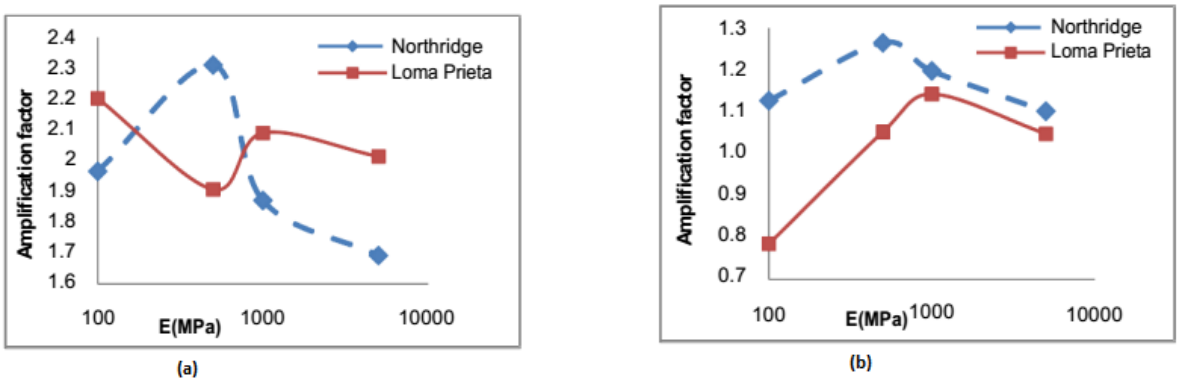

Figure 1. Amplification factor on the surface of improved grounds under near-fault earthquake with (a) PGA=0.2g and (b) PGA=0.7g

The PGA and amplification factor on the surface of the natural ground under far-fault earthquakes with PGAs=0.2g are presented in table 8. The natural ground in this study is composed ofsoft clay and has a large fundamental period. This site under far-fault Loma Prieta earthquake withPGA=0.2g, shows a linear behavior and due to the approximate coincident of its fundamental periodwith the predominant period of the earthquake, resonance happens. Improvement makes the site stifferand brings its fundamental period far from the predominant period of the excitation. So it is seen fromFig.3 that under Loma Prieta earthquake, as the elastic modulus of piles increases, the amplificationfactor decreases. Under far-fault Northridge earthquake with PGA=0.2g, the trend of the effect of theelastic modulus of piles on the amplification factor, considering the fundamental periods of improvedgrounds and the predominant period of the earthquake, is acceptable.

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

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

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

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

The PGA and amplification factor on the surface of the natural ground under far-fault earthquakes with PGAs=0.7g are presented in table 9. This site under far-fault earthquakes withPGAs=0.7g, shows a non-linear behavior. From Fig. 4, it can be observed that the previouslydiscussed trends for the improved ground under far-fault Loma Prieta earthquake with PGA equal to0.2g is repeated by the improved ground under far-fault Loma Prieta earthquake with PGA equal to0.7g. Under far-fault Northridge earthquake, the amplification factor first increases and then decreaseswith respect to elastic modulus of the piles.

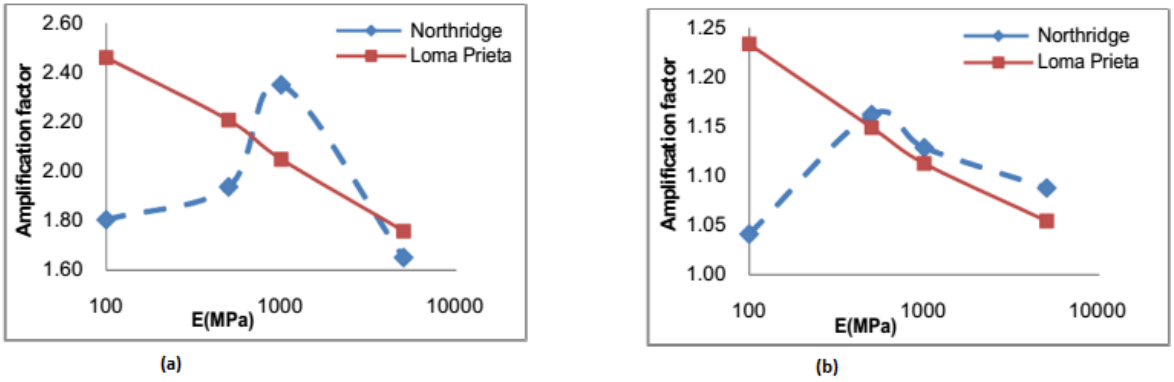

Figure 2. Amplification factor on the surface of the improved grounds under far-fault earthquake with: (a) PGA: 0.2g and (b) PGA: 0.7g

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

Figs. 3a & 4a 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, Figs. 5c & 6cshow that the effect of the improvement on the spectral ordinates. It is observed that under near-faultLoma Prieta earthquake with PGA=0.2g, the improved ground with E_{pile}=5000 MPa de-amplifies themotion for intermediate periods (between 0.58 and 1.64 sec), but under Loma Prieta earthquake withPGA=0.7g the improvements de-amplify the motion at short periods (smaller than 0.5sec) forapproximately all of the young's modules and large periods (larger than 1.6sec) for E_{pile}=1000 & 5000MPa.

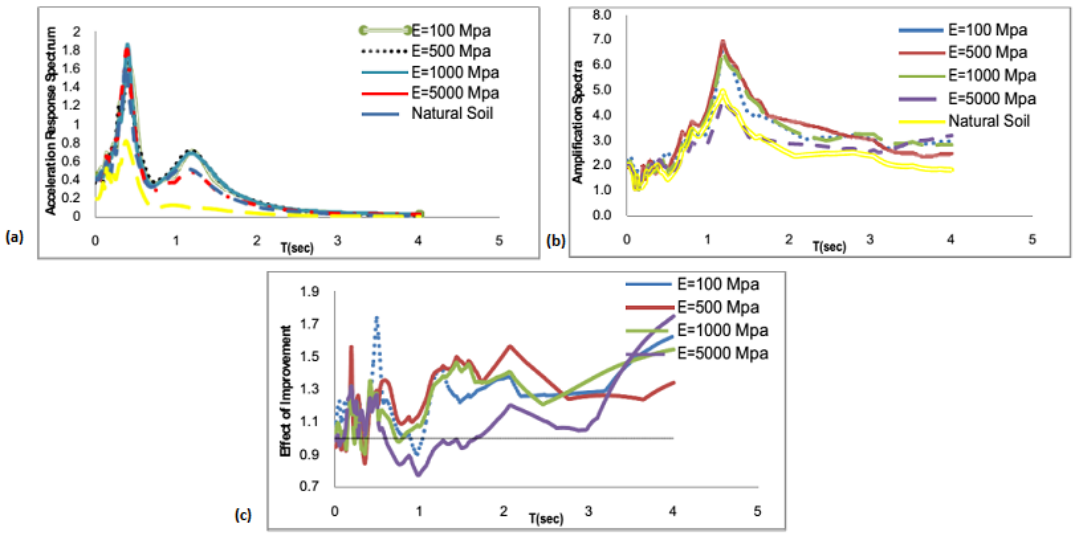

Figure 3. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Loma Prieta earthquake with PGA=0.2g: (a) elastic response spectra, (b) amplification of S_a, (c) the effect of improvement on S a

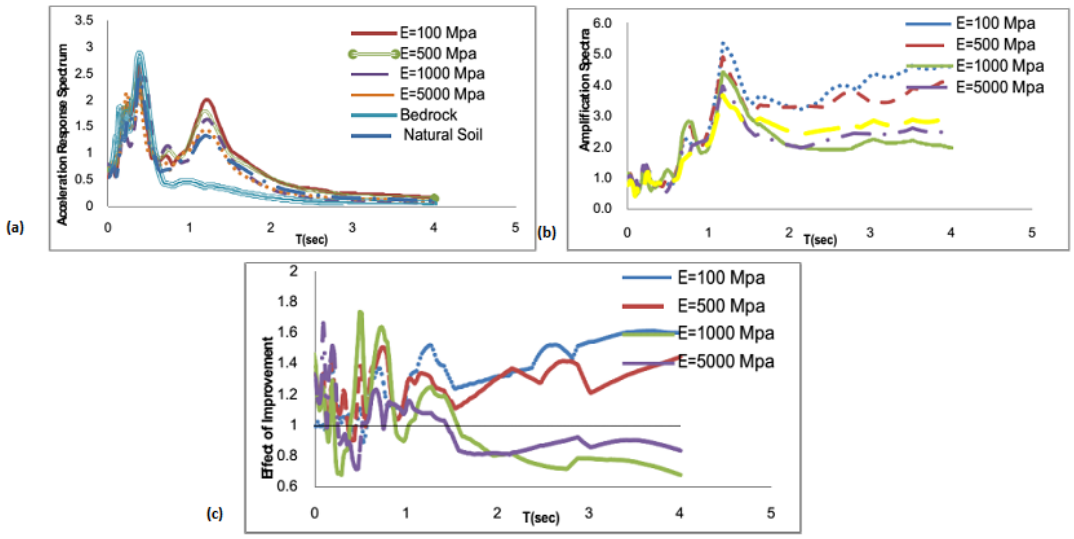

Figure 4. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Loma Prieta earthquake with PGA=0.7g: (a) elastic response spectra, (b) amplificationof S_a, (c) the effect of improvement on S a

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 Figs. 5a & 6a, the acceleration response spectra have two peaks. The improved ground exhibits greater peakspectral accelerations at shorter periods, and the peak spectral acceleration of the improved ground atlarger 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 E_{pile}=5000 MPa. Fig. 7c shows that underNorthridge earthquake with PGA=0.2g, the improvements de-amplify the motion for intermediateperiods (between 0.64 and 1.2sec). Fig. 8c shows that under Northridge earthquake with PGA=0.7g, theimprovements de-amplify the motion for intermediate periods (between 0.52 and 1.3 sec & between and 3.2 sec) except E_{pile}=500 MPa. The improved ground with E_{pile}=500 MPa only de-amplifies the motion for intermediate periods (between 0.52 and 1.3 sec).

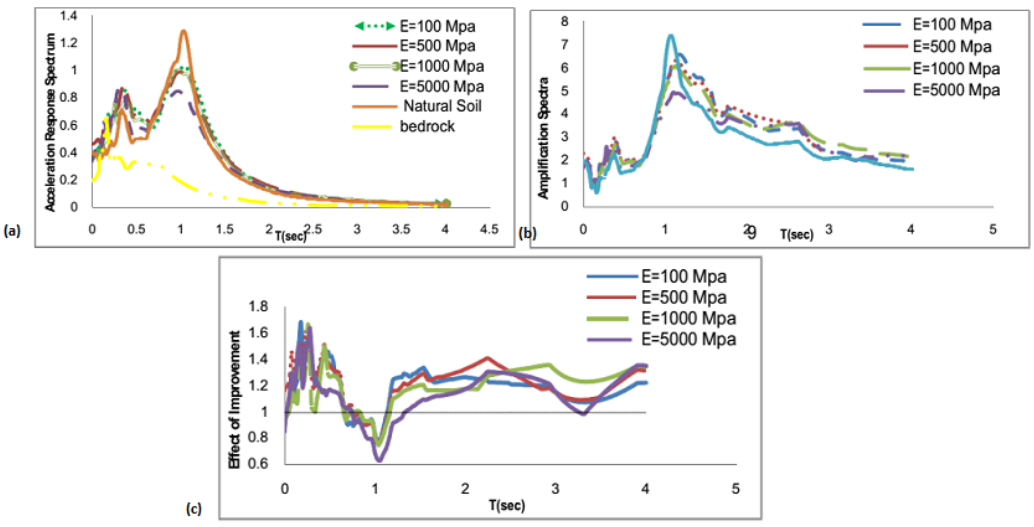

Figure 5. Comparison of seismic response on the surface of the natural ground and its improvementunder near-fault Northridge earthquake with PGA=0.2g (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa

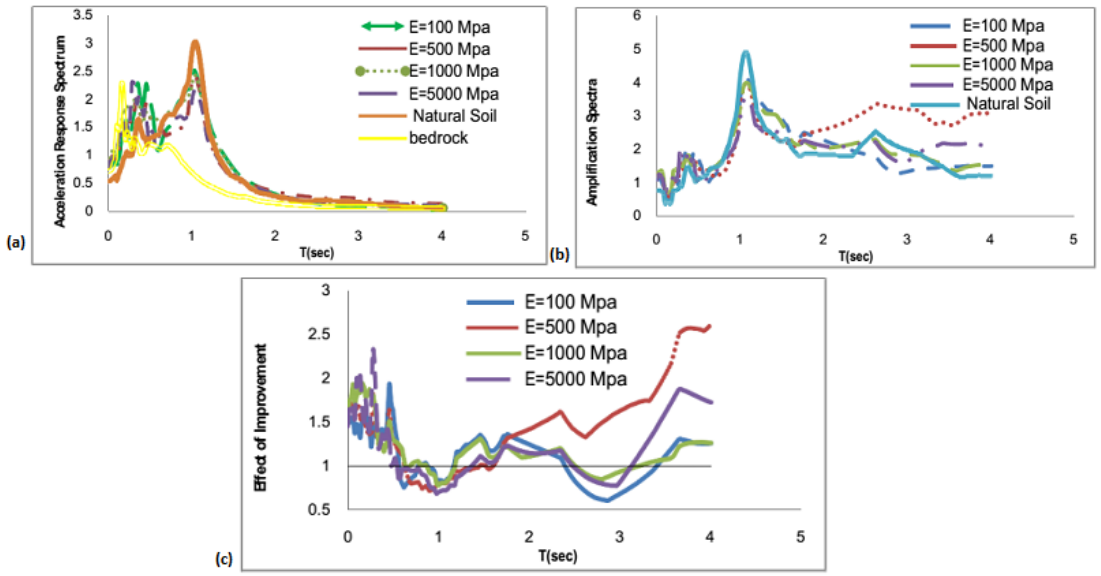

Figure 6. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Northridge earthquake with PGA=0.7g (a) elastic response spectra, (b) amplificationof Sa, (c) the effect of improvement on Sa.

Therefore, figures 3, 4, 5 & 6 shows that the acceleration response spectra depend strongly on the ground motion input. Under Loma Prieta earthquake, the acceleration response spectra have also twopeaks, but in contrast with Northridge earthquake, the acceleration response spectra of the naturalground are approximately smaller than the acceleration response spectra of the improved ground at the two peaks.

As it can be seen in Figs. 7a & 8a, under far-fault Loma Prieta earthquake like the near-fault ones (Figs 3 & 4), the acceleration response spectra for the improved ground exhibits greater spectralaccelerations at the two peaks. Fig.7(c) shows that all of the improvements de-amplify the motion atshort periods (approximately T<0.1 sec). The improved ground with E_{pile} = 5000 MPa also de-amplifies the motion at intermediate and large periods. The significant point that can be seen in Fig. 10cis that the acceleration response spectra for improved ground with E_{pile} =5000 MPa is less than theacceleration response spectra of the natural ground for periods greater than 0.54 s e c .

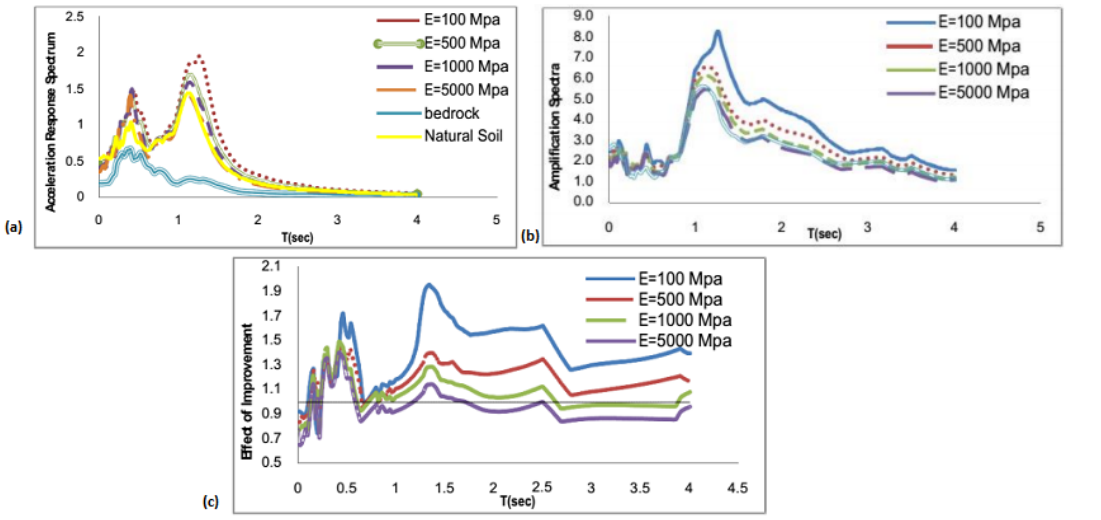

Figure 7. Comparison of seismic response on the surface of the natural ground and its improvementunder far-fault Loma Prieta earthquake with PGA=0.2g (a) elastic response spectra, (b) amplificationof Sa, (c) the effect of improvement on Sa.

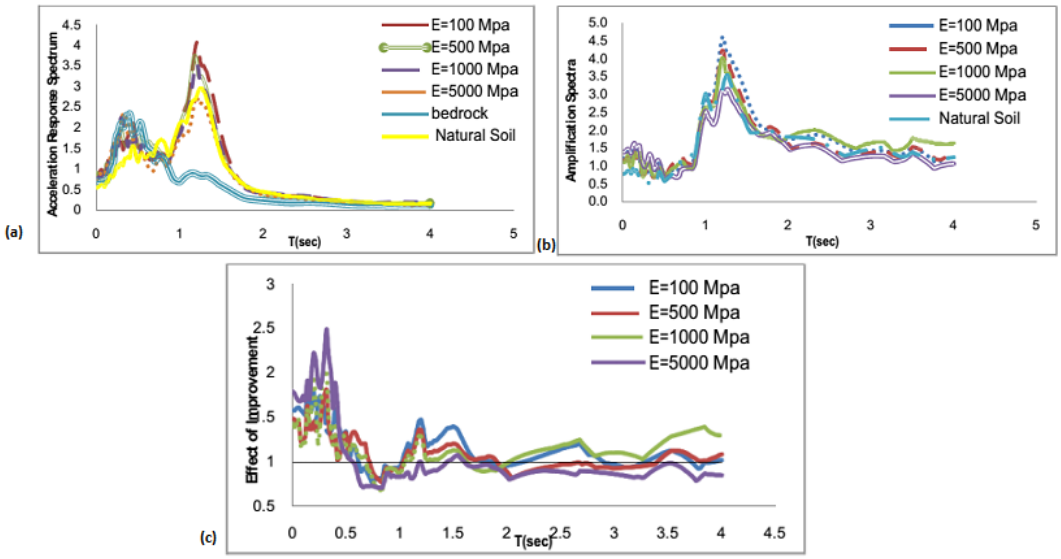

Figure 8. Comparison of seismic response on the surface of the natural ground and its improvementunder far-fault Loma Prieta earthquake with PGA=0.7g (a) elastic response spectra, (b) amplificationof Sa, (c) the effect of improvement on Sa.

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

In Fig. 9c, it can be observed that the improved ground with E_{pile}=5000 MPa de-amplifies the motion forall periods except for short periods (i.e. 0.5 sec < T), but other improvements de-amplify the motionjust for intermediate periods (0.58 < T < 1.2 sec). Fig. 12c shows that the improved ground with E_{pile}=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 < 1.02sec.

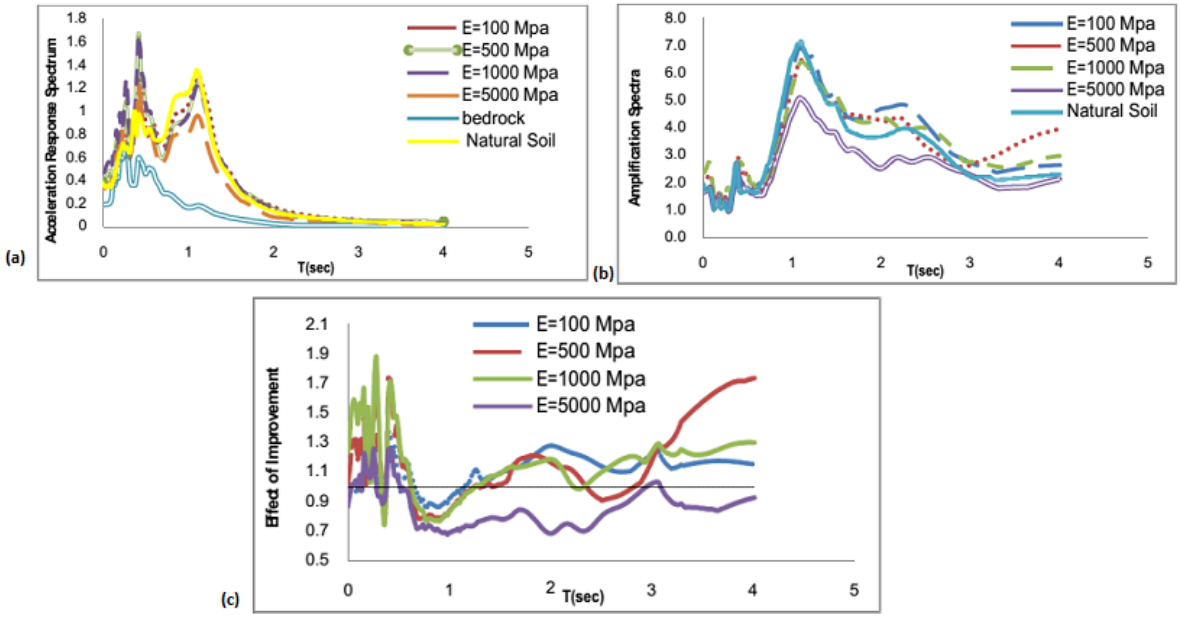

Figure 9. Comparison of seismic response on the surface of the natural ground and its improvementunder far-fault Northridge earthquake with PGA=0.2g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on S_a

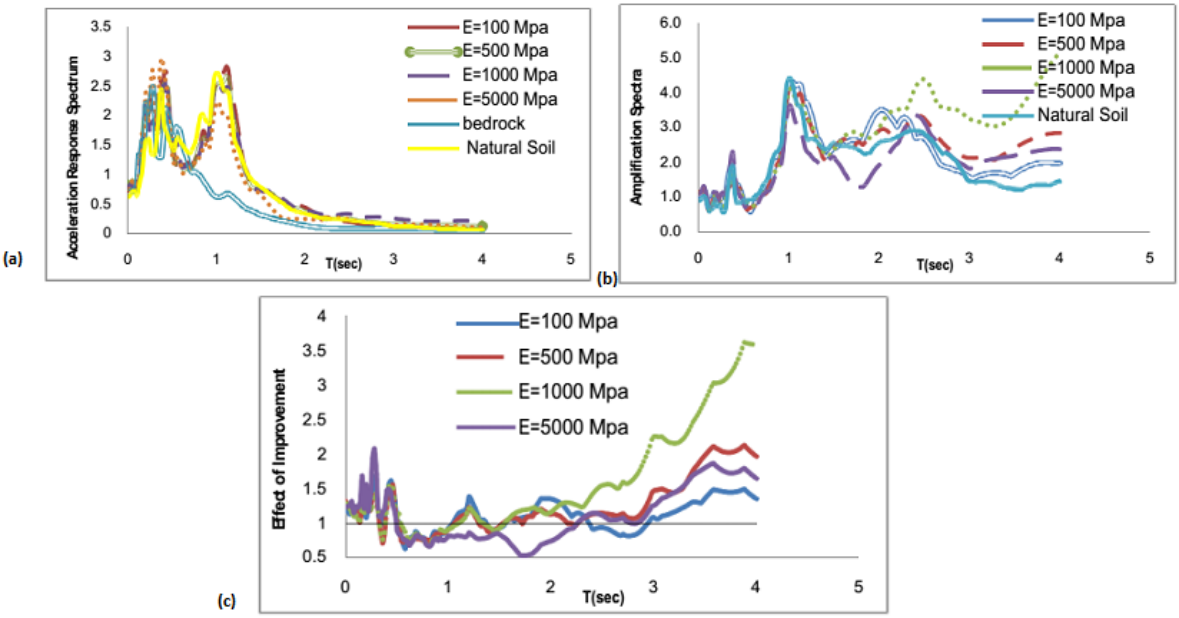

Figure 10. Comparison of seismic response on the surface of the natural ground and its improvement under far-fault Northridge earthquake with PGA=0.7g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on Sa.

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

But under Northridge earthquake the improved ground with E_{pile}=5000 MPa de-amplifies the motion atshort 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 rangedfrom 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.

Table 10. The amplification factor for improved ground with E_{pile}=1000 MPa under Loma Prieta earthquake

s/b	**Near- Fault** PGA=0.2g	**Far-Fault** PGA=0.7g	PGA=0.2g	PGA=0.7g
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

Figs. 11 & 12 graphically show the acceleration response spectra for these analyses. As it can be seen, changing the pile distance ratio doesn't have any significant effect on the seismic response of the site.

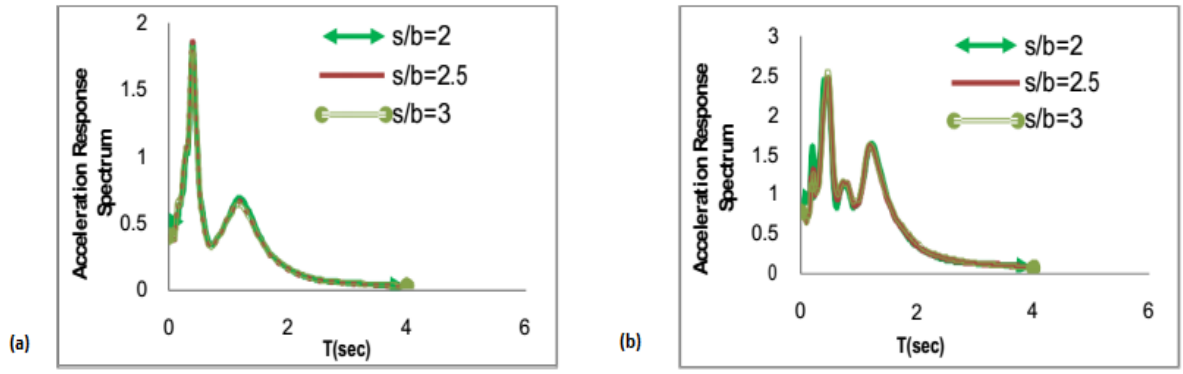

Figure 11. Acceleration response spectra for different pile distance ratios under near-fault Loma Prieta Earthquake with: (a) PGA=0.2g and (b) PGA=0.7g

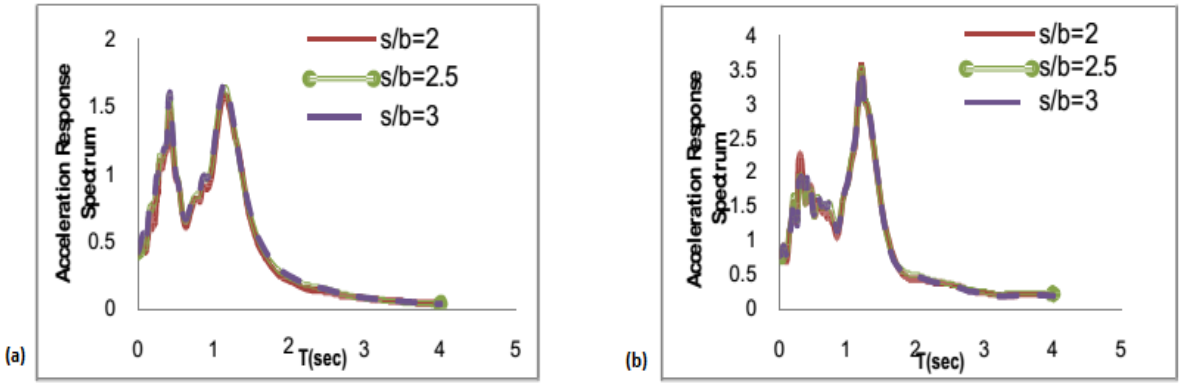

Figure 12. Acceleration response spectra for different pile distance ratios under far-fault Loma Prieta Earthquake with: (a) PGA=0.2g & (b) PGA=0.7g

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 Fig.17.

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

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

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=0.7g

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

From Fig. 18a, it can be observed that under near-fault Loma Prieta earthquake with PGA=0.7g, the natural ground in Babol city shows non-linear behavior and de-amplifies the motion. Improvement makesthe site stiffer, so strains become smaller and the improved ground shows elastic behavior. These are better depicted in Fig. 14b. Fig. 14c, which shows that the improvement de-amplifies the motion for periodsbetween 1.5 and 3.52 sec. Under near-fault Loma Prieta earthquake with PGA=0.7g, improvement withE_{pile}=1000 MPa in a 30-m-thick clay layer also amplifies the motion for periods larger than 1.5 sec(Fig.4c).

In this section, the acceleration response spectra (S_a for 5% damping), amplification spectra and the effect of improvement on S_a for the input motion at the ground surface for both natural ground and the improved ground in the Babol city are graphically shown. From Fig. 13a, it can be observed that under near-fault Loma Prieta earthquake with PGA=0.2g, the natural ground in Babol city amplifies the motion for all periods except for the periods between 0.06 and 0.26 sec, which can better be seen in Fig. 13b. As it can beseen in Fig. 13a, improvement makes the site stiffer and therefore increases the peak spectralacceleration at short periods and decreases the peak spectral acceleration at large periods**.** In contrastwith Fig. 3c in which improvement with E_{pile}=1000 MPa in a 30-m-thick clay layer approximately amplifiesthe motion for all periods, Fig. 13c shows that the improvement de-amplifies the motion for intermediate periods (between 0.78 and 2.18 sec).

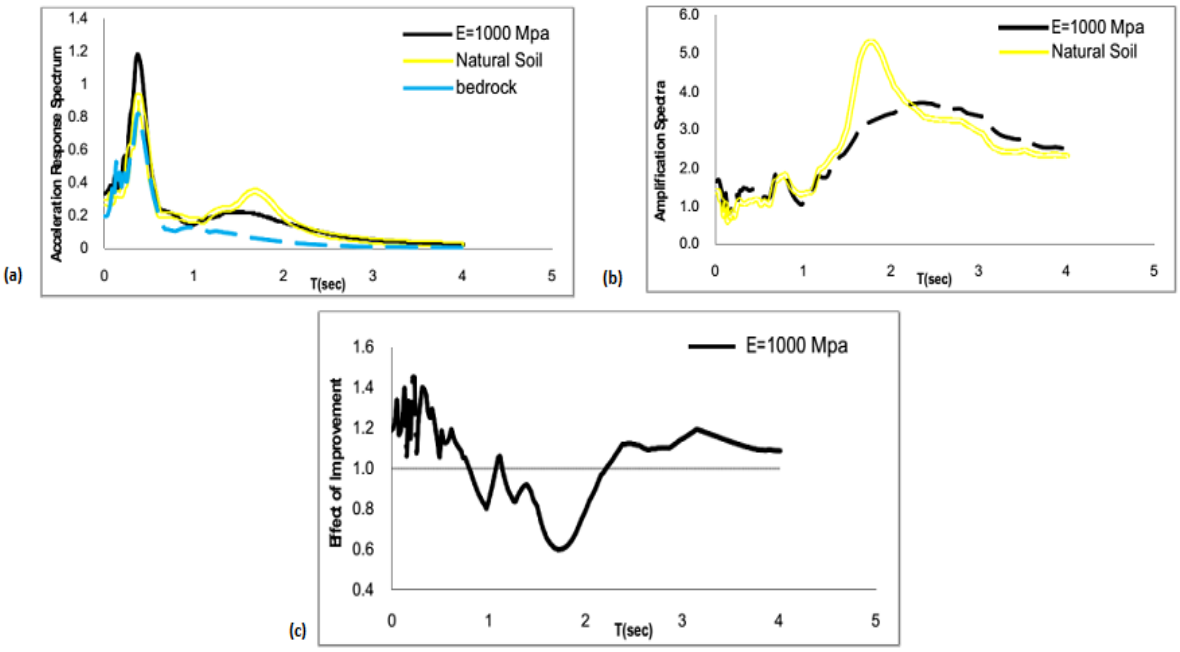

Figure 13. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Loma Prieta earthquake with PGA=0.2g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on S a

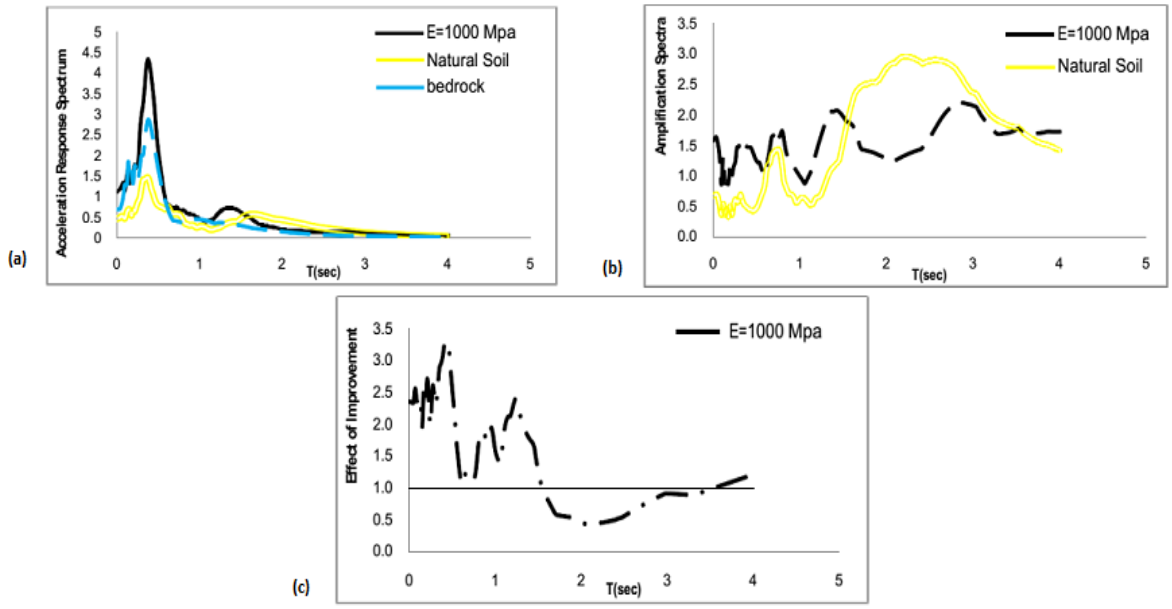

Figure 14. Comparison of seismic response on the surface of the natural ground and its improvement under near-fault Loma Prieta earthquake with PGA=0.7g: (a) elastic response spectra, (b) amplificationof Sa, (c) the effect of improvement on S a .

From Fig. 15a, it can be observed that under far-fault Loma Prieta earthquake with PGA=0.2g, the natural ground in Babol city amplifies the motion for all periods except for the periods between 0.2 and 0.3sec & 0.46 and 0.56 sec. In contrast with Fig. 7c, in which improvement with E_{pile}=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. Fig. 15c shows that the improvement de-amplifies the motion for periods between 1.5 and 3 sec. Underfar-fault Loma Prieta earthquake with PGA=0.7g, like the near-fault one with PGA=0.7g, the natural ground in Babol city shows non-linear behavior and the improved ground shows linear behavior (Fig.16a). The improvement de-amplifies the motion for periods larger than 1.6 sec (Fig. 16c). Therefore, under Loma Prieta earthquake with PGA=0.2g, the natural ground in Babol city shows linearbehavior and under Loma Prieta earthquake with PGA=0.7g, it shows non-linear behavior and de-amplifies the motion. Improvement makes the site stiffer, so strains become smaller and the improvedground 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 inthe natural ground in Babol city de-amplify the motion for large periods. As a result, it can be concluded that theacceleration response spectra also depend on soil layers.

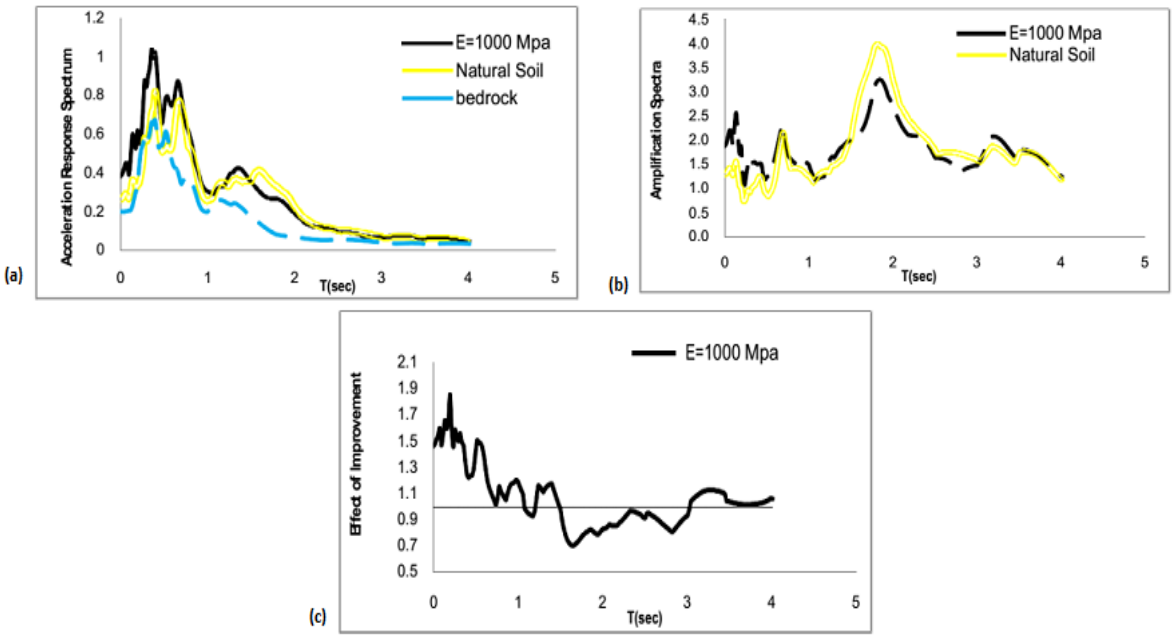

Figure 15. Comparison of seismic response on the surface of the natural ground and its improvementunder far-fault Loma Prieta earthquake with PGA=0.2g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on S a .

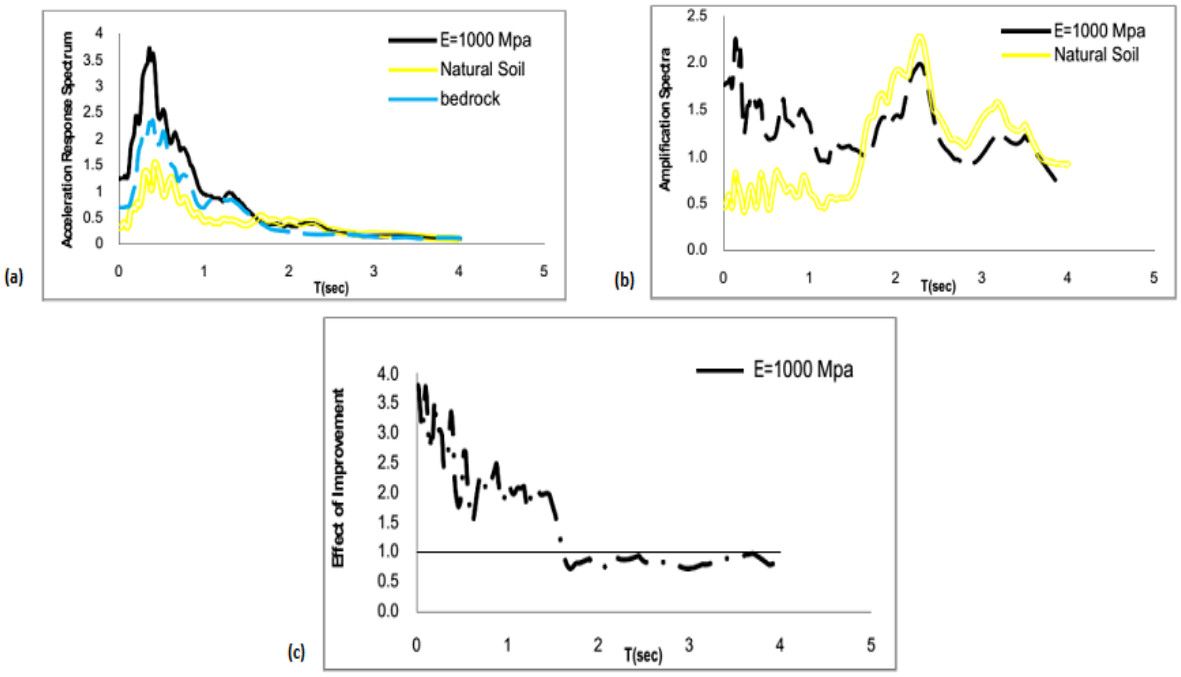

Figure 16. Comparison of seismic response on the surface of the natural ground and its improvement under far-fault Loma Prieta earthquake with PGA=0.7g: (a) elastic response spectra, (b) amplification of Sa, (c) the effect of improvement on S a

6. Conclusion

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

a) The values of PGA and amplification factor on the surface of the natural ground and improved grounds depend strongly on the fundamental period of the site, the predominant period and theintensity of the ground motion input.
b) 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 twopeaks and the improved grounds exhibit greater peak spectral accelerations at shorter periods and thepeak spectral acceleration of the improved ground at larger periods is smaller than the peak spectralacceleration of the natural ground. Under Loma Prieta earthquake, the acceleration response spectrahave also two peaks, but in contrast with Northridge earthquake; the acceleration response spectra ofthe natural ground are approximately smaller than the acceleration response spectra of the improvedground at two peaks.
c) From the figures of the effect of improvement on S_a, 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=0.2g, the improved grounds with E_{pile} = 5000 MPa also de-amplify themotion at periods larger than 1.5 sec.
d) 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.
e) Under Loma Prieta earthquake with PGA=0.2g, the natural ground in Babol city shows linear behavior; and under Loma Prieta earthquake with PGA=0.7g, it shows non-linear behavior de-amplifying themotion. Improvement makes the site stiffer, so strains become smaller and the improved ground showselastic behavior. As it can be seen from this section, the seismic response of the natural ground in Babol city isdifferent from the seismic response of a 30-m-thick clay layer. The amplification factors of theimproved grounds are greater than the amplification factors of the natural grounds in Babol andimprovement in this area de-amplifies the motion for large periods. So it can beconcluded that the acceleration response spectra also depends on soil layers and its characteristics.

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