Effectiveness of Proposed Relationship for Increasing of Bending Stiffness of Circular Micropile Group in Sandy Soil

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ABSTRACT

The increase of effective period of structures results from the increase of foundation movement due to changes of soil stiffness. In high-rise buildings, due to the seismic motions, the bending moment in sub-structure will cause foundation rotation. The increase of rotation in the sites with different shear wave velocity will cause different behaviors. The increase of the site stiffness leads to the decrease of settlement and generation of uplift condition in the foundation. This circumstance will ultimately lead to the increase of structural movements and seismic response. Applying the circular micropile group as foundation will reduce and control the rotations of foundation. In this paper, by means of FLAC3D software and by parametric study of the inclination angles, distance ratio, and slenderness changes in circular micropiles group, a new equation is developed. Developed expression is used for showing how to affect the decrease of foundation rotations in sites with high shear wave velocity and to decrease structural seismic responses by presenting necessary diagrams.

Keywords:
Rocking stiffness; Effective period; Subgrade reaction modulus; Rotational angle of micropile foundation; Uplift

1. Introduction

Rocking motions have an important role in increasing the effective period of structures. More than 90% of changes of structural period are related to rocking motion of foundation [1]. Construction of high-rise structures on shallow foundations, which are placed on stiff sites, due to the decrease of foundation settlement and the increase of bending moments, will create uplift movement in foundation. When the earthquake occurs, the structural period is increased and, finally, the seismic responses of structure will increase.

Seismic motions will increase displacement in the roof, which will lead to the increase of bending moments in substructure. However, if the site is soft, the soil is not able to withstand large bending moments, and the settlement will increase in the corners of the foundation. The increase of bending moments leads to the increase of settlement, and here the foundation rotation will increase, but uplift motion will not appear. The construction of structures with shallow foundation on stiff sites will increase because of uplift phenomenon, but this amount will be smaller than soft sites in which uplift phenomenon has not emerged.

The use of circular micropile group will have a great effect on controlling seismic motion of the structure because of the circular shape of group and the increase of inclination angle of micropiles. The application of circular micropiles group with different application radius in micropiles group can control the foundation motions properly and can finally decrease the structural response.

Bearing capacity of circular micropiles group could be a function of number, length, inclination angle and diameter of micropiles, and this capacity varies in different densities and seismic motions. Moreover, in comparison with the regular foundation, subgrade reaction modulus of micropiles foundation will be increased. Applying the circular micropiles group will reduce the foundation settlement. The increase of inclination angle of circular micropiles group in soft sites will also increase bearing capacity and subgrade reaction modulus [2, 3].

Inclination angle will not have any role in increasing rocking stiffness of the piles in high-rise structures. This parameter is effective only in horizontal stiffness of foundations [4].

The increase of safety factor resulting from the ratio of bearing capacity to axial load imposed to foundation $\frac{N_{U0}}{N_U}$ can increase rocking stiffness of foundation and decrease its rotations. As the safety factor increases more and more, the effect of rocking motion of foundation will decrease [5].

This paper studies the effect of rocking stiffness changes of foundation due to the injection of circular micropiles group, and effective parameters on increasing the efficiency in stiff site (Type 2 according to the Iranian Standard 2800 [6]). Thickness, inclination angle, number and pressure of micropile injection are the effective parameters among the others in reducing the rocking motion of micropile foundation. The results of this study are highly consistent with the results of previous analytical and experimental studies.

2. Modeling

In this study, the finite difference software of FLAC3D was used to model foundation, soil and structure. The analyzed structure includes the columns and the equivalent mass of a 23-story structure. The participating mass in seismic calculations of structure is 5920 tons, which is widely spread throughout the column. A broad foundation in dimensions of $10 \times 10 \times 1$ m, which is on Type 2 soil based on Iranian Standard 2800 [6], and with shear wave velocity of 375 m/s has been used. The features of soil foundation, and structure are shown in Table (1). The static settlement of the structure is 5.4 mm and, considering the imposed static, the amount of subgrade reaction modulus is 1.07×10^8 N/m^3.

Table 1. Property of soil and foundation.

	Soil	Foundation	Unit	Symbol
Density	2100	2500	Kg/m3	ρ
N_u	0.35	0.25	-	ν
Elasticity	7.96E+08	2.22E+10	Pa	E
Friction	21	-	Degree	φ
Cohesion	5E+04	-	Pa	C
Tensile	13E+04	-	Pa	T

The minimum space between the center of the structure and model borders should be 3-4 times of the horizontal foundation radius and 2-3 times of the vertical foundation radius [7]. This value for rectangular foundations is shown in Eqs. (1) and (2).

$$X\ or\ Y\ Direction \geq 2\times(3\sim4)\left(rh=\sqrt{\frac{B\times L}{\pi}}\right) \tag{1}$$

$$Z\ Direction \geq 2\times(2\sim3)\left(rz=\sqrt{\frac{B\times L}{\pi}}\right) \tag{2}$$

Due to large dimensions of circular micropiles group and its orientation beneath the foundation, and in order to avoid seismic wave distortions, the dimensions of the model are considered as 100×100×50 m. The analyzed model is shown in Figure (1).

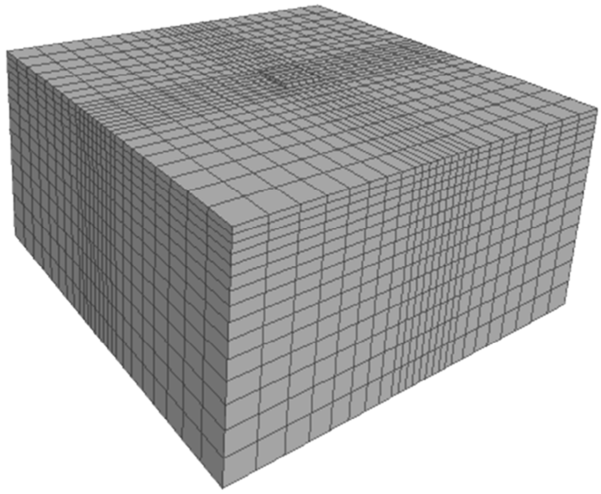

Figure 1. Soil and foundation model.

A total of seven records were selected to cover a range of frequency content, duration and amplitude. These records come from earthquakes having a magnitude (MW) range of 6.2 to 7.3. Information pertinent to the ground motion data sets, including station, components of earthquake and peak ground acceleration (PGA) of vertical and horizontal components are presented in Table (2).

2.1. Model Validation

To evaluate the model, the experimental and numerical results from FLIP software [8] was used. In this work, a sinusoidal harmonic acceleration with 0.1 HZ frequency and input acceleration of 0.005g was employed. The goal of the comparison between the finite element model and the experimental work is to ensure that the model including its elements, material properties, real constants and convergence criteria is adequately simulating the response of the member. Figure (2) presents the acceleration response histories of experimental and analytical work from FLIP and FLAC3D program. Figure (2) shows that the FE method can almost exactly follow the measured data. Taking into account of many unknown input parameters; however, this level of accuracy is regarded as acceptable.

3. Factors Affecting Rocking Stiffness

Generally, the interaction effects between soil and structure result from the flexibility of soil under the foundation and relative motion between the foundation and free surface. In high-rise structures, the inertia force generated in the structure creates large shear forces and bending moments in foundation. These forces will increase foundation displacement in comparison with the free surface. The results obtained from some studies [1, 9] show that high-rise structures have a primary role in foundation movements so that, in gigantic structures, more than 90% of period is related to rocking motion of foundation.

Rocking stiffness of foundation depends on several factors such as shear modulus of soil, foundation dimensions, Poisson's ratio, and rotation angle of foundation. The difference of foundation displacement in NS and EW directions and the angular changes of foundation due to the application of seismic motion are shown in Figure (3).

The more the structural height is, the more the

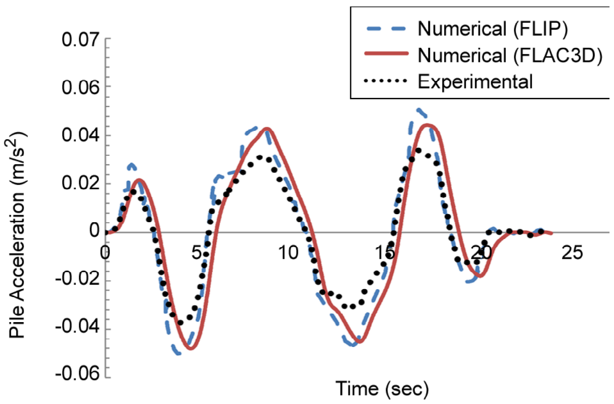

Figure 2. Model validation.

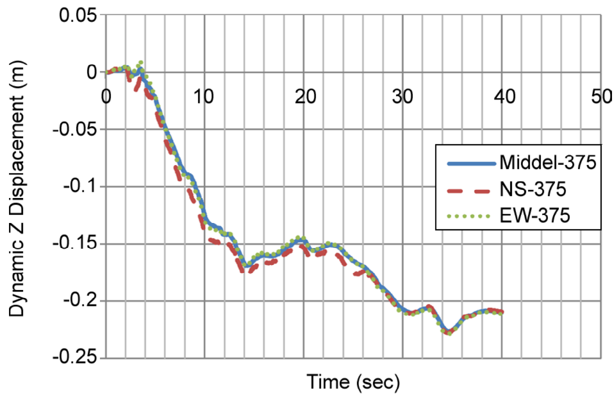

Figure 3. Vertical displacement of foundation in the EW and NS directions.

Table 2. Selected ground motion database.

	Earthquake	Year	Station	M_w	PGA-H_{max} (g)	PGA-H_{min} (g)	PGA-V_{ert} (g)
1	Gazli (USSR)	1976	Karakyr	7.1	0.718	0.608	1.264
2	Imperial Valley	1979	Bonds Corner	6.4	0.755	0.588	0.425
3	Morgan Hill	1984	Coyote Lake Dam	6.2	1.298	0.711	0.388
4	Erzincan (Turkey)	1992	Erzincan	6.8	0.515	0.496	0.248
5	Landers	1992	Lucerne	7.3	0.785	0.721	0.818
6	Northridge	1994	Rinaldi Rec Stn	6.7	0.838	0.472	0.852
7	Kobe (Japan)	1995	KJMA	6.9	0.821	0.599	0.343

moments imposed to the foundation resulting from seismic motions will be. The maximum bending moment that a foundation can withstand until the uplift is the critical moment, which depends on bending stiffness and rotation angle of foundation and subgrade reaction modulus as bellow:

$$M_{critical} = K_V . I . \theta_{critical} \quad (3)$$

$$\theta_{critical} = \frac{2.N}{K_V . B . L^2} \quad (4)$$

where K_V is the modulus of subgrade reaction, I is bending stiffness of foundation, $\theta_{critical}$ is the angle of critical rotation of foundation under the seismic motions, N is axial static force exerted on foundation, B is the width, and L is the length of foundation. The rate of rocking stiffness of foundation is shown in Eq. (5).

$$K_\theta = \frac{M_{critical}}{\theta_{critical}} = \frac{k_V . I . \theta_{critical}}{\theta_{critical}} = K_V . I \quad (5)$$

As it is observed, the rate of rocking stiffness of foundation depends on flexural stiffness of foundation and the type of seismic site. Rocking stiffness in Equation 5 could be used when there is no separation between foundation and soil (uplift). Therefore, with regard to the settlement, dimensions of foundation, and the exerted load on it, the amount of critical rotation of foundation equals 1.1×10^{-3} rad, and the biggest rotation angle of foundation under the exertion of seismic loads also equals 3×10^{-3} rad. As a result, the rotation angle is bigger than the critical angle and uplift phenomenon will appear [10]. Rocking stiffness of foundation when uplift appears is shown in Eqs. (6-12) [11].

$$N = \frac{1}{2} . x . B . \sigma_2 \quad (6)$$

$$\sigma_2 = v_2 . K_V \quad (7)$$

$$v_2 = \theta . x \quad (8)$$

$$N = \frac{1}{2} . x^2 . B . \theta . K_V \rightarrow x = \sqrt{\frac{2.N}{B.\theta.K_V}} \quad (9)$$

$$M = N . \left(\frac{L}{2} - \frac{x}{3} \right) \quad (10)$$

$$M = N . \left(\frac{L}{2} - \sqrt{\frac{2.N}{9.K_V . B . \theta}} \right) \quad (11)$$

$$K_{\theta uplift} = \frac{1}{\sqrt{18.K_V . B}} . \left(\frac{N}{\theta} \right)^{\frac{3}{2}} \quad (12)$$

As shown in Eq. (12), rotation stiffness highly depends on the angle of rotation of foundation, Figure (4).

Generally, stiff site in comparison with the soft site, have less static and dynamic settlement due to the increase of stiffness. As a result, the bending moment of the high-rise structures, after a slight settlement within the substructure, will cause the separation of shallow foundation from the soil and uplift phenomenon will appear.

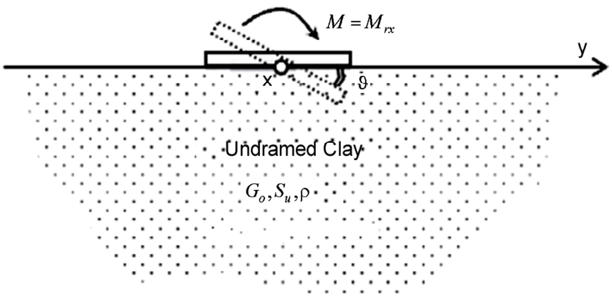

Figure 4. Rocking motion of the foundation [5].

4. Micropile Foundation

Micropiles are small piles whose application in soft soils with high injection pressure can reduce the motions and increase the flexural stiffness of foundation. The use of inclined micropiles will increase the system plasticity and will use all potential of micropile to increase the flexural stiffness of foundation against bending moments.

Some studies have been done on micropile group and circular micropile group in the form of lack of contact between foundation and soil, or even common area between micropile foundation and soil [2, 12 and 13]. These studies show that subgrade reaction modulus depends on the density and stiffness of soil so that as the density increases, subgrade reaction modulus increases too. On the other hand, the inclination angle of micropile has a positive effect on soils with low and medium density [14]. Figure (5) shows the effect of application of circular micropile group in previous studies on subgrade reaction modulus in various densities.

In addition, the studies show that bearing capacity of micropile foundation depends on the soil density. As the inclination angle increases, the bearing capacity increases in soils with low and medium density and it decreases in soils with high density. Figure (6) shows the bearing capacity of micropile foundation in various inclination angles [2].

The micropiles used in this research were studied in three diameters of 100, 150, 200 mm and the same length of 10000 mm and had the slenderness of 100, 67, 50 (L/D), respectively. 16 micropiles within the distance of S/D = 3, 4, 5 C/C were placed around circles with the radius of $R = \frac{3.D.n}{2.\pi}$ in which D is diameter, and n is the number of micropiles, Figure (7). The soil used in this study is according to Iranian standard 2800 Type-2 weathered conglomerate.

Static analyses of network micropiles injection in foundation shows that foundation settlement reduced from 5.4 mm to 5.2 mm with the injection of circular micropile group within the foundation.

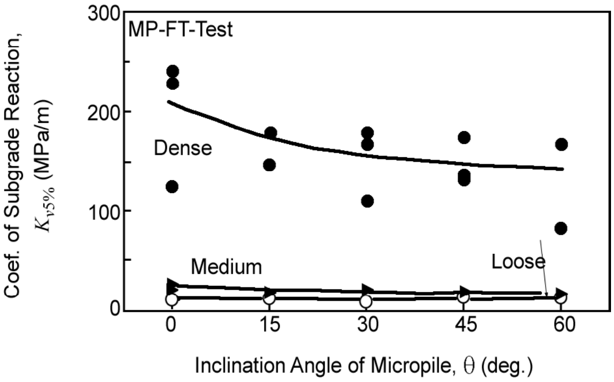

Figure 5. Module of substrate reaction at different densities [2].

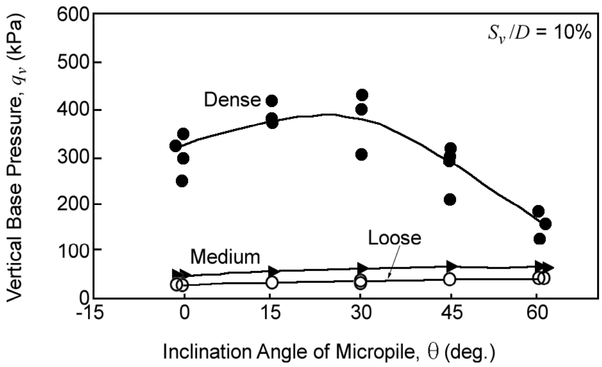

Figure 6. Bearing capacity of micropile foundation at different inclination angles [2].

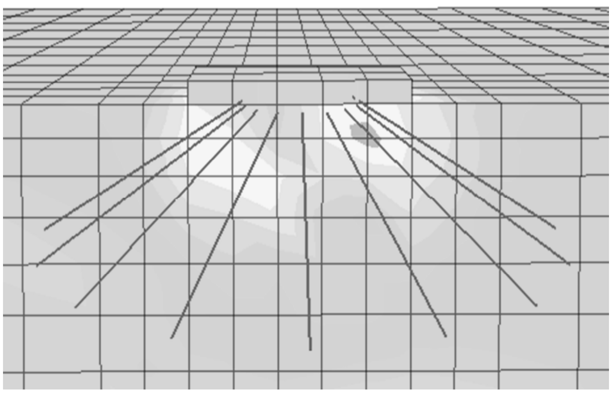

Figure 7. Micropile foundation used in the analyses.

4.1. Bearing Capacity

Bearing capacity of circular micropile group will decrease as the inclination angle of micropile increases. Figures (8) to (10) show the loading capacity of circular micropile group within three slenderness of 50, 67, and 100.

As shown in Figures (8) to (10), in stiff sites, the increase of inclination angle of micropile will decrease the loading capacity of the group.

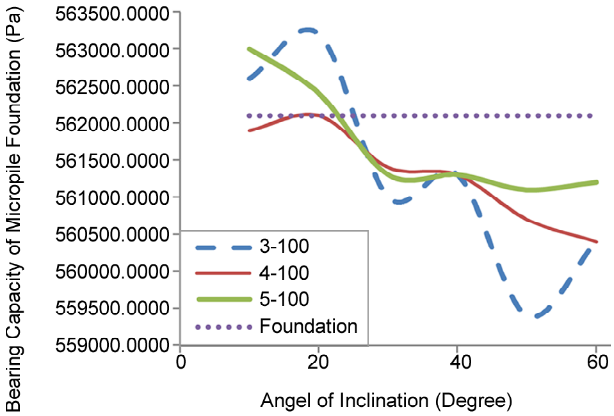

Figure 8. Bearing capacity of micropile foundation comparison to the regular foundation with relative slenderness of 100.

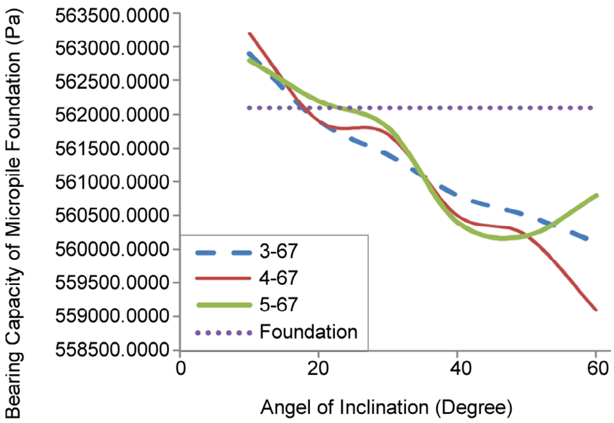

Figure 9. Bearing capacity of micropile foundation comparison to the regular foundation with relative slenderness of 67.

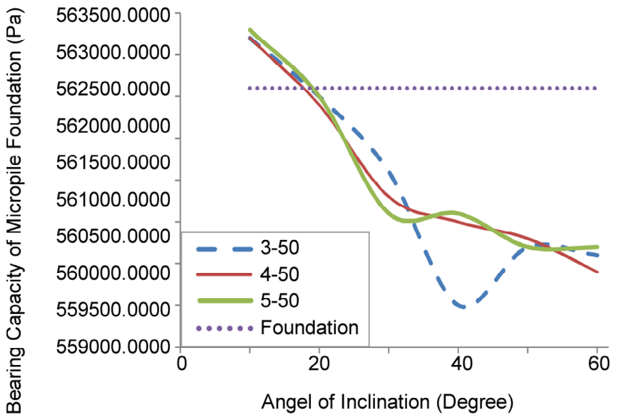

Figure 10. Bearing capacity of micropile foundation comparison to the regular foundation with relative slenderness of 50.

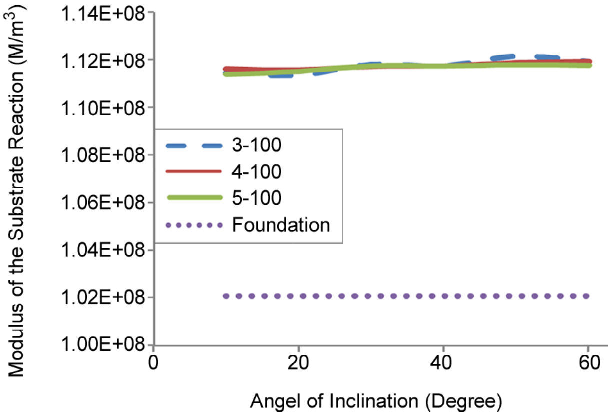

Figure 11. Module of subgrade reaction in relative slenderness of 100.

4.2. Modulus of the Subgrade Reaction

Considering two factors of settlement and loading capacity of micropile foundation, the reaction modulus of micropile foundation subgrade increase in comparison to normal foundation. This increase in three slenderness levels of 50, 66, and 100 and within three different distances (SD = 3, 4, 5) is shown in Figures (11) to (13).

Figures (11) to (13) show that subgrade reaction modulus increases slightly as the inclination angle increases.

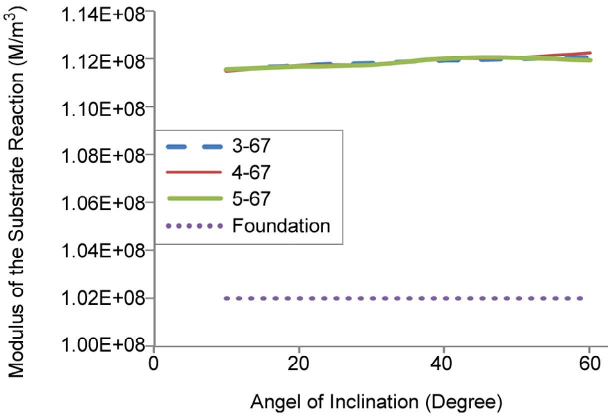

Figure 12. Module of subgrade reaction in relative slenderness of 67.

4.3. Rotation Angle

Generally, piles have more bearing capacity than micropiles due to their surface area and/or their high wall friction with soil. When tilted piles are used, the inclination angle of pile use the passive pressure of soil and increases plasticity in the piles. This behavior ultimately leads to the use of all bending capacity of the surface area and tolerates a great part of bending moments and does not allow the foundation to rotate more, Figure (14). Therefore, the decrease in rotation angle of foundation leads to decrease of structural period.

Small surface area of micropiles makes them withstand fewer forces than the piles, and as the number of micropiles increases the group bearing will increase, too. Figures (15) to (17) show the rotation angle of foundation before and after the injection of circular micropile group.

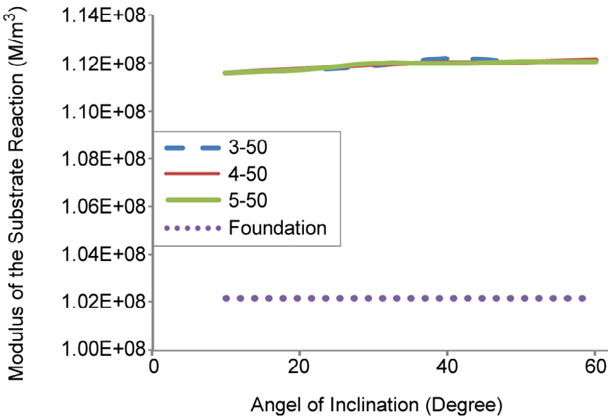

Figure 13. Module of subgrade reaction in relative slenderness of 50.

These figures also show that the rotation angle of micropile foundation will decrease as the circular micropile application increases. The results show that as the inclination angle of micropile decreases, the micropile foundation rotation will decrease, too.

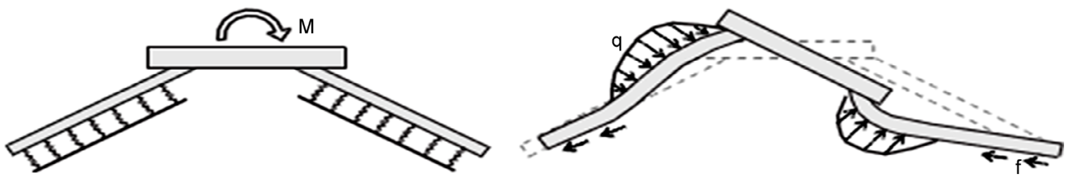

Figure 14. Pile plasticity by increasing the angle of inclination.

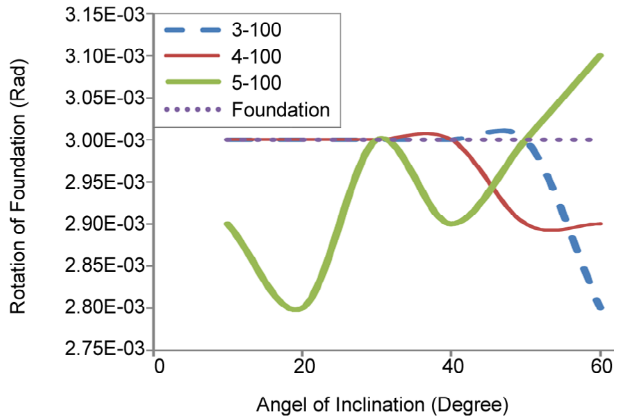

Figure 15. Rotation angle of micropile foundation relative to the normal foundation with relative slenderness of 100.

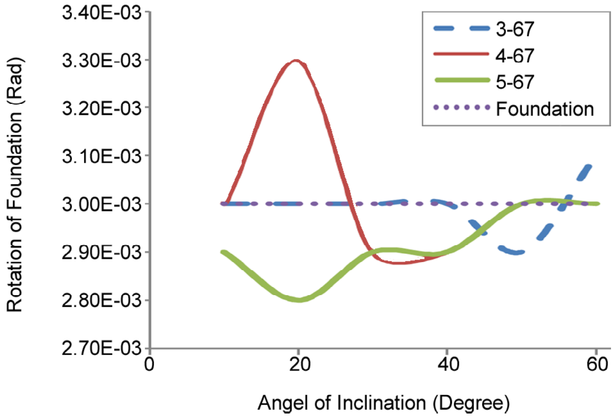

Figure 16. Rotation angle of micropile foundation relative to the normal foundation with relative slenderness of 67.

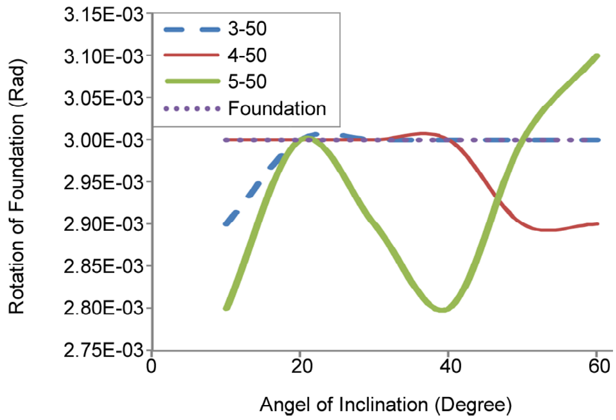

Figure 17. Rotation angle of micropile foundation relative to the normal foundation with relative slenderness of 50.

5. Proposed Equation

Eq. (12) showed that foundation rocking stiffness with the occurrence of uplift condition highly depends on foundation rotation angle, applied forces to the foundation, site reaction modulus, and foundation dimensions. The results showed that static settlement of micropiles foundation decreased 0.2 mm through the use of circular micropiles group so that if the above value is ignored, the static settlement of foundation center is stable and according to the Eq. (13).

$$DV_{st} = \frac{B.q_0}{E_S}.(1-v^2).\beta \tag{13}$$

Bearing capacity of circular micropiles group is much less than bearing capacity of single micropile due to minor settlements. Moreover, in stiff sites, the bending moment at the foundation will tend to pick up the foundation due to minor settlements. Therefore, in such sites, micropiles group acts as a controller to avoid foundation uplifting. Figures (18) to (20) show the bearing capacity of circular micropiles group in different slenderness and the distance ratios.

Eq. (14) shows micropile rocking stiffness when uplift appears:

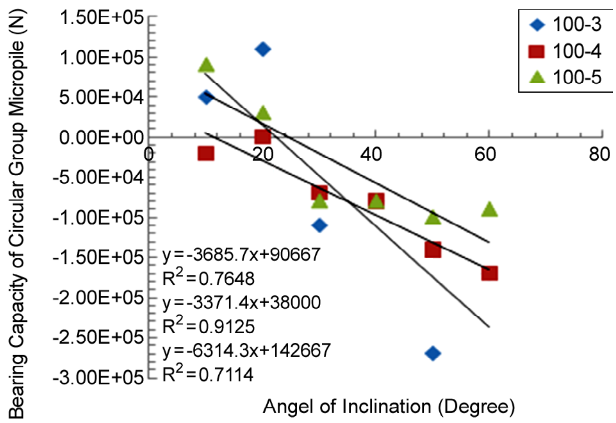

Figure 18. Bearing capacity of circular micropiles group with the relative slenderness of 100.

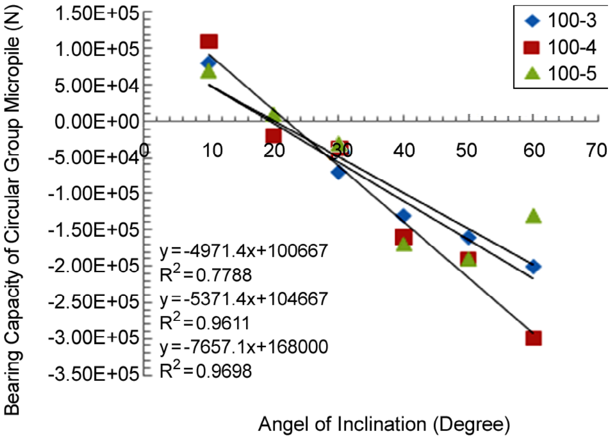

Figure 19. Bearing capacity of circular micropiles group with the relative slenderness of 67.

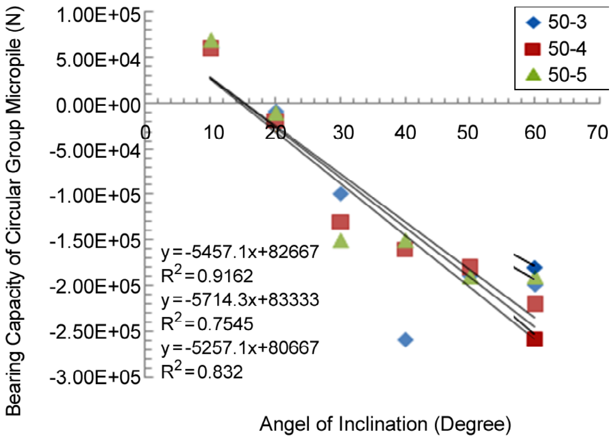

Figure 20. Bearing capacity of circular micropiles group with the relative slenderness of 50.

$$K_{\theta uplift} = \frac{1}{\sqrt{\frac{18.E_S.B}{(1-v^2).\beta.L}}}.\left(\frac{N}{\theta}\right)^{\frac{3}{2}} \tag{14}$$

In this equation, E_S is the elastic modulus of subgrade, B is the foundation width, L is the foundation length, v is Poisson ratio, θ is foundation rotation angle (rad), and β is foundation flexibility coefficient, which is determined from Figure (21).

Eq. (14) shows that rocking stiffness of foundation in uplift condition depends on several factors such as type of soil, foundation dimensions, applied force on foundation, and foundation rotation angle. The results showed that if circular micropile group is applied, the angle of foundation rotation will decrease. Figures (22) to (24) show the normalized rotation angle of micropiles foundation in comparison to regular foundation in different distance ratios and slenderness.

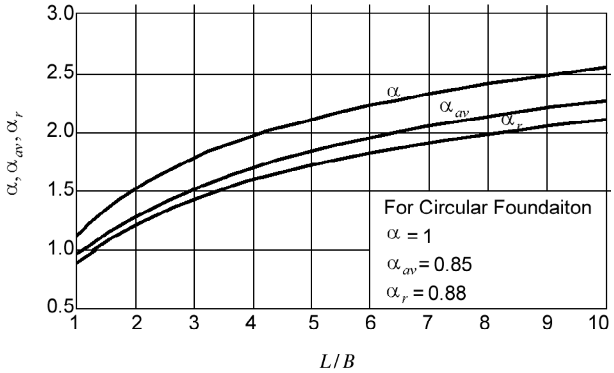

Figure 21. Determination of foundation flexibility coefficient (β) [15].

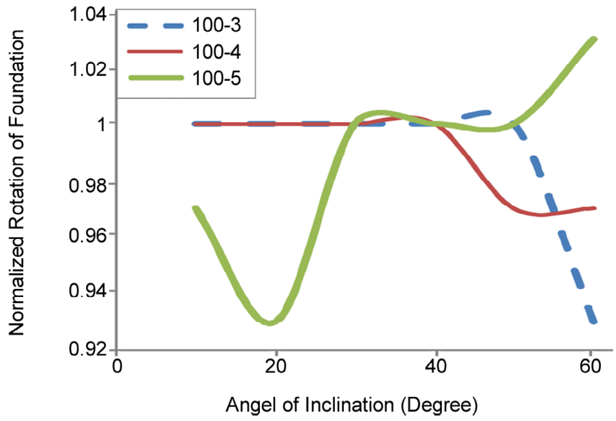

Figure 22. Normalized rotation angle of micropiles foundation with relative slenderness of 100.

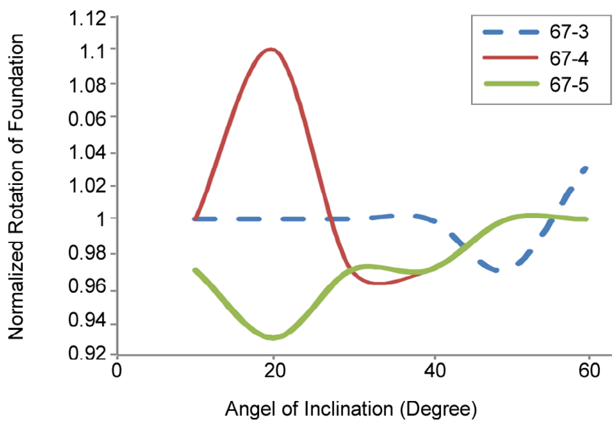

Figure 23. Normalized rotation angle of micropiles foundation with relative slenderness of 67.

Figures (22) to (24) show that the distance ratio ($S/D = 5$) in smaller inclination angles of micropiles group decreases the foundation rotation. Results show that as the inclination angle of micropile group increases, the distance ratio of S/D should be decreased. Moreover, as the inclination angle of micropiles group increases, the micropile slenderness should be decreased. Figure (25) illustrates the

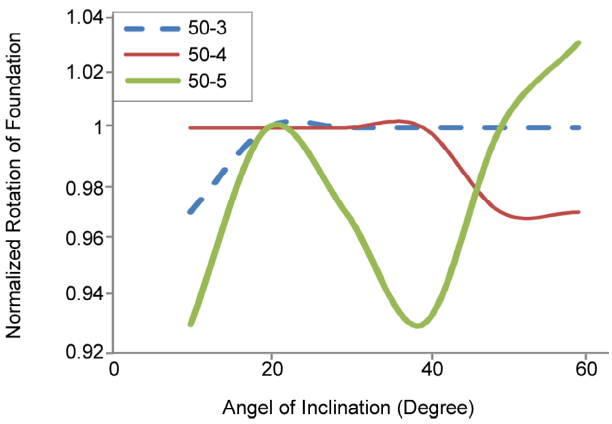

Figure 24. Normalized rotation angle of micropiles foundation with relative slenderness of 50.

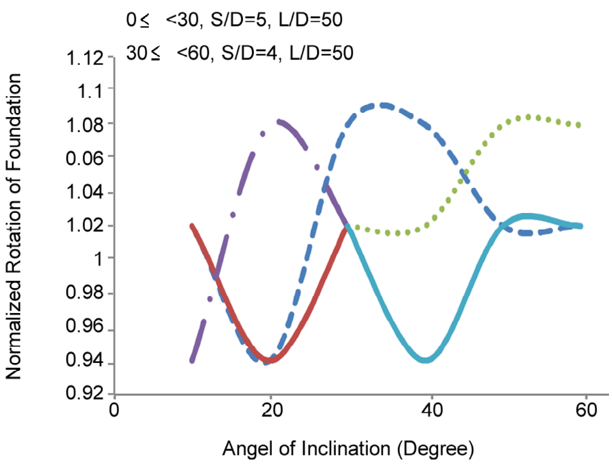

Figure 25. Minimum normalized rotation angle of micropiles foundation compared to normal foundation.

minimum normalized rotation angle of micropile foundation compared to normal foundation.

6. Response Spectrum of Micropile Foundation

When the seismic motion happen, the decrease of foundation rotation leads to the decrease of seismic response. Figure (26) shows that the highest seismic response of the structure on the normal foundation is 111 m/s^2.

Application of circular micropiles group in normal foundation will reduce foundation rotation, structural period, and structural seismic response. Figures (27) to (32) show the structural response spectrum in the use of micropiles foundation.

As it is observed, seismic responses will reduce as the micropile slenderness (*L*/*D*) decreases. The minimal seismic responses of the structure occur in micropiles with large diameters. The radius and

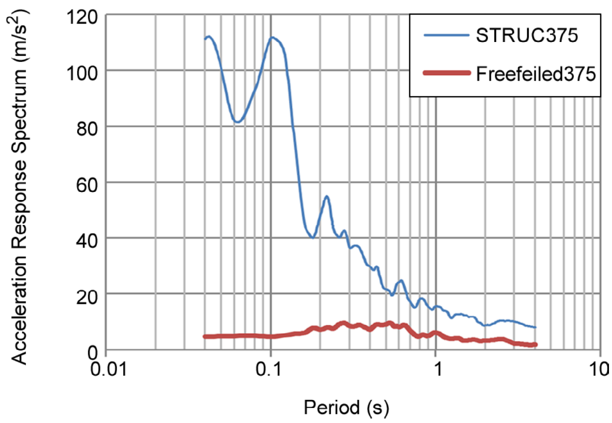

Figure 26. Seismic response of the structure on the normal foundation.

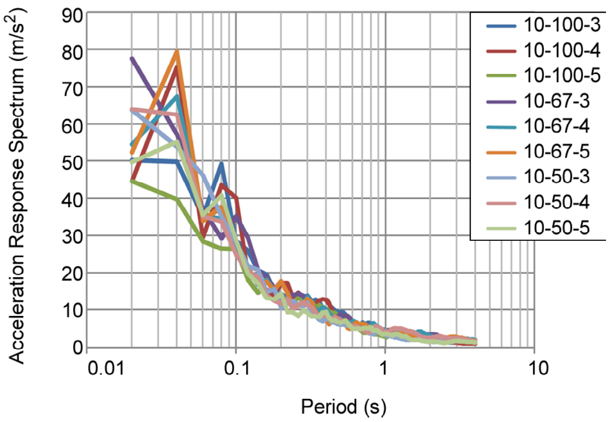

Figure 27. Structural response spectrum of micropile foundation with the inclination angle of 10 degrees.

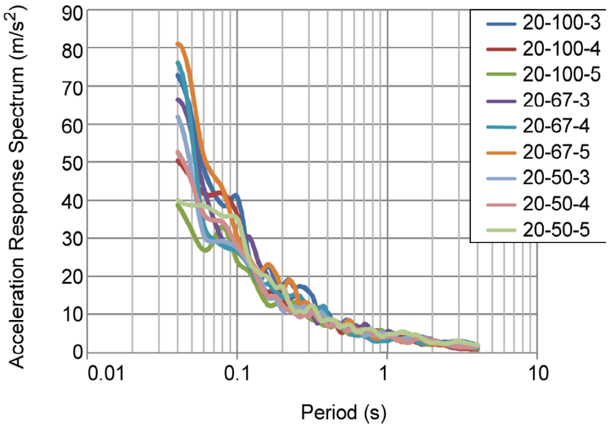

Figure 28. Structural response spectrum of micropile foundation with the inclination angle of 20 degrees.

inclination angle of micropile has a large effect on the seismic responses of the structure. Therefore, in smaller inclination angles, the radius of exerted micropile should be larger, and in bigger inclination angles the radius of exerted micropile group should decrease.

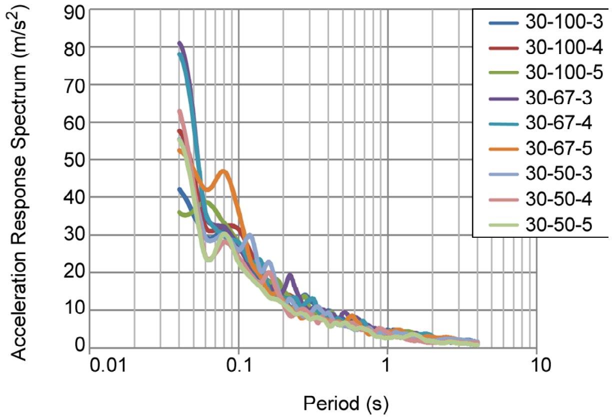

Figure 29. Structural response spectrum of micropile foundation with the inclination angle of 30 degrees.

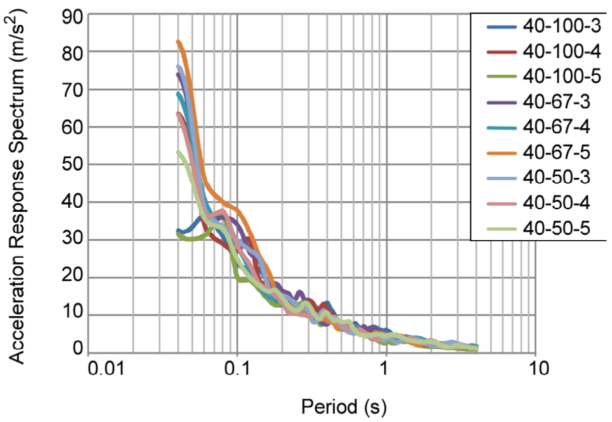

Figure 30. Structural response spectrum of micropile foundation with the inclination angle of 40 degrees.

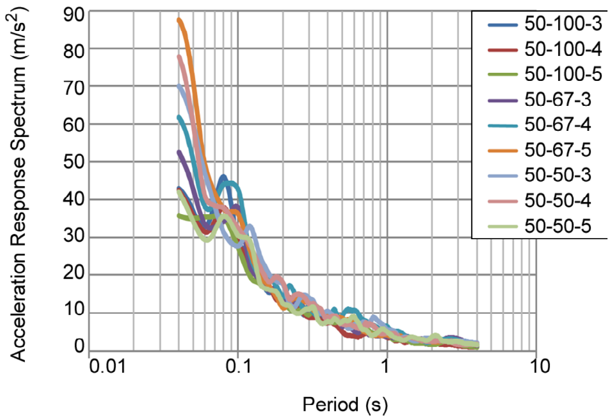

Figure 31. Structural response spectrum of micropile foundation with the inclination angle of 50 degrees.

7. Conclusion

Application of circular micropiles group in the foundation will decrease the foundation settlement as much as 0.2 mm and will increase the site reaction modulus. Reduction of settlement in stiff sites leads to force ingestion by circular micropile

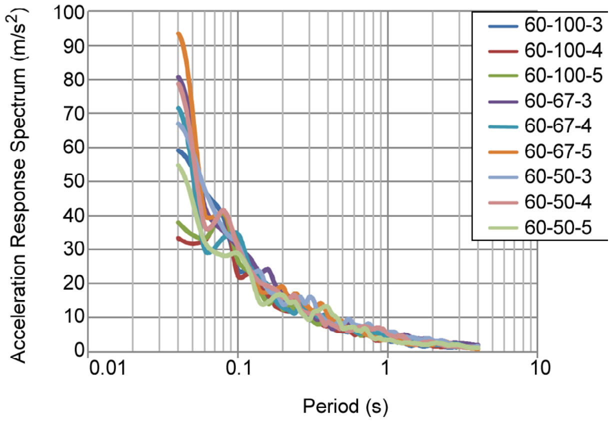

Figure 32. Structural response spectrum of micropile foundation with the inclination angle of 60 degrees.

group, so that the bearing capacity of group will be less than the bearing capacity of single micropile.

The results have shown that the increase of micropile radius leads to the decrease of foundation rotations and seismic responses of the structure. In soils with high shear wave velocity, the bending moment within the base of high-rise structures will uplift the foundation from the ground. This occurs because of the decrease of static settlement and increase of reaction modulus of the structure. Therefore, the increase of micropile radius in group system leads to the decrease of foundation rotation and seismic response of the structure.

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