Finite Element Analysis of the Seismic Behavior of Inclined Micropiles by Using PLAXIS

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Abstract
This research is about the study of the behavior of inclined micropiles due to seismic loading. Analysis is done by using a dynamic finite element modeling. The soil media is assumed with Rayleigh damping and micropiles are modeled like elastic beam elements. The structure of the micropiles are defined as a single degree of freedom which is composed by a concentrated mass and a column. The first chapter of this article is involved the technical literature of the behavior of inclined micropiles. The second post is explained about the numerical model used in this study. The third part is about the analysis on influence of micropiles inclination on the seismic behavior of a group of micropiles embedded in a homogeneous soil with a uniform stiffness and the fourth part is done the same analysis on inclined micropiles which are in a soil layer with a depth based in the increasing stiffness. The results of this research give the valuable date about the influence of micropiles inclination on dynamic amplification and or the seismic induced internal forces in micropiles.

Keywords: Micropiles, Dynamic analysis, Inclined micropiles, Finite element

1- Introduction
For using the micropiles in seismic retrofitting or seismic zones we need to know about analysis of the seismic-induced response for the micropiles with inclined elements. In fact, because the stiffness and resistance of vertical micropiles to lateral loading is small, using inclined micropiles is the potential alternative for inertial forces and for making sure about the stability the foundations under seismic loading. But using the micropiles in seismic area has limitation which is for designing the piles, because due to several researches, the function of inclined is not suitable. The inclined piles may be have a big energy on piles or if the inclined of caudles is not symmetric, permanent rotation may develop due to varying stiffness of the pile group in each direction. According to the French recommendation (AFPS) [1] using the inclined piles in seismic areas is forbidden, but reinforcement of soil can be include inclined elements. The seismic recommendation (Eurocode EC8) [2]. Indicates that inclined piles shouldn’t be use for transmitting lateral loads to the soil, but if these piles are used, they should design bending loading. On the other hand, according to Gazetas and Mylonakis’s report [3] currently the different observation is recorded which is shown that inclined piles, in certain cases, has a good function for the structure they support and the piles. One of the observation which support it happens in Kobe earthquake. Which one of the few quay-walls that survived the disaster in Kobe harbor was a composite wall which is relying on inclined piles and the near wall supported on vertical piles was totally devastated. Moreover, centrifuge tests and pseudo-static analysis which is done by Juran et al [4] showed that pile inclination cause first the decrease on both the pile cap displacement and bending moment at the pile cap connections and second the increase in axial force on piles.

The reference [9], also, compare the 3-D model with the results of the tests in Saitama university [8]. The pile supports a superstructure with a natural frequency $f_{st} = 7 \text{ Hz}$. It is shown that the finite element modeling is reproduce the tests. Then the other modelings is done for inclined piles and it is shown that the change on the head of pile and bend on pile connection to the pile's head reduces the angle of micropiles and increases the stiffness.

The result of this research shows the influence of micropiles inclination on seismic response of the soil- micropile-structure system. The analysis is done by PLAXIS program [5,6] that has the ability to analysis the 2-D dynamic and 3-D static. The results which is obtained from this research provided intersting information on seismic response of the soil-micropile structure system.
2- Numerical Model

Numerical Model of this research is done by the finite element program [5,6]. The 2-D for analysis of micropiles- soil- structure interaction. The superstructure is modeled as a single degree of freedom system composed of a concentrated mass and a column. While the beam elements are used for micropiles model. The behavior of soil and structure materials is assumed to be elastic with Rayleigh damping. The damping matrix \([c]\) results from a combination of the mass and stiffness matrixes:

\[
[c] = a_M [M] + a_k [k]
\]

(1)

\(a_M\) and \(a_k\) depends on Material damping. For the \(i\) th mode, the damping ratio \(\xi_i\) is related with natural frequency \(\omega_i\):

\[
\xi_i = \frac{a_M}{2\omega_i} + \frac{a_k \omega_i}{2\omega_i} \quad \xi = \frac{a_M}{\omega_i} + \frac{a_k \omega_i}{\omega_i}
\]

(2)

The seismic loading is done by changing harmonic acceleration which is based of the soil mass. Lateral boundaries are placed at a large distance from the micropiles in order to minimize the effect in reference [7]. Absorptive boundary conditions are imposed at lateral boundaries of the soil mass to minimize reflection of waves at the boundaries. Analysis is performed in the time domain using the implicit Newmark time integration scheme.

3. Micropiles in a homogeneous soil

Analysis is first performed on a group of two rows of micropiles embedded in a homogeneous soil layer underlined by rigid bedrock (Fig1). The thickness of the soil layer is equal to \(H_s = 15\) m. An elastic constitutive relation with Rayleigh damping is assumed for the soil–micropiles–structure system. Analyses was carried out with the following characteristics for the soil material: Young’s modulus of the soil \(E_s = 8\) MPa, Poisson’s Ratio \(\nu = 0.45\); damping factor \(\xi = 5\%\): The fundamental frequency of the soil layer is equal to \(f_1 = 0.67\) Hz (\(V_s/4H_s\); where \(V_s\) is the shear wave velocity, \(H_s\) is the thickness of the soil layer).

It is noteworthy that it is possible to calculate \(a_M\) and \(a_K\) from equation 1, having damping coefficient for two different frequencies. However here we assume contribution of stiffness and mass to damping to be equal, and thus for \(\xi = 5\%\), we get \(a_M = a_K = 0.0225\).

Micropiles spacing ratio is equal to \(S/D_p = 5\); \(D_p\) denotes the micropile diameter. The micropile length is \(L_p = 10\) m, its axial and flexural rigidities are, respectively, \(E_pA_p = 1100\) MN and \(E_pI_p = 0.85\) MN m². The structure is modeled as a single degree of freedom system composed of a concentrated mass \(m_{st} = 40\) ton, and a column with a height \(H_{st} = 1\) m. Its fixed base fundamental frequency is equal to \(f_{st} = 1.36\) Hz.

Micropiles are connected to a cap which is free of contact with the soil. The finite element mesh used in the numerical simulations for inclined micropiles is shown in Fig 2. It includes 261 fifteen-node elements and 9 plate elements. Lateral boundaries are placed at a distance \(R_l = 60\) m (240 \(D_p\)) from the central axis of the micropile-group in order to minimize any boundary effect.
Figure 2. mesh used for analyses of soil-micropile-structure system. Micropile inclination is equal to 0, 7, 13 and 20 degrees from top to bottom.

The seismic loading is applied at the base of the soil mass as a harmonic acceleration. The amplitude of the load is $a_g = 0.2 \, \text{g}$, while its frequency $f_{load}$ is assumed to be equal to the fundamental frequency of the soil layer ($f_1 = 0.67 \, \text{Hz}$).
Figure 3. soil with homogeneous elasticity, left: horizontal acceleration (m/s²), right: internal forces induced in micropile

Figure 3, shows horizontal accelerations in the soil mass at the time when phase of acceleration at cap is 90 degrees, that is when the acceleration is maximum. Also, envelope of internal forces induced in micropile due to seismic loading is depicted in figure 3. Ratio of accelerations induced in the cap and in the structure is listed in table 1:

Table 1. ratio of maximum acceleration in the cap and in the structure to bedrock acceleration (acceleration amplification) for the case of homogeneous soil

<table>
<thead>
<tr>
<th>Micropiles inclination angle</th>
<th>ratio of maximum acceleration in the structure to bedrock acceleration</th>
<th>ratio of maximum acceleration in the cap to bedrock acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>11.98</td>
<td>8.59</td>
</tr>
<tr>
<td>7°</td>
<td>10.40</td>
<td>7.66</td>
</tr>
<tr>
<td>13°</td>
<td>9.21</td>
<td>6.95</td>
</tr>
<tr>
<td>20°</td>
<td>8.03</td>
<td>6.04</td>
</tr>
</tbody>
</table>
Digrams on the left side of figure 3 reveal that with an increase in micropile inclination, horizontal acceleration induced in the soil body under the structure is diminished. Also, axial compressive and tension force for vertical micropiles decreases almost linearly in depth. However, for inclined micropiles, maximum compressive axial and tensile load are distributed over the length of micropiles more consistently. In fact, maximum axial force, either compressive or tensile, is constant over top two-thirds length of the micropile and decreases linearly in bottom one thirds part.

Maximum shear force is always induced at the micropiles head. This force is decreased intensively by increasing micropile inclination. In fact, for an inclination equal to 20 degrees, the shear force is decreased to 25 percent of its value for vertical micropiles. In addition to this maximum value which is observed at the micropile head, there is another peak at a depth of 1.5 meters. Amplitude of this peak shear is far smaller than the head shear for vertical micropiles. However this peak is more close to head shear for inclined micropiles. Bending moment exhibits a similar trend, though the second peak is almost disappeared with increasing micropiles inclination.

It is evident, from table 1, that the amplification in structure is always 30 to 40 percent larger than the cap. That shows the critical role of dynamic amplification of structures in any similar analysis.

4. Soil with increasing elasticity in depth

Elasticity modulus is generally larger in deeper soils. This section analysis inclined micropiles in a soil with increasing elasticity in depth. It is assumed that young’s modulus is equal to 1500 KPa from surface to a depth of 1.0 meters and it is increased afterwards at a rate of 350 KPa per meter. By applying a pulse at the bedrock, the natural frequency of the soil layer was found equal to 0.52 Hz. The same frequency is considered for the harmonic load. Also, displacement amplitude is equal to 0.1838 meters which results in a bedrock acceleration of 0.2 g.

Figure 4, shows horizontal accelerations within the soil mass at a phase angle of 90 degrees for the cap. The internal forces’ envelopes’ is also shown in figure 4. The ratio of induced accelererations in the cap and in the structure is listed in table 2:

Table 2. ratio of maximum acceleration in the cap and in the structure to bedrock acceleration, case of increasing elasticity in depth

<table>
<thead>
<tr>
<th>Micropiles inclination angle</th>
<th>ratio of maximum acceleration in the structure to bedrock acceleration</th>
<th>ratio of maximum acceleration in the cap to bedrock acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>20.3</td>
<td>16.21</td>
</tr>
<tr>
<td>7°</td>
<td>18.81</td>
<td>16.11</td>
</tr>
<tr>
<td>13°</td>
<td>14.27</td>
<td>12.64</td>
</tr>
<tr>
<td>20°</td>
<td>12.28</td>
<td>11.26</td>
</tr>
</tbody>
</table>
By examining the diagrams in figure 3, one can conclude that with increase in micropile inclination, horizontal acceleration induced in the soil body is first increased. For inclinations beyond 7 degrees however, it starts to diminished. Also, axial compressive and tensile force in vertical micropiles decreases almost linearly with depth, though the trend is not as linear as in the homogeneous soil. For inclined micropiles, the tensile and compressive axial forces are induced in a more consistent manner in the micropiles. Factually, the maximum axial force, either compressive or tensile, is moved from micropile’s head to the middle. Maximum shear force here is also always induced at micropiles’ heads. This shear force decreases tremendously with inclination. In fact, an inclination of 20 degrees, decreases the maximum induced shear to 10 percent of its value for vertical micropiles. In addition to this maximum value at micropile head, another peak is formed at a depth of 0.5 to 3 meters with a reverse direction to that of the head, and decreasing value with increasing inclination. Bending moment also exhibits a similar trend, though it’s second peak is closer to the soil’s surface.

Table 2, similar to table 1, shows that amplification in the structure is 30 to 40 percent larger than amplification in the cap. That is critical fact to be considered in any pseudo-dynamic analysis.

5. Conclusion

This research is done by finite element modeling to analysis the influence of micropiles inclination on response to seismic loading. The study is done in 2 cases, which concern micropiles embedded in homogeneous soil layer with a constant stiffness and a soil layer with a depth based-increasing stiffness.

The numerical simulations which is here, shows the inclination of micropiles which improve the micropile’s performance with respect to seismic loading. This improvement on soil function with fix hardness in depth is shown better. But if we regard the soil based-increasing in depth we must have more attention on suitable incline.
But in both cases inclined piles cause the decrease in both shearing forces and bending moment induced by seismic loading. This effect is readily observed in homogeneous soils. However, for depth-based increasing elasticity, the appropriate inclination should be chosen more precisely. In both cases however, inclined micropiles reduce the amplification induced in superstructure compared to vertical micropiles.

References