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# Evaluation of Static and Dynamic Behavior of Rigid Columns

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## ABSTRACT

Construction on soft soils often requires utilization of ground improvement techniques in order to solve the problems associated with bearing capacity and stability. These techniques, in addition to traditional preloading techniques, include various applications to the ground based on rigid columns. Today, rigid columns can be modelled on a computer using the finite element method (FEM) prior to the implementation in the ground and complex ground-structure interaction mechanisms associated with the applicability of a suitable soil improvement technique can be investigated. In this study, rigid columns including rammed aggregate piers (RAP), jet grouting (JG) and bored pile (BP), are tested in realistic finite element models for both static and dynamic cases. Here, we consider 17 m uniformly distributed load foundation in FEM modelling. Long term consolidation analysis is performed in the numerical models to compute stress and deformation variations for static case. The performance of  rigid columns in the numeric model is also computed using real earthquake data. In the static analysis, the settlement values prior to the ground improvement, was around 52.55 cm. After installation, the settlement values has dropped dramatically. Following the RAP installation, the value has decreased to 26.04 cm. We have also observed a decrease in other two installations where the settlement values are 19.11 cm and 7.3 cm for the JG and the BP installations, respectively. Our dynamic analysis also shows an improvement in the settlement values regardless of any rigid inclusion ground improvement. It is worthy of note that these installations considerably enhance building performance in the FEM models.

**Keywords:** FEM, Ground improvement techniques, Static-dynamic analysis.

## INTRODUCTION

The increase in human population and urbanisation has resulted in lack of suitable lands for engineering construction such as housing or industrial facilities. Under this circumstances, ground improvement which is the modification of existing site ground properties to maintain better performance under design loading conditions. Ground improvement methods are utilized for new projects to allow implementation of sites with poor soil conditions. The use of ground improvement method can improve the bearing capacity and the slope stability; decrease settlement and accelerate consolidation process. The selection of an appropriate method depends on soil type, site condition, structural properties, the loads applied and the time limitation for the improvement process as well as the economic performance of the design project.

Many developments have been constructed on soft soils when the physical resistance of the soils are not sufficient to support the structures. Soft clays, loose sands, expansive soils are the most common soil types which have been investigated for many decades. These types of soils generally have low bearing capacity and exposed to large settlements when the structural force are employed. Ground improvement methods have been developed as compelling element of geotechnical engineering for the purpose of improving the soil properties in a given region. There are several ground improvement methods available in the literature however the choice of an appropriate technique is highly dependent on local soil properties (Xanthakos et al., 1994). Application of ground improvement methods can enhance soft soil properties which enables engineers to construct even an extereme designs. These techniques are preferred because they are more economical than the traditional geotechnical approach. The methods to be used in these operations vary according to the type of ground and the distribution of grain diameter (Mitchell and Katti, 1981).

Computation of ground settlement before and after the construction period becomes a practical tool for engineers. Assesing the soil response against static and dynamic loads can provide time and economic advantages before the construction. Understanding the suitability of a possible ground improvement technique that supposed to be installed during the design, is also crucial. In this study, three ground improvement techniques have been investigated on a problematic soil in order to assess which technique is more suitable for the study area. Here, we test the techiques of Rammed Aggregate Piers (RAP), Jet Grout (JG) and deep foundation systems of the Bored Piles (BP) under static and dynamic loads and present the results systematically.

## GROUND IMPROVEMENTS

### *Rammed Aggregate Piers (RAP)*

Stone column method was first developed in Germany in 1930s and have been using in Turkey for the last couple of decades. Rammed aggregate piers is a type of stone column method. In this concept, the weaker part of the soil replaced with compacted vertical columns of stone and they cast as in-situ reinforcement of soft cohesive soil (Durgunoglu et al., 1982). The concept of The Geopier® and Impact® RAP methods are the most widely used sub-methods in geotechnical engineering (Karstunen and Leoni, 2009). Stone columns provide an increase in bearing capacity of the soil (Kanmaz, 2014). In the Impact® method, , the mandrel with a diameter of 36 cm is lowered to the desired depth and the well-graded natural crushed stone is filled into it. Then the mandrel is lifted 1 m upwards and 67 cm downwards to crush the crumbs with the hammer. The result of the compaction is a layer thickness of 36 cm with a diameter value of 36 cm which is 50 cm. Gradually this process continues up to the surface, with a column diameter of 50 cm and a layer thickness of 33 cm at each level.

### *Jet-grouting (JG)*

Jet-grout technique is a type of soil improvement technique which involves the injection of a stabilizing fluid into the subsoil under high pressure combined with high velocity. This technique is commonly used in tunnel engineering (Coulter and Martin, 2006), deep excavations (Peng et al., 2011) as well as constructions (Parlak, 2017). Jet-grouting technique uses the injection of high-speed fluids into the design sub-soil through tiny-diameteral nozzles to erode the soil. Then the eroded soil is mixed with injected grout to form a soil-cement column of a cylindirical shape (Shen et al., 2013) It also reduces settlement, like other improvement methods, by increasing bearing capacity in the ground environment (Wood, 2004).

### *Bored Piles (BP)*

Drilling piles are used in cases where the ground improvement methods are not sufficient in the case of overloads and excessive settlements (Karstunen and Leoni, 2009). The purpose of the utilizing piled bases is to transfer the building loads to a solid deep layer. The piles can be made of wood, steel and reinforced concrete according to the material being manufactured. In terms of preferring the right pile type; soil profile, loadings and pile dimensions in the study area, ought to be considered (Önalp and Sert, 2010).There are different types of piles in engineering applications. Depending on the area of use; end pile, friction pile, pull pile and compression pile. Depending on the construction methods; bored piles, casting piles, screwed piles and injected piles (Wood, 2004).The drilling rigs are placed in the drilled hole and then piercing pile production is completed by pouring concrete.

## MATERIALS AND METHODS

In the study, four different soil layers were identified in the PLAXIS 2D finite element program and analyzed using plane deformation (Plane Strain) model. We have used hardening soil model in the software, in order to simulate the behaviour of soil which express the elastoplastic properties of soil by using the unloading, reloading and oedometer loading stiffness. This model is also characterized by the stress-dependency of stiffness moduli (Brinkgreve, 2004).

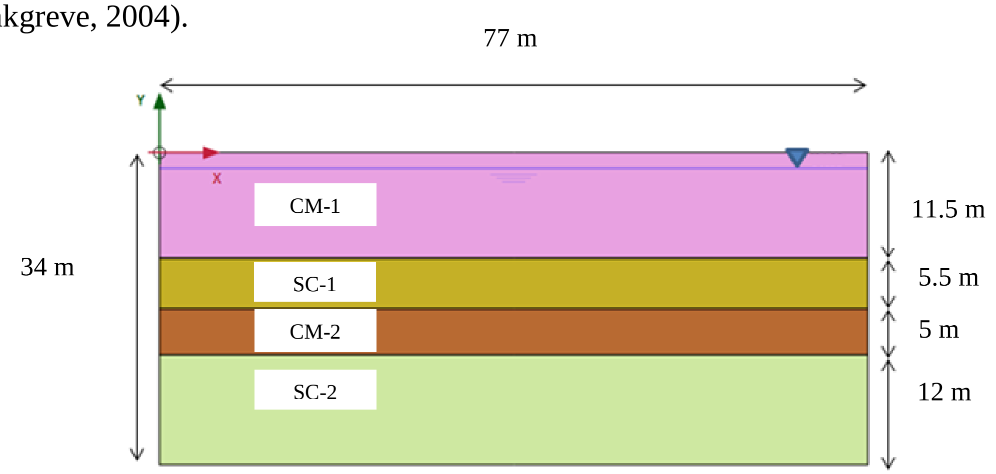



**Figure 1**. Modelling of soil layers in the FEM software.

The boundary conditions in 4 different soil layers are taken as the minimum ($x_{min}$) 0 m, maximum ($x_{max}$) 77 m in horizontal plane where the minimum ($y_{min}$) 0 m and maximum ($y_{max}$) 34 m in the vertical plane. 15 noded points of triangular area has been selected in the finite element model. Prior to the FEM analysis, we have conducted a systematic research for choosing the best element distribution; finally, the results have showed that the fine mesh is the most appropriate one. The soil foundation and rigid column parameters, used in the analyses, are given in Tables 1. to 3.

**Table 1**. Soil parameters used in the analysis.

| | CM-1 | SC-1 | CM-2 | SC-2 |
|---|---|---|---|---|
| **Material Model** | Hardening Soil | Hardening Soil | Hardening Soil | Hardening Soil |
| **Drain Condition** | Drained | Drained | Drained | Drained |
| $\rho$ **(kN/m$^3$)** | 18 | 19 | 18 | 19 |
| $\rho_{sat}$ **(kN/m$^3$)** | 19 | 20 | 19 | 20 |
| $E_{50}$ **(kPa)** | 2773 | 16800 | 6240 | 20000 |
| $E_{oed}$ **(kPa)** | 2773 | 16800 | 6240 | 20000 |
| $E_{ur}$ **(kPa)** | 8319 | 50400 | 18720 | 60000 |
| $\nu'_{ur}$ | 0.2 | 0.2 | 0.2 | 0.2 |
| $c'$ **(kPa)** | 10 | 5 | 23 | 10 |
| $\phi'$ **(°)** | 25 | 35 | 20 | 33 |
| $\psi$ **(°)** | 0 | 5 | 0 | 3 |

**Table 2**. Foundation parameters.

| Material | Material Model | Drain Condition | $\rho$ (kN/m$^3$) | E (GPa) | $\nu$ |
|---|---|---|---|---|---|
| **Foundation** | Linear Elastic | Non-porous | 24 | 30 | 0.2 |

In computations, RAPs with a diameter of 50 cm, JGs with a diameter of 60 cm and BPs with a diameter of 60 cm, are tested according to the Impact® method (Brinkgreve, 2004). All ground improvements have been installed in four different soil model presented in Fig.1, over 77 m plane spaced 1.7 m apart horizontally. All column types are designed 17 m in length. The maximum stress transferred from structure to the ground is 100 kPa. The groundwater level is 1.7 m in the study area.

## RESULTS AND DISCUSSION

During the analysis, previous consolidation settlement were examined without rigid columns under the distributed uniform load. At other stages, total (u), vertical ($u_y$) and horizontal ($u_x$) settlements were analyzed for consolidation in the static state and in the dynamic state by defining rigid column groups under the uniformly distributed load (RAP, JG and BP).

### *Static Analysis*

At initial phase, without any rigid column identification, long-term consolidation analysis is performed on the foundation which is exposed to 100 kPa distributed uniform load. In consolidation analysis, staged construction selected a total of 52.55 cm of settlement was observed under a load of 100 kPa, as shown in Figure 2. Then, we have obtained a total of 52.55 cm of settlement which is exceeded the allowable range of settlement values discussed in Karstunen and Leoni, (2009). Therefore it is proposed a ground improvement in the study area.

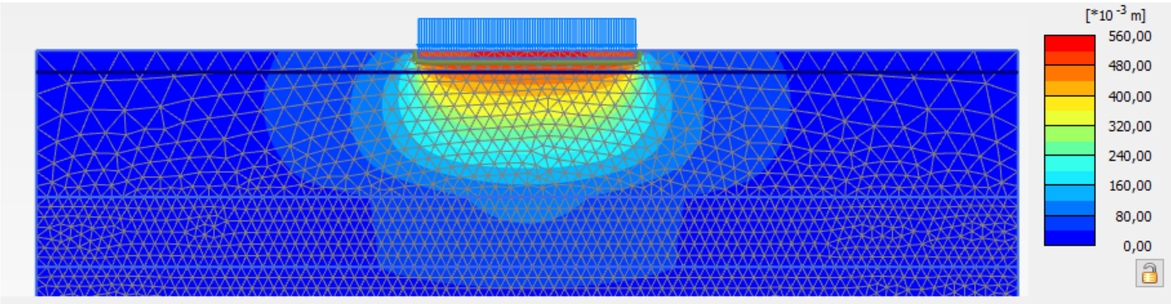
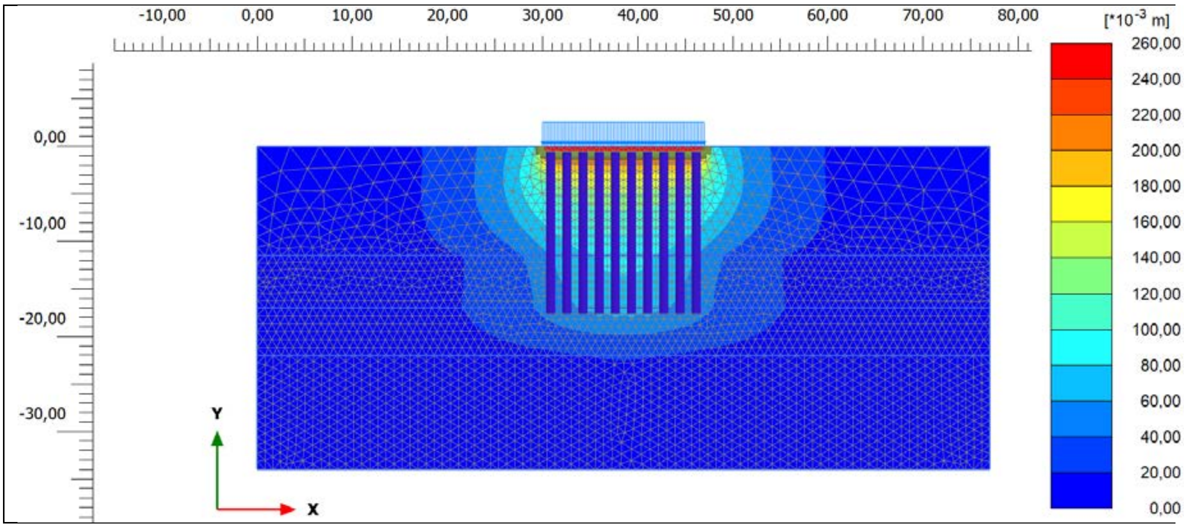
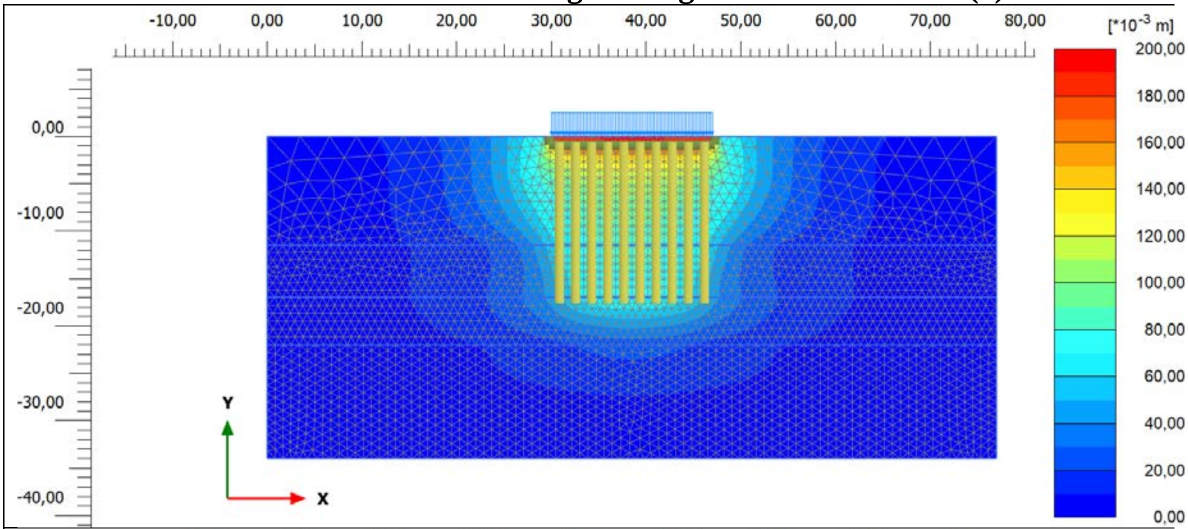



**Figure 2**. Total Settlement in the FEM model (redrawn after Mungan, 2016).

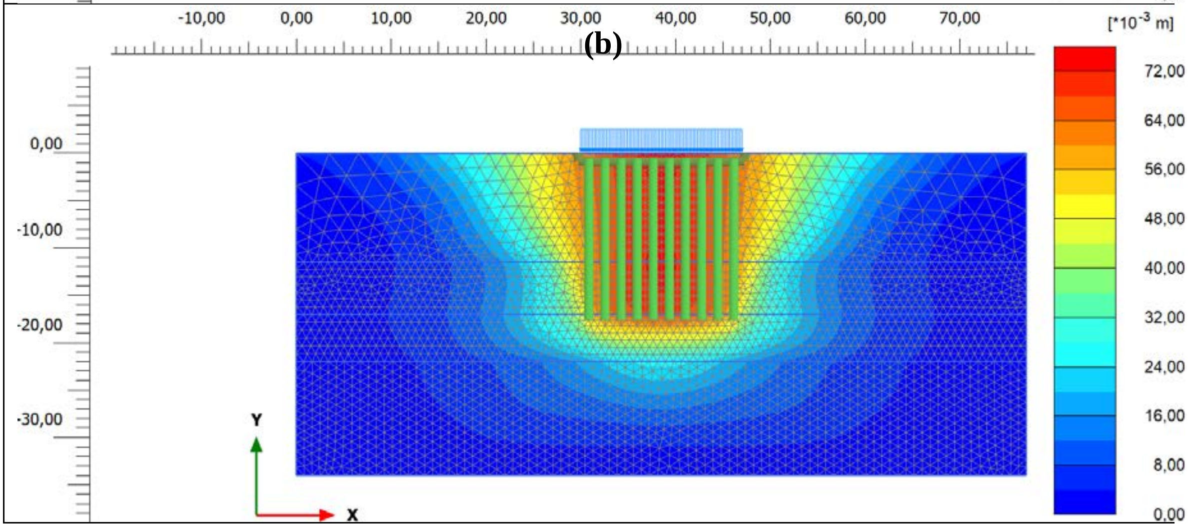
We have discussed the three feasibility-oriented techniques obtained from the FEM analyses, in the following sections. In order to decrease the settlement values obtained in the initial phase, we have used RAP in the FEM first-stage. In this method, all improvement techniques were modelled by using embedded beam row which allows to define a distance between the columns where the distance was selected as 1.7 m. as shown in Fig. 3. By using the ground improvement techniques we have obtained decreased calculated settlement values. Those values are 26.04 cm, 19.11 cm and 7.3 cm for RAP, jet-grouing and bored pile, respectively (Fig. 3). The results show an considerably improved settlement values when compared to the initial phase discussed earlier (See also Fig. 2).




**(a)**




(b)




(c)

**Figure 3**. Total displacement in FEM modelling improved with a) RAP, b) JG and c) BP.

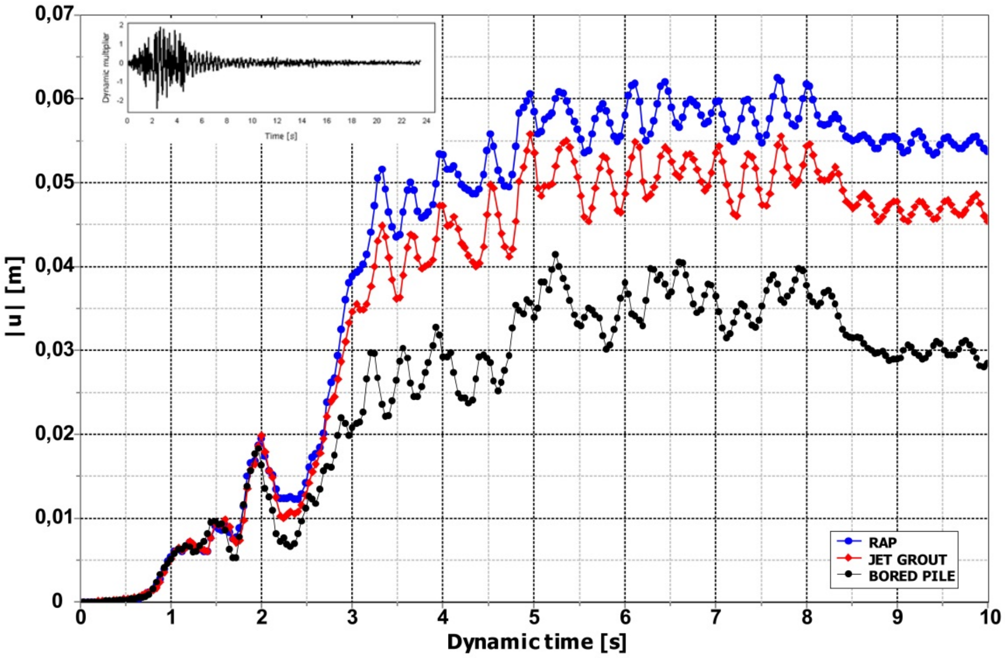
***Dynamic Analysis***

The numerical model is subjected to two different strong ground motion data in the dynamic analyses. The earthquakes, used in the dynamic analyses, have magnitudes of $M_w$ 5.4 and $M_w$ 7.1. During the analyses, the foundation midpoint (point A) was selected as a reference point, at which horizontal displacement values for both earthquakes to be compared.

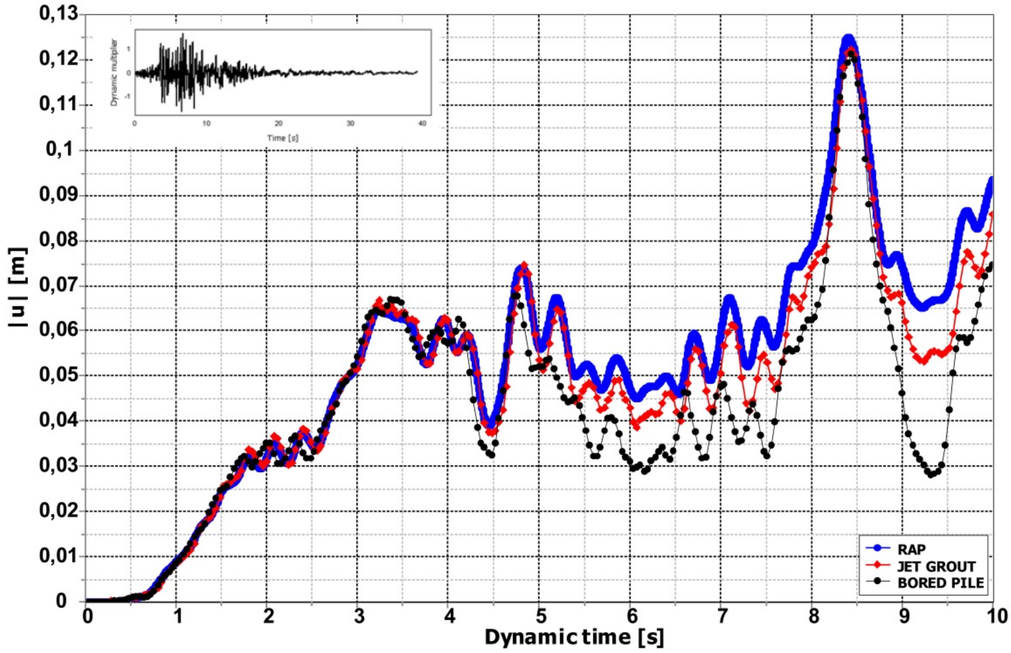
For the moderate earthquake ($M_W$ 5.4) at reference point A, we have obtained max horizontal displacement ($Umax_x$) 3.6 cm in RAP case, 3.6 cm in JG case and 3.5 cm in BP case. The results show that in all cases, we have obtained similar displacement values.When the magnitude is increased ($M_w$ 7.1), at reference point A, we have computed the maximum horizontal displacement values; ($Umax_x$), 10.8 cm, 11 cm and 11.8 cm for RAP, JG and BP cases, respectively. Considering two earthquake analysis, as expected, the displacement values has increased when the magnitude becomes larger.

At reference point (A), the calculated $Umax_y$ values are in Mw 5.4 case; 5.2 cm, 4.3 cm and 2.2 cm for RAP, JG and BP, respectively. For larger earthquake, we computed larger displacement values. For Mw 7.1 earthquake; we obtained 6.7 cm, 5.6 cm and 3 cm in the cases of RAP, JG and BP, respectively.

In terms of total displacement distribution at the reference point (A); it is concluded that when the magnitude of the earthquake increases, the calculated settlement values also increase whereas the calculated settlement values decrease when the ambient rigidity values decrease.




(a)




**(b)**

**Figure 4**. Total displacements in FEM modelling when subjected to a) $M_w$ 5.4 and b) $M_w$ 7.1 earthquake, in consideration of three improved method.

## CONCLUSION

Ground improvement methods can be applied in the ground conditions where excessive settlements are observed. Understanding this phenomenon is of importance in geotechnical engineering, in terms of assessing the suitability of ground improvement methods in problematic soils. Here, we have used a systematic approach by using three different techniques in FEM modelling to investigate which method is more suitable for the study area.

At initial phase, without using any improvement technique, we have computed a settlement value of 52.55 cm. This value is not in the admissible range when considered the ranges proposed by previous studies. Therefore, it appears to install a ground improvement in the study area. Three of the proposed improvement techniques in the literature; RAP, JG and BP have been modeled using finite element method. Our results show an gradual improvement in settlement values when the ground improvement techniques implemented in our modelling. In FEM analyses, we have obtained a clear improved calculated settlement values. Those values are 26.04 cm, 19.11 cm and 7.3 cm for RAP, jet-grouing and bored pile, respectively.

The numerical model is also subjected to two different strong ground motion data in the dynamic analyses. The earthquakes, used in the dynamic analyses, have magnitudes of $M_w$ 5.4 and $M_w$ 7.1. The calculated values at reference point, we have obtained max horizontal displacement ($Umax_x$) of 3.6 cm in RAP case, of 3.6 cm in JG case and of 3.5 cm in BP case for $M_w$ 5.4 earthquake. We have computed the maximum horizontal displacement values;

($Umax_y$), 5.2 cm, 4.3 cm and 2.2 cm for RAP, JG and BP cases, respectively.

When Mw 7.1 earthquake used in analyses, we have computed the maximum horizontal displacement values; ($Umax_x$), 10.8 cm, 11 cm and 11.8 cm for RAP, JG and BP cases, respectively. Also we computed the maximum vertical values ($Umax_y$) of 6.7 cm, 5.6 cm and 3 cm in the cases of RAP, JG and BP, respectively.

In terms of settlement performance in both static and dynamic analyses, the calculated settlement values are lower in the BP case when compared to the other two cases. Therefore, using bored pile columns in deep foundation are more advantageous than the ground imporvement methodes of RAP and JG in this type of soils given in the study. It is also note that the results are highly model dependent so the choice of improvement techniques can vary for different regions.

In terms of economic aspects, the ground improvement techniques are usually preferred because of their lower costs. However, in this recent study, we have obtained smaller settlement values in an addmissible range for the BP case when compared to those obtained in other cases. So we propose to consider the BP method for an alternative solution for such a problematic soil investigated in the recent study.

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