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The Effects of Jet-Grout Column Socket Length and Uniaxial Compression Strength on Liquefaction

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ABSTRACT

Soil liquefaction is one of the seismic events causing significant damage in our country and around the world. To mitigate potential loss of life and property during earthquakes, ground improvement should be conducted in areas with problematic soils. In recent years, jet grouting technique is frequently used both in our country and worldwide to mitigate soil liquefaction. The fundamental principle of this technique is to enhance the shear strength parameters of the soil and to restrict deformations within the soil. In this study, the influence of jet-grout column socket length and uniaxial compressive strength of the column on preventing liquefaction was investigated using finite element software. A series of dynamic analyses were performed for different socket lengths. The effect of socket length on shear deformations within the columns and the surrounding soil was studied. In the analyses, soil exhibiting liquefaction behavior was represented using the effective stress based UBC3D model. Additionally, jet-grout columns were placed beneath an impermeable foundation that was surrounded by diaphragm walls on both sides.While examining the excess pore water pressure ratio (R_u), which is one of the key parameters for liquefaction, it was observed that the R_u parameter decreased with an increase in socket length. The numerical analysis results show that the socket length plays a significant role in mitigating liquefaction; jet-grout columns should be designed not to move along with the soil and to restrict soil movement. In addition to these analyses, the impact of uniaxial compressive strength was examined for two different strength parameters. The results indicate that uniaxial compressive strength is effective in controlling liquefaction. It has been concluded that the uniaxial compressive strength should be elevated as much as possible to counteract shear stresses during earthquakes.

Keywords: Jet-grout, numerical analyses. Liquefaction, mitigation.

ÖZET

Zemin sıvılaşması ülkemizde ve dünyada önemli hasarlara neden olan deprem olaylarından biridir. Olası depremlerde meydana gelecek can ve mal kayıplarının önüne geçilmesi amacıyla bu tür sorunlu zeminlerde iyileştirme yapılmalıdır. Son yıllarda ülkemizde ve dünyada sıvılaşmayı önleme amacıyla sıklıkla jet grout tekniği kullanılmaktadır. Bu tekniğin temel prensibi uygulandığı zeminin dayanım parametrelerini iyileştirmesi ve zemin içinde oluşan deformasyonların kısıtlanmasıdır. Bu çalışma kapsamında jet grout tekniği ile yapılan zemin iyileştirme çalışmalarında sıvılaşmanın önlenmesi için jet grout kolonlarının soket boyunun etkisi ve jet-grout kolonu tek eksenli basınç dayanımının etkisi sonlu elemanlar yazılımı ile irdelenmiştir. Farklı soket boyları için bir dizi dinamik analiz yapılmıştır. Soket boyunun, kolonlar ve zemin içerisindeki kayma deformasyonlarına etkisi incelenmiştir. Analizlerde, sıvılaşma davranışı gösteren zemin efektif gerilme tabanlı UBC3D modeli kullanılarak temsil edilmiştir. Ayrıca jet grout kolonlar her iki tarafında diyafram duvar ile çevrili geçirimsiz bir temelin altında bulunmaktadır. Farklı soket boylarına sahip yedi farklı nümerik model kurulmuştur. Yapılan nümerik analizler soncunda soket boyunun artmasıyla zemindeki ve kolonlardaki kayma deformasyonlarının azaldığı fakat kayma gerilmesinde değişim olmadığı görülmüştür. Sıvılaşma için anahtar parametrelerden biri olan aşırı boşluk suyu basıncı oranı (R_u) incelendiğinde soket boyunun artmasıyla birlikte R_u parametresinin azaldığı görülmüştür. Analiz sonuçları soket boyunun, sıvılaşma üzerinde önemli bir rol oynadığını göstermektedir. Bu analizlere ek olarak tek eksenli serbest basınç dayanımının etkisi iki farklı dayanım parametresi için incelenmiştir. Analizler sonucunda tek eksenli basınç dayanımı parametresinin sıvılaşma üzerinde etkili olduğu anlaşılmıştır. Deprem sırasındaki makaslama gerilmelerine karşı koyması açısından tek eksenli basınç dayanımının mümkün olduğu kadar yükseltilmesi gerektiği ortaya çıkmıştır

Anahtar kelimeler: Jet-grout, sayısal analiz, sıvılaşma, zemin ıslahı.

1. INTRODUCTION

Soil liquefaction is one of the events causing significant damage in regions with high seismic risk. This phenomenon generally occurs in loose saturated sands, silty sands or silts resulting in shear strength loss. It can lead to large ground deformations causing loss of property and sometimes life. In recent large-scale earthquakes including the February 6, 2023, Earthquakes, damages attributable to liquefaction were noted in structures and lifelines (Hamada et al. 1996; Mollamahmutoglu et al. 2003). Various methods have been developed to mitigate liquefaction potential of a soil profile. Considering ease of application and its relatively low cost, jet grouting has become one of the most preferred solutions in recent years.

The objective of this method is to generate soilcrete columns, which are commonly called as high modulus or jet-grout columns in construction industry. The jet grouting method allows for the improvement of soils of varying characteristics such as clay or sand-gravel mixtures. The method involves injecting a mortar mixture into the soil under high pressure. As a result of cement-water mixture injection into the soil under high pressure shear strength and elastic modulus of the soil-cement mixture increase (Martin et al., 2004). Upon application, columns with significantly higher rigidity compared to the soil are formed within the soil profile.

Previous studies have shown that the behavior of jet-grout columns is more complex than initially thought and that the behavior of these columns depends on various parameters (Olgun, 2014). This study addresses the role of socket length of the jet-grout column in the underlying non-liquefiable soil layer and uniaxial compressive strength on excess pore water pressure generation. A series of dynamic finite element analyses were conducted for this purpose.

2. MATERIALS AND METHODS

The characteristics of the liquefiable soil layer within the analyses model were based on the soil parameters of the Wildlife Liquefaction Array, WLA, (Holzer and Youd, 2007) research site, located at the southern end of the San Andreas Fault in Imperial Valley and devoted for acquisition of excess pore water pressure data to calibrate the UBC-3D PLM constitutive soil model (Petalas and Galavi, 2013). Instrumentation of this research site was first carried out by USGS in 1982. Subsequently, in 2001, a significant upgrade was performed by NEES, including the addition of next-generation accelerometers and equipment to measure ground motion and pore water pressure, thereby substantially enhancing the research capabilities of the site. WLA has critical importance for understanding events like liquefaction and ground movements.

Numerical analyses were based on finite element method (FEM) utilizing Plaxis 2D software that runs under plain-strain conditions. The FEM effectively handles the complexity of boundary conditions. The analysis model is 80m wide and 36m deep and consists of four consecutive soil layers. From the surface to a depth of 6m, there is soft clay; between 6m and 10m, there is liquefiable sandy soil, whereas between 10m and 20m, there is medium stiff clay. At the bottom most layer of the model, there is stiff clay between 20m and 36m. The model's x-direction boundaries attained "free field" boundary conditions (Figure 1). Jet grout column diameter was set as B=60 cm with a center-to-center spacing of S=3B. Although investigation of the influence of a basement and impermeable foundation that overlies the liquefiable soil layer is out-of-scope of this proceeding, presented results, however, belong to such model where socket length and jet-grout column strength were the only variables. The jet-grouting section of the model is bounded on both sides by impermeable diaphragm walls. In the model jet-grout columns are placed between -6 and -10 elevations.

The free-field boundary condition allows earthquake waves to damp out at the outer boundaries of the soil profile, thereby simulating more realistic soil behavior at its horizontal boundaries without any energy reflection.

An earthquake record from the Hector Mine earthquake was used during the analyses. The Hector Mine Earthquake (M_w=7.1) occurred in California in 1999. The earthquake record was passed through a 20 Hz 'Low Pass' filter. This process was applied to cut off high-frequency components that could distort the analysis results, generally referred to as 'noise.' Following this process, the effective duration of the earthquake record was calculated and truncated to optimize computation speed. The input motion was provided to the model as a velocity-time series.

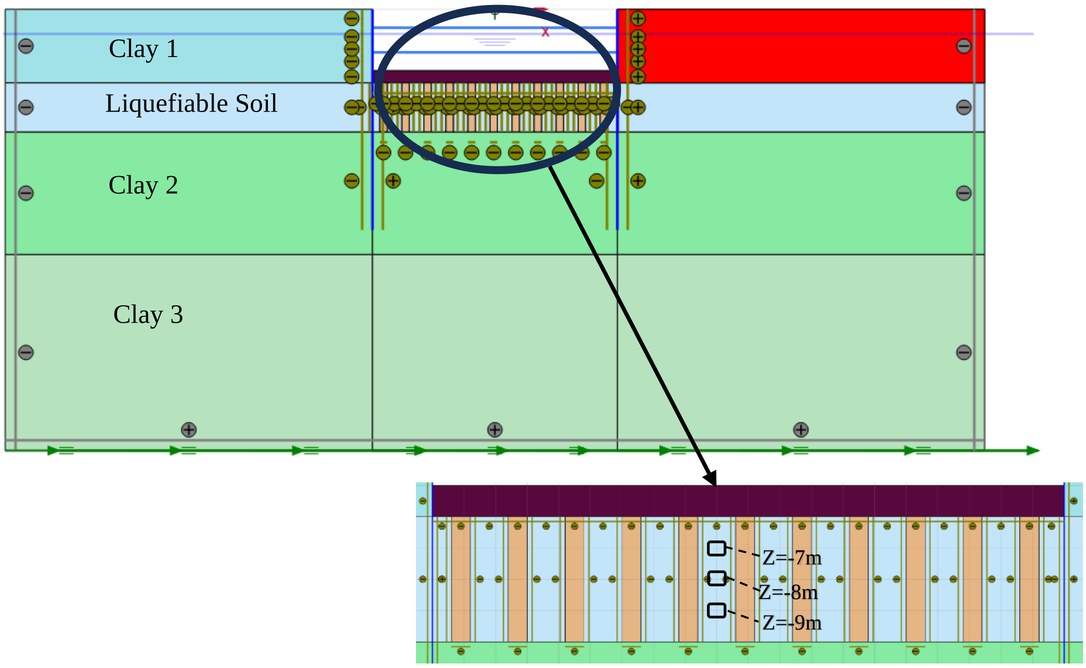

Figure 1. Plaxis model and cross-sectional view

3. NUMERICAL ANALYSES

In this section, the focus is on the calculations conducted for two main variables being the socket length, L_{socket}, and column's uniaxial compressive strength, q_u. A total of six runs were made as tagged in Table 1. In the first part, the effect of unconfined compressive strength was examined, followed by the examination of the socket length's effect. These analyses were evaluated based on the parameter of excess pore water pressure (R_u), shear stresses and shear deformations in jet-grout columns and surrounding soil. All calculations were made using the soil and jet grout column properties as specified in Table 2 and Table 3.

Table 1. Variables of the study

Analyses Name	**Description**
A0	q_u = 2 MPa, L_{socket} =0
A1	q_u = 2 MPa, L_{socket} =1.67B
A3	q_u = 2 MPa, L_{socket} =5B
A6	q_u = 2 MPa, L_{socket} =10B
B0	q_u = 15 MPa, L_{socket} =0
FF	Free Field

3.1. Influence of Unconfined Compressive Strength

The R_u parameter represents the ratio of excess pore water pressure to initial vertical effective stress. Variation of R_u for two different values of unconfined compressive strength (q_u) are presented. Graphs were given for depths of 7m, 8m, and 9m in the liquefiable soil layer. Comparisons are made for these depths. The B0 analysis with a 15 MPa unconfined compressive strength partially reduced initiation of liquefaction but has not significantly diminished it (Figure 2). An increase in unconfined compressive strength substantially reduced shear deformations in the soil (Figure 2).

Table 2. Parameters of the Clay Layers

Symbol	Value			Unit
	Clay Layer 1	**Clay Layer 2**	**Clay Layer 3**	
Y_{unsat}	18	18	18	kN/m^3
Y_{sat}	20	20	20	kN/m^3
G_0^{ref}	36000	65000	122000	-
$Y_{0.7}$	2.00E-04	4.00E-04	4.00E-04	-
ν_{ur}	0.2	0.2	0.2	kN/m^2
E_{50}^{ref}	1800	10000	30000	kN/m^2
E_{oed}^{ref}	1800	9000	30000	kN/m^2
E_{ur}^{ref}	8000	35000	90000	kN/m^2
p^{ref}	100	100	100	kN/m^2
m	0.6	0.75	0.7	-
c	10	20	40	kN/m^2
ϕ	24	25	28	◦
ψ	0	0	0	◦
R_{inter}	0.67	0.67	0.67	-
K_0^{nc}	0.5933	0.5774	0.5305	-

Table 3. Variables of the columns and surrounding liquefiable soil layer

(a) Jet Grout Column Variables

Symbol	Value		Unit
	q_u=15 Mpa	**q_u= 2 Mpa**	
Y_{unsat}	18	18	kN/m^3
ν_{nu}	0.3	0.3	-
E_{ref}	3.10E+06	5.00E+05	kN/m^2
G_{ref}	1.19E+06	1.92E+05	kN/m^2
E_{oed}	4.18E+06	6.73E+05	kN/m^2
V_s	807.1	323.7	m/s
V_p	1510	605.7	m/s
c_{ref}	3685	342	kN/m^2
ϕ	38	54	◦
ψ	0	0	◦
Tensile Strength	1530	160	kN/m^2
R_{inter}	1	1	-

(b) SandUBC 3D Variables

Symbol	Value	Unit
φ_{cv}	22	◦
φ_{p}	23	◦
c	0	kN/m^2
K_G^e	855	-
K_G^p	250	-
K_B^e	599	-
n_e	0.5	-
n_p	0.5	-
m_p	0.5	-
R_f	0.81	-
P_A	100	-
σ_t	0	kN/m^2
fac_{hard}	0.2	-
$N_{1.60}$	8	-
fac_{post}	0.02	-

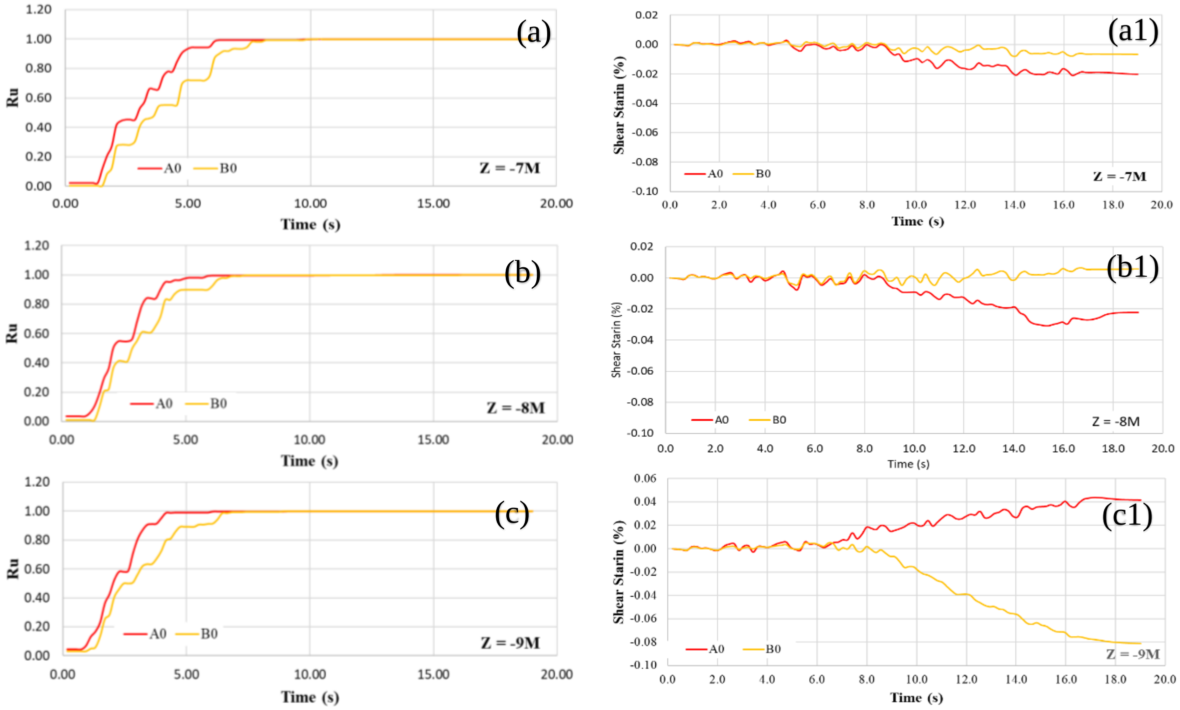

Figure 2. Variation of R_u and Shear Deformation in A0 and B0 Analyses

3.2. Influence of the Socket Length

In this section, the comparisons of shear deformation and the R_u parameter for various socket lengths are presented. The results show that as the socket length increases, the R_u parameter decreases. Additionally, the effect of shear deformation was examined, and it was observed that shear deformation increases with the increase in socket length. These results are supported by graphs obtained for the depths of 7m, 8m, and 9m (Figure 3). These findings reveal that the socket length of jet grout columns has a significant impact on shear deformation and the R_u parameter in liquefiable soils.

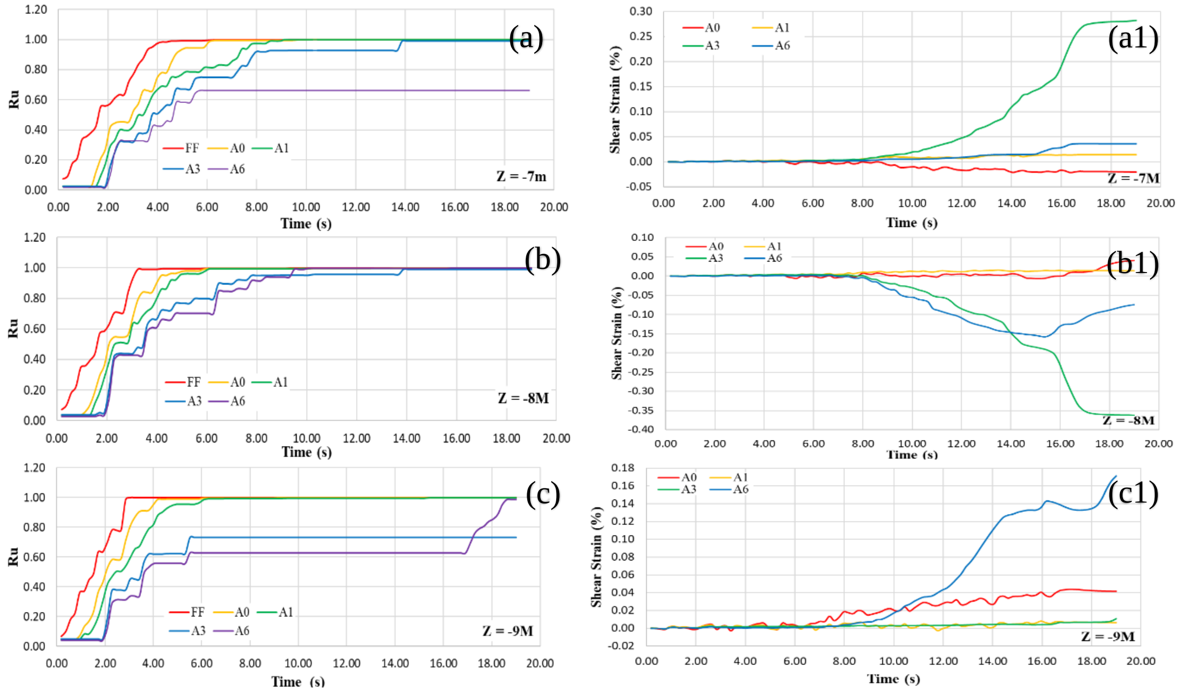

Figure 3. Variation of R_u and Shear Deformation in A0, A1, A3, and A6 Analyses

4. CONCLUSIONS

This study targeted to study influence of the socket length and uniaxial compressive strength of jet grout columns on the initiation of liquefaction using the finite element analysis method. Liquefiable soil was modeled by means of UBC3D-PLM constitutive model.

The results showed that with the increase in uniaxial compressive strength (q_u), a delay in reaching to Ru value of 1 took place, meaning that initiation of the liquefaction was delayed, but liquefaction was not completely prevented. Additionally, it was found that the increase in uniaxial compressive strength led to a decrease in shear deformations occurring in the soil.

It was seen that the increase in socket length would lead to a decrease in the R_u parameter. When the socket length sufficiently increased, initiation of liquefaction was prevented. Also, the increase in socket length led to an increase in shear deformations occurring in the soil.

In this study, it was found that uniaxial compressive strength (q_u) and socket length might be considered as significant parameters affecting liquefaction. Although further analyses in 3D and field measurements are still necessary to confirm the findings, it appears that these parameters may be considered in the design and implementation of jet grout columns. Future studies may include the optimization of these parameters and the exploration of alternative jet-grout column dispositions.

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