Liquefaction prevention performances of existing liquefaction countermeasure methods

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ABSTRACT

In this paper, different liquefaction mitigation methods are compared in terms of reduction in the settlement of embankment crest and the development of excess pore pressures. The study model Dynamic Compaction, Jet Grouting, Sheet Pile Enclosure, and Gravel Drain installation in order to determine the most effective method in terms of reducing settlement and pore pressure. The used FEM program is PLAXIS 2D and the material models employed are the Mohr-Coulomb, Hardening Strain, and UBC3D-PLM for the embankment, rolled fill, and the liquefiable sand, respectively. It is found out that the sheet pile enclosure and the gravel drain give the greatest reduction in vertical settlement and pore pressure, respectively. However, it is the dynamic compaction that reduces both vertical displacement and pore pressure development.

Keywords: Liquefaction, Mitigation, Earthquake, Settlement, Pore Pressure

1 INTRODUCTION

Liquefaction induced damages to embankments have been observed in many prominent earthquakes such as the 2004 Mid-Niigata Earthquake, 2007 Noto Peninsula Earthquake, and 2009 Suruga Bay Earthquake. Settlements resulting from the liquefaction of embankment foundation layer, can cause inaccessibility of the highway and thus impede relief efforts. Adalier (1996), Elgamal et al. (2002) and Towhata (2006) made extensive use of centrifuge tests and in-situ data in order to develop liquefaction mitigation methods.

In this study, a numerical analysis modeling for different methods including dredging, jet grouting, sheet pile, and gravel drainage was used to evaluate effective practical ways to mitigate the damages due to liquefaction. Conducted numerical modeling was carried out through calibration methods reported in the literature. Sinusoidal wave was employed as the input motion. Settlement and pore water pressure for each method were analyzed.

2 NUMERICAL MODELING

2.1 Input Motion and Soil Properties

The input motion was a 0.36g tapered sinusoidal motion with a frequency of 1.5 Hz and a duration of 10 seconds. The applied seismicity was based on the 0.18g centrifuge experiments by Parra et al. (1996) multiplied by two in order to account for seismically active areas (Fig. 1).

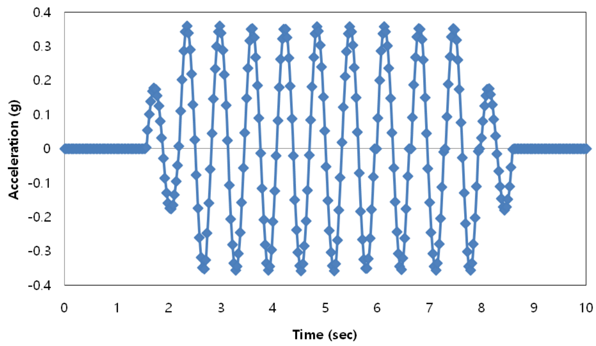

Fig. 1. Input Motion

In these numerical models, the dynamic compaction increases the density of the sand layer from 40% to 90% which is based on the study of Elgamal et. al. (2002) and Adalier (1996). Moreover, the primary mode of failure in this study is the settlement induced in embankments due to the contraction of loose sand foundations. Therefore, it is critical that the underlying layer to be modeled with a more sophisticated material model.

Table 1. UBC-3D PLM Parameters for Loose and Dense Sand

Parameters	D_r = 40 %	D_r = 90 %
γ_{unsat}	13 kN/m^3	13 kN/m^3
γ_{sat}	14 kN/m^3	14 kN/m^3
$(N_1)_{60}$	7.36	37.26
ϕ_{cv}	37.5°	43.27°
ϕ_{pi}	37.57°	47.72°
K_G^e	843.65	1447.82
K_B^e	590.55	1013.47
K_G^P	237.10	6130.05
R_f	0.82	0.64

2.2 Numerical Modeling of Mitigation Methods

Deep Dynamic Compaction uses a hammer drop to increase the density of in-situ sands as much as Dr=90%. The study of Adalier (1996) states that actual field tests demonstrate this upper bound increase. The dense sand column has a diameter of 3m referring to the study of Elgamal et al, (2002) and the influence radius by Oshima and Takada (1997). Three columns were modeled placed at both toes and under the embankment center. The layout of the model is seen in Fig. 2.

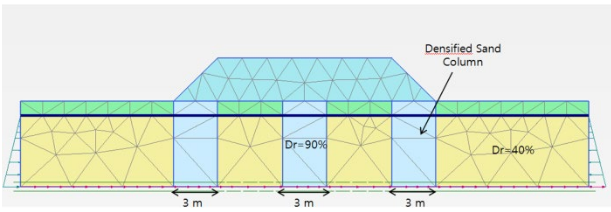

Fig. 2. Geometric Layout Deep Dynamic Compaction

Jet Grouting uses a grout plug to fill in the voids and make a non-porous and virtually homogenous mixture (Fig. 3). The loss of voids eliminates the development of excess pore pressure and improves the bearing capacity of the soil. The geometry takes the same form as that of the Deep Dynamic Compaction Model. The grout plug properties were extracted from the work of Chan (2005) in which jet grout modeling used in PLAXIS.

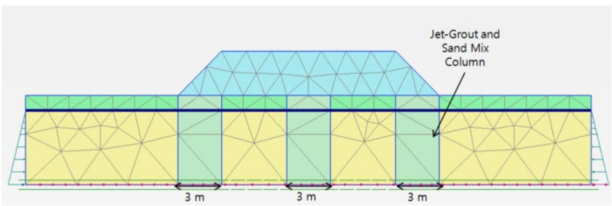

Fig. 3. Geometric Layout of the Jet Grout Model

Sheet Pile enclosure is a structural intervention that restricts the movement of the enclosed soil in order to prevent lateral spreading and ultimate settlement of the embankment. The sheet piles are tied together by tie-rods in order to prevent them from bursting out and causing abrupt spreading and damage to the embankment. The tie-rods are installed at the middle third of the sheet pile as seen in Fig. 4.

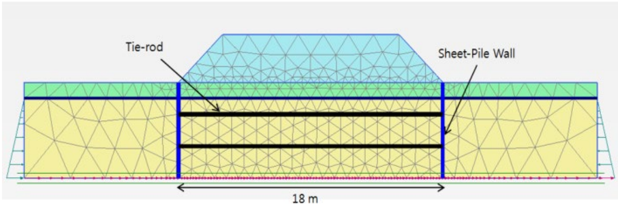

Fig. 4. Geometric Layout of the Sheet Pile Enclosure Model

The use of gravel drains is intended to relieve the excess pore pressure of the soil by providing the pore fluid and escape route. The rapid dissipation of excess pore pressure acts as a prevention of liquefaction and its corresponding settlement. The drain function in PLAXIS was used to simulate the effects of gravel drains against liquefaction. The gravel drains were spaced at 2 meters apart numbering at 10 units as seen in Fig. 5.

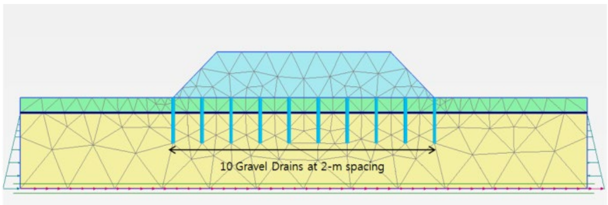

Fig. 5. Geometric Layout of the Gravel Drain Model

3 NUMERICAL ANAYLSIS RESULTS

As the results indicate in Fig. 6., the most effective reduction in vertical settlements can be observed in the Sheet Pile Enclosure case. Although all the mitigation methods passed the failure criteria, it can be seen that the jet grout produced a heaving result instead of a settlement result. The reason for this is that the pores of the column are blocked and therefore there is no room for the jet grout column to compress thus pushing the embankment upward when the lateral spreading loose sand tilts it (Fig. 7.).

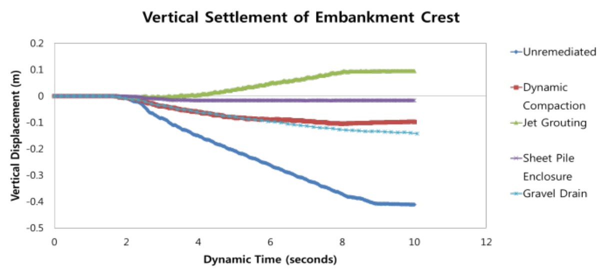

Fig. 6. Comparison of Vertical Settlement of Embankment Crest using Various Methods

The initial vertical confining stress was 85 kPa. Fig. 7. displays the excess pore pressure of different methods while the excess pore pressure ratio is used to determine the performance remark.

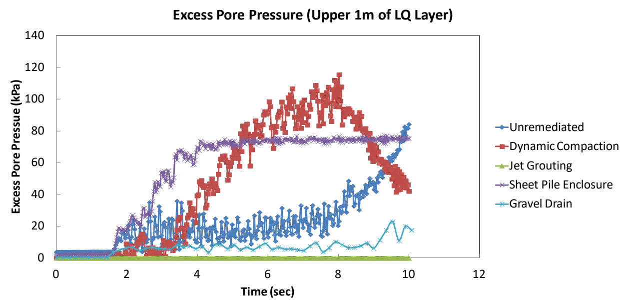

Fig.7. Excess Pore Pressure Development at 1m of LQ Layer for Various Methods

4 CONCLUSION

Numerical analysis was carried out to analyze the liquefaction resistance characteristics of various liquefaction countermeasures in embankments. The summary and conclusions are as follows.

Numerical results show that the use of sheet piles was the most effective method in reducing vertical settlement. In jet grouting, there was a heaving result instead of settlement, because the void of the column was clogged and the jet grouting column could not be compressed, so that the loose sand spreading horizontally tilts and pushes up the embankment. In terms of excess pore water pressure, gravel drainage and jet grouting showed the best results with the dissipation of pore water. In the future, it is necessary to compare the performance of the liquefaction countermeasure methods for more various superstructures.

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REFERENCES

Adalier, K. (1996) "Mitigation of earthquake induced liquefaction hazards", Ph.D. Thesis, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Elgamal, A., Parra E., Yang, and Z., Adalier, K. (2002), Numerical analysis of Embankment Foundation Liquefaction Measures, J. of Earthquake Engineering, Vol.6, No.4, 2002 pp.447-471.

Towhata, I. (2006), On three-stage mitigation of liquefaction-induced hazards, Asian Journal of Civil Engineering (Building and Housing), Vol.7, No.4, 2006, pp.429-452.

Chan, M.P. (2005), “Analysis and Modeling of Grouting and its Application” M.Sc. Thesis, Faculty of Engineering and Surveying, University of Southern Queensland, Queensland, Australia.

Oshima, A., Takada, N. (1997), “Relation between compacted area and ram momentum by heavy tamping”. 14th International Conference on Soil Mechanics and Foundation Engineering, Hamburg, Germany, Vol.13, No.4, pp.1161-1164.

Parra, E. (1996), "Numerical modeling of liquefaction and lateral ground deformation including cyclic mobility and dilation response in soil system." Ph.D. Thesis, Dept. of Civil Engineering, Renssealaer Polytechnic Institute, Troy, NY.