

CASE STUDIES FOR OIL TANK ON LIQUEFIABLE SANDY GROUND SUBJECTED TO EXTREMELY LARGE EARTHQUAKES AND COUNTERMEASURE EFFECTS BY COMPACTION

Noriaki SENTO¹, Susumu YASUDA², Nozomu YOSHIDA³, Kenji HARADA⁴

SUMMARY

Liquefaction-induced settlements of storage tanks on liquefiable sandy ground have been observed in past earthquakes. These problems can be mitigated by improving potentially liquefiable layer, but it is impossible to prevent occurrence of liquefaction completely under extremely large earthquakes. Therefore it is necessary to carry out performance-based design by considering the allowable displacement for a particular type of structure. In practical design, reliable analytical procedures are necessary to predict liquefaction-induced settlements of structures, not only qualitatively but also quantitatively.

This paper presents the effects of countermeasure against liquefaction by compaction such as sand compaction pile method by considering a storage oil tank founded on the improved ground, comparing the seven liquefaction analysis codes mostly used for practical design in Japan. These codes are based on the principle of effective stress analyses based on elasto-plasticity theory, effective stress analyses based on multi-mechanism theory and static equilibrium analysis with decreased shear modulus due to liquefaction. Same conditions such as tank and ground dimensions, soil profiles, undrained cyclic resistance of sand, and boundary conditions were used for analyses. The effect of input wave amplitude and configuration of compacted soil cross section were studied.

Analytical results showed that although there are differences among codes in vertical displacement quantitatively, almost reasonable tendencies on input wave amplitude and the effectiveness of countermeasure were confirmed qualitatively. These data may be useful to determine the countermeasure configuration in cross section for storage tank foundations.

¹ Department of Civil Engineering, Tohoku University

² Department of Civil & Environmental Engineering, Tokyo Denki University

³ Earthquake Engineering Center, OYO Corporation

⁴ Soil Engineering Division, Fudo, Construction Co., Ltd.

INTRODUCTION

In past earthquake surveys, structures on the ground with countermeasure against liquefaction have often been reported as remaining intact even though they were subjected to extremely large earthquakes. Especially, in the 1995 Hyogoken Nambu Earthquake, insignificant residual deformations were observed on the sites improved by compaction such as manmade islands named as Port Island and Rokko Island [1]. Based on these examples, it was considered that this type of ground improvement worked effectively under a strong earthquake. However, no clear conclusion has been obtained, in the case of intense earthquake, as to whether liquefaction occurred in the improved ground, or to what extent and to what sort of mechanism the accompanying deformation was attributable.

On the other hand, rational decision on the configuration of countermeasure in cross section is of interest to engineers in the practical design. In Japan, when storage tanks and buildings are constructed on liquefiable ground, countermeasure against liquefaction is usually applied not only under the corresponding structure but also additional horizontal width of 2/3 or 1/2 times the improved depth [2], [3]. Iai et al. [4] suggested a configuration by considering horizontal pore water pressure migration and failure line due to passive and active earth pressure conditions. But for building design in urban areas, it is difficult to secure enough additional improved area. Thus, it is necessary to study the decision method for rational countermeasure configuration against liquefaction.

To study the aforementioned factors by analytical approach, hypothetical ground models varied in a cross section of countermeasure configuration were considered. In addition, earthquake input motion varied in maximum acceleration amplitude levels were applied to the models. Seven computer codes frequently used in Japan were used to solve these boundary value problems. Behaviors obtained by a particular computer code are introduced and fundamental characteristics of tank settlement are mentioned later. Finally discuss the effectiveness of improvement and its appropriate configuration in cross section by using obtained results statistically.

ANALYSES OF HYPOTHETICAL MODELS

Hypothetical models

A hypothetical model of ground with a storage tank was used for the analysis. Six different cases by varying configurations in cross section were conducted as shown Figure 1 to evaluate the improvement effect due to compaction. Ground is 60 m in width and 16 m in depth. Storage tank is 10 m in width and 12 m in height. Three case studies were considered, namely Case A, Case B and Case C. Case A represents the unimproved ground while Case B represents the fully improved ground. Partially improved with four different configurations in cross section are induced in Case C. Improved area of Case C-1 is 30 m in width and 16 m in depth, Case C-2 is 10 m in width and 16 m in depth, Case C-3 is 30 m in width and 8 m in depth and Case C-4 is 10 m in width and 8 m in depth. In order to ensure failure in the model ground, the area replacement ratio(*as*) was fixed at a rather small value of 5%. The area replacement ratio is defined as volumetric proportion of installed sand piles when the original ground volume is taken as 1.0. Thus, higher the improvement ratio is, greater the improvement effect is.



Figure 1 Cross view of each case.

Seven different liquefaction analysis codes were used for the analyses. A summary of six effective stress analysis codes are shown in Table 1. Four effective stress analysis codes are based on elasto-plasticity theory [6, 7, 9, 11.]. Other two effective stress analysis codes are based on multi-mechanism theory and undrained stress path model [5, 10]. The remaining code, ALID [12], is a code based on static equilibrium with liquefaction-induced degraded shear modulus and is used frequently in practical design for simplified estimation of liquefaction-induced residual ground deformation.

Table 1 Summary of analysis codes.									
Code name	name Formulation* Dime		Constitutive model	Remarks					
FLIP[5]	Undrained	2	lai Model	Multi-mechanism, Stress path model					
STADAS2[6]	u-p	2	Modified Tobita and Yoshida model etc.	Elasto-plastic model					
LIQCA[7]	u-p	2, 3	Oka model	Elasto-plastic model					
DIANA[8],[9]	u-p	3	Nishi and Kanatani model etc.	Elasto-plastic model					
NUW2[10]	u-w	2	lai model	Multi-mechanism, Stress path model					
STADAS[11]	u-p	2	Yoshida model etc.	Elasto-plastic model					

* u: deformation of soil skeleton, p: pore water pressure, w: relative deformation to soil skeleton and pore water

Table 2 and Table 3 indicate the physical properties including liquefaction resistance in 5 loading cycles (R_{L5}) and in 20 loading cycles (R_{L20}) of the unimproved and improved ground by compaction respectively. The data of liquefaction resistance were obtained by conducting undrained cyclic triaxial tests for undisturbed soil samples taken from both unimproved and improved sites in Kobe Port Island [13]. It is a well known factor that horizontal stress increased in the sand compaction pile improved ground [14]. In the research study, the coefficient of earth pressure at rest (K_0) in the improved ground was set at 0.8 according to the low area replacement ratio (*as*) of 5% [13]. The storage tank was regarded as linear elastic material with unit weight of 8.0 kN/m³, Young's modulus of 100,000 kN/m² and Poisson's ratio of 0.3.

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Soil	Name	Depth (m)	Unit weight (kN/m ²)	Ko	Shear Velocity V _s (m/s)	Poisson's ratio v	Internal friction angle ¢ (deg.)	Liquefaction resistance	
								R_{L5}	R _{L20}
Gravel	B1 (above water table)	0-3	18.9	0.5	140	0.3	41.8	-	-
	B1	3-8	21.7	0.5	170	0.3	41.8	0.23	0.15
	B2	8-16	21.6	0.5	200	0.3	39.5	0.31	0.20

Table 2 Parameter for simulation (Unimproved ground).

Soil	Name	Depth (m)	Unit weight (kN/m ²)	K₀	Shear Velocity V _s (m/s)	Poisson's ratio v	Internal friction angle ¢ (deg.)	Liquefaction resistance	
								R_{L5}	R_{L20}
Gravel	B1(above water table)	0-3	19.8	0.8	140	0.25	42.3	-	-
	B1	3-8	22.2	0.8	190	0.25	42.3	0.50	0.32
	B2	8-11	22.0	0.8	210	0.25	42.4	0.35	0.23
	B3	11-16	22.3	0.8	220	0.25	43.3	0.41	0.27

Table 3 Parameter for simulation (Improved ground).

The NS direction wave component at GL-16.4 m of Hyogoken-nambu earthquake in 1995 in Kobe Port Island was used as the input wave (Figure 2) for the simulation. The wave of incidence was separated theoretically from the recorded wave [15]. Maximum acceleration amplitude of the wave is 410 gal. This wave may be related to the extremely large wave improbably happens during the service life. In Japan, this type of earthquake wave is called 'Level 2' seismic wave. The allowable damage that can be recovered after Level 2 seismic wave is considered in the performance based design. On the other hand, the wave which occurs more than one time during the service life is called 'Level 1' seismic wave. Under Level 1 seismic wave design, functions of structures must be remained. The effect of acceleration amplitude was studied by varying the acceleration amplitude waves between 0.3 G (294 gal) and 0.15 G (147 gal). Acceleration amplitude of 0.15 G has been treated as 'Level 1' seismic level by the authors. The vertical displacement of the tank was considered as the absolute settlement at the center of the tank in the evaluation.



Figure 2 Time history of input wave for simulation.

Typical results by an analysis code

Typical examples were simulated by using code FLIP. Figure 3 indicates the relationship between undrained cyclic stress ratio and number of loading cycles at double axial strain amplitude of 5% for both test results and analytical results. The open and close circles are the test results of the unimproved and improved soils at layer B1 respectively. The broken and solid lines indicate the simulation results of unimproved and improved soils respectively. It can be noted that simulation results are well agreed with test results for corresponding double amplitude axial strain level.



Figure 3 Relation between cyclic stress ratio and number of loading cycles.

The effect of input wave acceleration amplitude and the effect of improved configuration in cross section were studied by using FLIP considering six different cases illustrated in Figure 1. It should be noted that tank displacement obtained by FLIP does not include a displacement due to dissipation of excess pore water pressure, as FLIP is based on the constitutive model under undrained condition.

Typical Results of boundary value problems

The variation of vertical displacement at the center of the tank with time for both unimproved (Case A) and improved (Case B) ground subjected to 410 gal wave is depicted in Figure 4. It is seen that vertical displacement in the unimproved ground is 87.1 cm and in the improved ground is 8.6 cm. This is a clear indication that fully improved by compaction (as=5%) will cause significant reduction in vertical settlement (90%).



Figure 4 Time history of vertical displacement of tank in the simulation by FLIP.

Displacement and excess pore water pressure ratio distribution of unimproved case (Case A) at the end of shaking (at 20 seconds) is illustrated in Figure 5. Darker parts in the excess pore water pressure ratio

distribution shown in Figure 5 are going to be liquefied. Both layer B1 which is under the ground water level and upper part of layer B2, far from the tank, subjected to liquefaction. However it can be noted that pore water pressure slightly increase in the zone near to the tank and ground exactly under the tank. In addition, higher static shear stresses due to gravity were appeared in these zones. As a result, larger displacements occur in this area and cause the larger settlement of the tank. Figure 6 shows the displacement and excess pore water pressure ratio distribution of fully improved case (Case B) at the end of shaking. Maximum excess pore water pressure ratio in the improved ground was 0.9. As a result, smaller settlement of the tank was observed when compared with the unimproved ground. The effect of improved width is illustrated with the help of data obtained by varying the improved width and keeping improved depth constant. Displacement and excess pore water pressure ratio distribution of partially improved ground at the end of shaking is shown in Figure 7 and Figure 8. Figure 7 represents the improved width of 30 m (Case C-1) and Figure 8 represents the improved width of 10 m (Case C-2). In both these cases, improved height was kept fixed at 16 m. The comparison of Figure 7 and Figure 8 clearly indicate that larger improved width has caused significant reduction in the settlement. Therefore it can be noted that by allocating additional improved width to corresponding structural width is highly effective to reduce the settlement of the tank. Residual settlements in Case C-1, Case C-2, Case C-3 and Case C-4 are 9.2 cm, 43.7 cm, 18.2 cm and 65.1 cm respectively. Illustrations for Case C-3 and Case C-4 are skipped due to limitation of space in the paper. However sequence of effective improvement can be summarized as Case B, Case C-1, Case C-2, Case C-4 and Case A. According to the general point of view, abovementioned order may be accepted except Case C-3 and Case C-2. However, there is no exact answer for the above uncertainty and it is very difficult to discuss in detail only by the result obtained from one analytical code. The effect of input wave and improvement configuration in cross section based on the analytical results by all codes will discuss in the next section.



Figure 5 Residual deformation modes and excess pore water pressure ratio distribution. (Unimproved; Case A)



Figure 6 Residual deformation modes and excess pore water pressure ratio distribution. (Fully Improved; Case B)



Figure 7 Residual deformation modes and excess pore water pressure ratio distribution. (Partially Improved; Case C-1)



Figure 8 Residual deformation modes and excess pore water pressure ratio distribution. (Partially Improved; Case C-2)

SUMMARY OF RESULTS BY ALL ANALITICAL CODES

Authors have interested in confirming not only the variation of output from the analyses currently proposed for the evaluation of liquefaction-induced residual deformation, but also the effective configuration in cross section and the effect of input wave amplitude. Summary of the results obtained by using the seven analytical codes are discussed.

Figure 9 shows a relationship between vertical displacement of the tank and maximum acceleration of input wave for Case A and Case B. The purpose of choosing 'a' to 'g' to represent code names is all codes show different relationships for the same input wave conditions. It can be noted that data are spread over a wide range and coefficient of variant at each input wave amplitude vary between 0.52 and 0.58 in unimproved ground and 0.67 and 0.89 in improved ground. By only considering the variation of the coefficient of variant, it can be concluded that results of different analytical methods are varying significantly even though the same liquefaction strength is expected. Main reason for this variation is, even though liquefaction strength curves for a particular strain level are fitted, analyses do not always give acceptable results under wide range of strain levels [16]. In addition, it is very difficult to evaluate the complicated stress conditions below the tank and surrounding ground. Therefore authors have concluded that some degree of scattering may be acceptable by taking aforementioned reasons into consideration in the present state. However, a qualitative tendency that vertical displacement of tank increase with wave amplitude in linear or nonlinear manner for both unimproved and improved ground is clearly appeared in Figure 9.



The effect of improved configuration on vertical displacement of tank is illustrated in Figure 10. Horizontal axis represents the variation of improved configuration from unimproved (Case A) to fully improved (Case B) condition. Since the relationship between vertical displacement of tank and different improved configuration (Figure 10(a)) could be well defined for each analytical code, vertical displacement ratio with respect to unimproved case were calculated for each analytical code and plotted against different improved configurations (Figure 10(b)). At least two important points may be seen from this figure. Firstly, vertical displacement ratio decreases with increasing the effect of improvement. Even though, data spread over a wide range, the effectiveness of countermeasure against liquefaction is described qualitatively. Secondly it may be seen from the figure, even though unimproved and fully improved cases are well described in all codes, the partially improved effect changes is not much clear. The general tendency of decreasing vertical displacement with improved effect could not be seen in some codes, such as code 'b' and code 'c'. However these codes are also classified as elasto-plastic constitutive model due to limited unknown information. In these codes, under partially improved cases, it is presumed that liquefaction occurred in the unimproved area due to redistribution of shear stresses from the improved ground. As a result, larger strains development in the unimproved soil attributes to the larger vertical displacement of tank than that of Case A. On the contrary, the results of other codes are straightforward due to simplicity on solution and constitutive model.



Figure 10 Effect of improved configuration on vertical displacement of tank.

However, still there are some shortcomings in these codes during the evaluation of partially improved cases. On the other hand, field evidences had been observed that the zones densified with sand compaction piles and rod (vibro) compaction did not subsidence even though unimproved zone reached almost 45 cm subsidence [1] under Level 2 earthquake in Port Island and Rokko Island. Thus, performance based design to predict settlement of the tank on improved ground should be carried out carefully not only by analytical procedure but also by taking these field evidences into consideration.

CONCLUDING REMARKS

The input acceleration level and improved configuration in cross section were examined by using seven analytical codes frequently used in Japan for liquefaction problems. The limited evidences show that, although different numerical values of vertical displacements were observed for different codes, they showed the same behavior on input wave amplitude and the effectiveness of countermeasure against liquefaction qualitatively. Even though further studies are necessary to predict vertical settlement of a storage tank on improved ground quantitatively, these data are expected to be use in designing countermeasure configuration in the future.

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