Liquefaction analysis of damaged river embankment in 2011 Tohoku earthquake

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1. INTRODUCTION

River embankment, a large-scale earth infrastructure, is usually vulnerable to earthquake. For instance, more than 2000 river embankments were damaged during the 2011 Tohoku earthquake. This would result in huge economic losses and inconvenience of the neighboring residents. According to the investigation, one of the main reasons for the damage is soil liquefaction. Therefore, in order to predict liquefaction phenomenon and avoid future losses, it is necessary to consider soil liquefaction in numerical analysis. In this paper, one of the severely damaged river embankment during Tohoku Earthquake is studied. A numerical simulation was conducted according to its geometry which consists of a thick layer of saturated sand and layers of clayey sand. Analysis results are presented and compare with the actual deformation pattern.

2. CONSTITUTIVE MODEL

Governing equations used in this study are based on simplified three-phase model and finite deformation theory. The behavior of partially saturated soil is incorporated in the governing equation. An elastoplastic cyclic model (Oka et al., 1999) is used for liquefiable saturated sand whereas an elasto-viscoplastic model (Kimoto et al., 2015) is used for clayey sand and ground soil. Skeleton stress tensor is used in the constitutive model as:

$$\sigma'_{ij} = \sigma_{ij} - p\delta_{ij}\ ,\ p = S_r p^w + (1 - S_r)p^G \qquad (1)$$

where σ'_{ij} is skeleton stress tensor, σ_{ij} is total stress tensor, S_r is degree of saturation, p^w is pore water pressure and p^G is pore air pressure.

This study is an application of the elastoplastic model and elasto-visco plastic model that were proposed in the previous research. Van Genuchten's equation is adopted for soil water characteristic curve. Liquefaction analysis is performed using finite element program COMVIDY-2D developed by Oka et al. (2013). Detailed formulation and soil constitutive model may be found in Shahbodagh (2011).

3. FEM MODEL AND PARAMETERS

An embankment along Naruse River in Miyagi Prefecture is studied as it was severely damaged in Tohoku earthquake due to soil liquefaction. Embankment geometry, measured water table after the earthquake and underneath ground profile are shown in Figure 1. The embankment consists of multiple sandy clay layers with different stiffness and one liquefiable layer that is up to about 3.3 m. Maximum height of the embankment is 8.2m with 2.73 m width at its top. Engineering datum is set to be 50 m below ground level and constrain in both x and y direction. Equal-displacement is assigned at two extreme sides of the model. Ground acceleration of Tohoku earthquake at a depth of 80m measured at Tajiri in Miyagi Prefecture (MYGH06, KiK-net) is inputted for dynamic analysis, as shown in Figure 2.

Soil parameters are shown in Table 1 and Table 2. Elastic material parameters are available and used based on soil investigation report (MILT, 2011). Elasto-plastic parameters for saturated sand are generated based on liquefaction curve from laboratory test. Elasto-visco plastic parameters of Torishima clay are used for clayey sand and ground soil due to the lack of experimental data. Liquefaction curves of saturated sand and Torishima clay for the embankment are shown in Figure 3. Soil water characteristic curve of the embankment soil is shown in Figure 4. Initial degree of saturation of the embankment soil above the water level is assumed to be 60%.

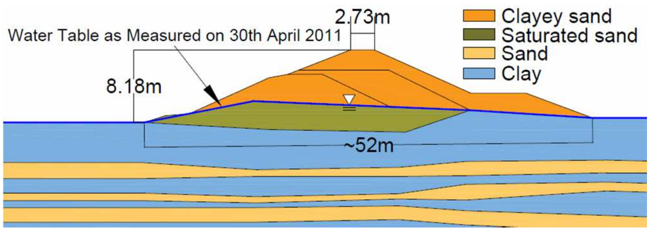

Figure 1. Simulation model

Keyword Liquefaction, FEM, Failure pattern, Embankment, Tohoku Earthquake
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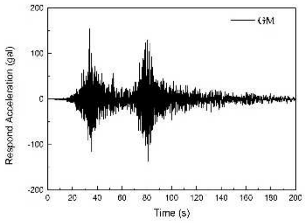

Figure 2. Input ground acceleration

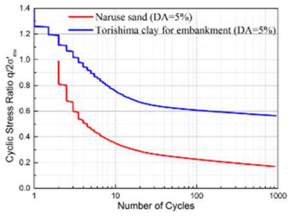

Figure 3. Liquefaction curve

Table 1. Soil parameters in simulation

Soil Parameters	Saturated Sand (EP)	Embankment Soil (EVP)	Ground Soil (EVP)
Density ρ (t/m³)		From Soil Test Data	
Specific Weight for Water γ_w (kN/m³)	9.81	9.81	9.81
Water coefficient of Permeability k_{ws} (m/s)		From Soil Test Data	
Gas coefficient of Permeability k_{gs} (m/s)	2.25E-02	5.87E-10	5.87E-10
Initial Void Ratio e_0		Calculated Assuming Sr=1.0 below WT and Sr=0.6 above WT	
Compression Index λ	0.05	0.341	0.341
Swelling Index κ	0.0057	0.019	0.019
Initial Elastic Shear Modulus Ratio G_0/σ'_{m0}		From Soil Test Data	
Stress Ratio at Critical State (Clay)/ Phase Transformation (Sand) M^*_m	0.891	1.24	1.24
Stress Ratio at Failure M^*_f	1.229	1.24	1.24
Hardening Parameters B^*_0, B^*_1, C_f	4500, 100, 0	100, 40, 10	100, 40, 10
Structural Parameters n,β	0.50, 50	0.30, 3.6	0.30, 3.6
Dilatancy Parameters $D^*0, \sigma'_{maf}/\sigma'_{mai}$	1.0, 6.0	-	-
Reference Value of Plastic Strian γ_r^{P*}	0.001	-	-
Reference Value of Plastic Strian γ_r^{e*}	0.003	-	-
Viscoplastic Parameter m'	-	24.68	24.68
Viscoplastic Parameter C_1 (1/s)	-	1.00E-14	1.00E-16
Viscoplastic Parameter C_2 (1/s)	-	3.83E-14	3.83E-16
Scalar Hardening Parameters A^*_2, B^*_2	-	5.9, 1.8	5.9, 1.8
Strain-dependant Parameters α',r	-	10, 0.4	10, 0.4

Table 2. Suction related parameters

Water Characteristic Parameters	Saturated sand, Clayey sand	Ground soil
van Genuchten Parameter α (1/kPa)	0.4	0.033
van Genuchten Parameter n'	3.0	1.083
Minimum Saturation S_{min}	0.00	0.00
Maximum Saturation S_{max}	0.99	0.99
Water permeability shape parameter a	3.0	3.0
Gas permeabilityshape parameter b	1.0	2.3
Suction Parameter SI	0.2	0.50
Suction Parameter Sd	0.1	0.25
Suction Parameter SIB	0.2	-
Suction Parameter Sdb	0.1	-

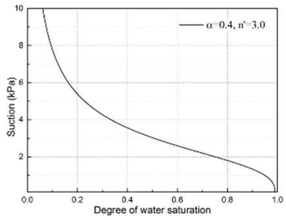

Figure 4. SWCC of embankment soil

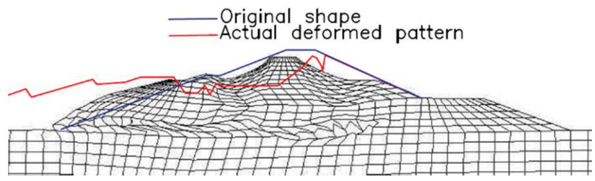

Figure 5. Embankment deformation pattern

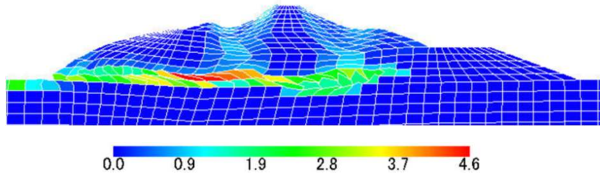

Figure 6. GAMP distribution after 200s

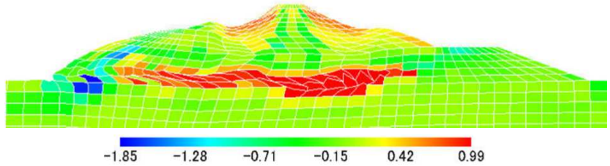

Figure 7. ESDR distribution after 200s

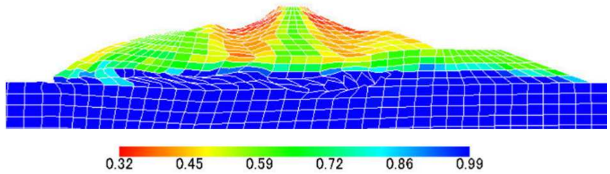

Figure 8. Degree of saturation distribution after 200s

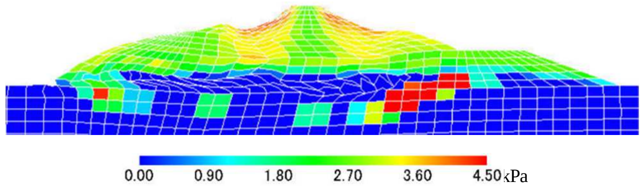

Figure 9. Suction distribution after 200s

4. RESULTS

Simulation results are shown in Figure 5 to Figure 9. Simulated deformation pattern and actual deformation pattern after 200s earthquake are presented in Figure 5. It could be observed that soil sliding occurred during earthquake. Sliding of the soil is difficult to be simulated by finite element analysis. Therefore, the deformation pattern result is not as large as the observed deformation on site. However, it is clear that the embankment has the tendency to slide towards the same direction as that of the actual sliding. Furthermore, the collapse location are similar as well. Distribution of accumulated plastic deviatoric strains (GAMP) is shown in Figure 6. High strain (up to 460%) occurred in saturated sand. Reduction ratio of skeleton stress ($ESDR = 1 - \sigma'_m/\sigma'_{mo}$) after 200s is presented in Figure 7. The saturated sand is completely liquefied as the ESDR within is mostly 1.0. Figure 8 and Figure 9 illustrate the distribution of degree of saturation and suction respectively. Maximum suction is approximately 4kPa when the degree of saturation is 32%. This result corresponds well to the SWCC used in the simulation as shown in Figure 4. It is also reasonable to see that lower degree of saturation results in higher suction.

5. CONCLUSION

According to the investigation, liquefaction of the soil in the river embankment is one of the main reasons for the damage of river embankment in Tohoku earthquake. In this paper, numerical simulation is conducted to study the soil liquefaction phenomenon. An elastoplastic model and an elasto-viscoplastic model are used in the constitutive model. Results are compared with the actual damaged pattern and discussed.

References:

1) Oka, F. et al. : Geotechnique, 49(5), pp. 661-680, 1999.
2) Kimoto, S., Shahbodagh Khan, B., Mirjalili, M and Oka, F., Int. J. Geomechanics, Vol.15, No.5, A4014005, 2015.
3) Oka, F., Shahbodagh Khan, B., Kimoto, S., Sadeghi, H,: Program COMVIDY-2D, large deformation dynamic analysis based on the three-phase mixture theory, Geomechanics Lab, Kyoto University, Jan. 2013.
4) Shahbodagh Khan, B.: PhD thesis, Geomechanics Lab, Kyoto University, 2011
5) Tohoku Regional development Bureau of MLIT, Report for the restoration of the river dikes of Kitakami river etc. December, 2011 (in Japanese).
6) National research institute for earth science and disaster resilience, 2011. KiK-net.