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NUMERICAL ANALYSIS OF DAMAGE OF RIVER EMBANKMENT ON SOFT SOIL DEPOSIT DUE TO EARTHQUAKES WITH LONG DURATION TIME

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ABSTRACT: we have analyzed model river embankments on the clayey foundation with different ground water tables using a dynamic liquefaction analysis method. From the analysis results, we have found that the effects of the water saturated region in the bank and the duration time of earthquake motion on the deformation behavior of river embankments are important. The results are consistent with the investigation results of the feature of the deformation and failure of the embankments due to the 2011 off the Pacific coast Tohoku Earthquake.

Key Words: River embankment,, Soft soil deposit, Liquefaction, Clayey soil, Great East Japan earthquake

INTRODUCTION

The 2011 off the Pacific coast Tohoku Earthquake damaged many soil made infrastructures such as river dikes, road embankment, railway foundations and coastal dikes. The river dikes and its related structures have been damaged at 2115 sites over the Tohoku and Kanto areas. In the present paper, the main patterns of the damaged river embankments are presented based on the in-situ research by the authors, MLIT and JICE. The main causes of the damage are, 1) Liquefaction of foundation ground, 2) Liquefaction of the soil in the river embankments with water saturated region above the ground level 3)Duration time of the earthquake is long since the fault zone was very large and the magnitude is 9.0. In the second part of the paper, we have analyzed model river embankments on the clayey foundation with different ground water tables using a dynamic liquefaction analysis method. From the analysis results, we have found that the effects of the water saturated region in the bank and the duration time of earthquake motion on the deformation behavior of river embankments are important. The results are consistent with the investigation results of the feature of the deformation and failure of the embankments due to the 2011 off the Pacific coast Tohoku Earthquake.

Pattern of the deformation and failure of river embankments

River embankments have been damaged due to the earthquake in both Tohoku and Kanto districts. The usual reason for the damage of the river embankments is a liquefaction of the foundation sandy ground which was observed at the failure of the left embankment of Yodogawa during the 1995 Hyogoken-Nanbu Earthquake. By the detailed study of the heavily damaged river embankments, we have found that the embankments on the soft clay deposit have been extensively collapsed due to the liquefaction. Typical patterns of soil profile are illustrated in Figure 1. Taking account of the investigation of the soil profile and the water table in the damaged embankments, the reason of the damage is a liquefaction of the water-saturated region bounded by the soft clay layers with smaller permeability. The effect of the water-saturated region is pointed out by MLIT. This region extends to the lower part of the embankments which have been settled below water table. The water table in the embankments which is higher than ground surface is formed by the rain fall and the capillary etc. In the following section we will show numerically analyzed results of the behavior of river embankments with the closed saturated region.

NUMERICAL ANALYSIS

Numerical method

It is well known that the one of the reason for the failure of the river embankment is earthquake loads. In this section, we have numerically analyzed the deformation behavior of river embankments during earthquakes using a soil-water coupled finite element analysis method. The two-dimensional water-soil analysis method has been developed based on the two-phase porous theory. In the numerical simulation of the dynamic behavior of ground, we used a liquefaction analysis program "LIQCA2D011" which has been developed by Oka et al.(Oka et al., 2005,2011).

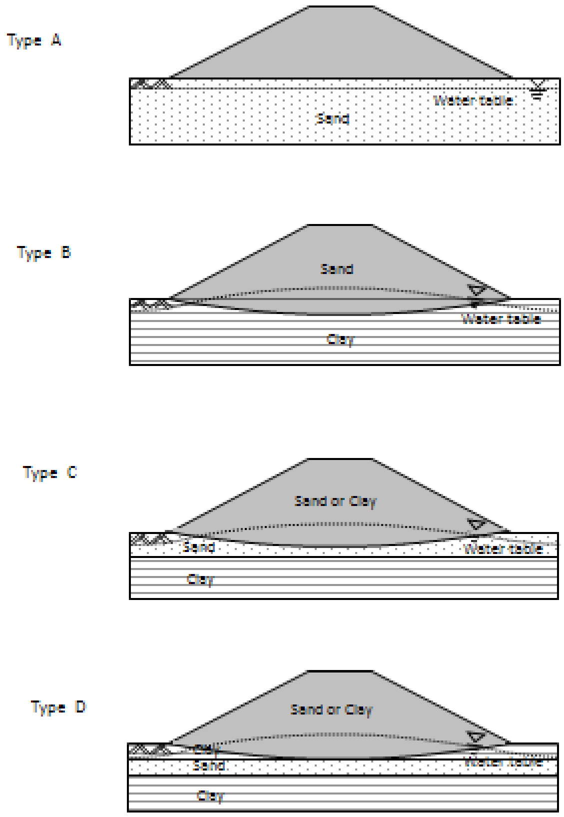


Fig. 1 Patterns of soil profile

The LIQCA2D11 adopted a u-p formulation with the finite element method and the finite difference method in the infinitesimal strain field. The equation of motion is discretized by FEM and the continuity equation is discretized by the finite difference method (e.g., Oka et al., 2004). As for the time discretization in the time domain, Newmark's β method is used. In addition, Rayleigh's damping is used in the analysis which is proportional to the initial stiffness matrix and the mass matrix.

For the constitutive model for soils, we have used a cyclic elasto-plastic model considering both the strain-induced degradation for sandy soils(Oka et al., 1999) and an elasto-viscoplastic model for clayey soils which has been developed recently(Kimoto, Sahbodagh, Mirjalili, and Oka 2012) based on the previous model(Oka et al., 2004) shown in Appendix. We have analyzed model river embankments with different soil profiles and water tables. In addition, we have studied the effect of saturated region in the embankment considering the duration of earthquakes. In the numerical analysis the u-p formulation was adopted. For the discretization of the equations of the motion (or equilibrium of the mixture) FEM (Finite Element Method) was used, while for discretization of the continuity equations of the pore fluids (water and gas) FDM (Finite Difference Method) was used. The time discretization is based on Newmark's β method, with β and γ set at 0.3025 and 0.6, respectively. The time increment in the calculation was set to be small enough to guarantee the accuracy of the results without having large computational time (i.e. 0.01 seconds).

3.2 Finite element mesh and boundary conditions

Figure 2 shows the model of the river embankment and the finite element mesh used in the analysis. The soil parameters are listed in Table 1 in which sandy soil is a liquefiable loose sand and for clay the parameters of soft clay at Torishima of the levee of the Yodo river (Mirialili, 2011) are used.
Table 2 indicates simulation cases with different soil profiles and earthquake motions. In the simulations we used different soil profiles with the clayey subsoil because the ground profiles of the many damaged embankments in Miyagi prefecture includes clayey soil layer about 10m thick.

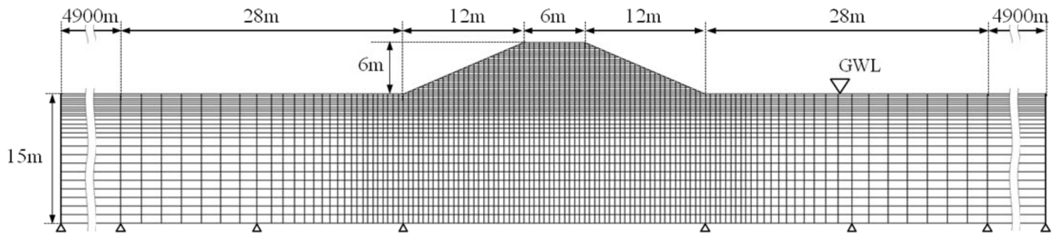


Fig.2 Finite element mesh and boundary conditions

Figure 3 shows the different soil profiles that taking account of the discussion in previous section; Type 2 illustrates the a levee embankment where the bottom of the embankment is below the ground water level. Type 3 shows the case in which the embankment is settled and ground water level is in the embankment. Type 3 corresponds to the typical case of severely damaged embankment due to the 2011 off the Pacific coast Tohoku Earthquake such as Shimokakanome-jyouryuu site of Naruse river. Type 4 corresponds to the case of the damaged embankment at Sekijyuku of Edo river (Kanto regional development bureau of MLIT, 2011. Figure 4 shows the input earthquake motions; Input 1 is an earthquake record obtained during the 1995 Kobe earthquake at a depth of 33m of Higashi Kobe ohashi. Input 2 is the earthquake record at a depth of 80m obtained at Tajiri ; MYGH06, KiK-net, 2011 (National Research Institute For Earth

Science and Disaster Prevention, 2011). The features of these waves are that the duration time of Input 2 is very long more than 2 min, which is longer than Input 1 but the maximum acceleration of Input 1 is larger than that of Input 2.

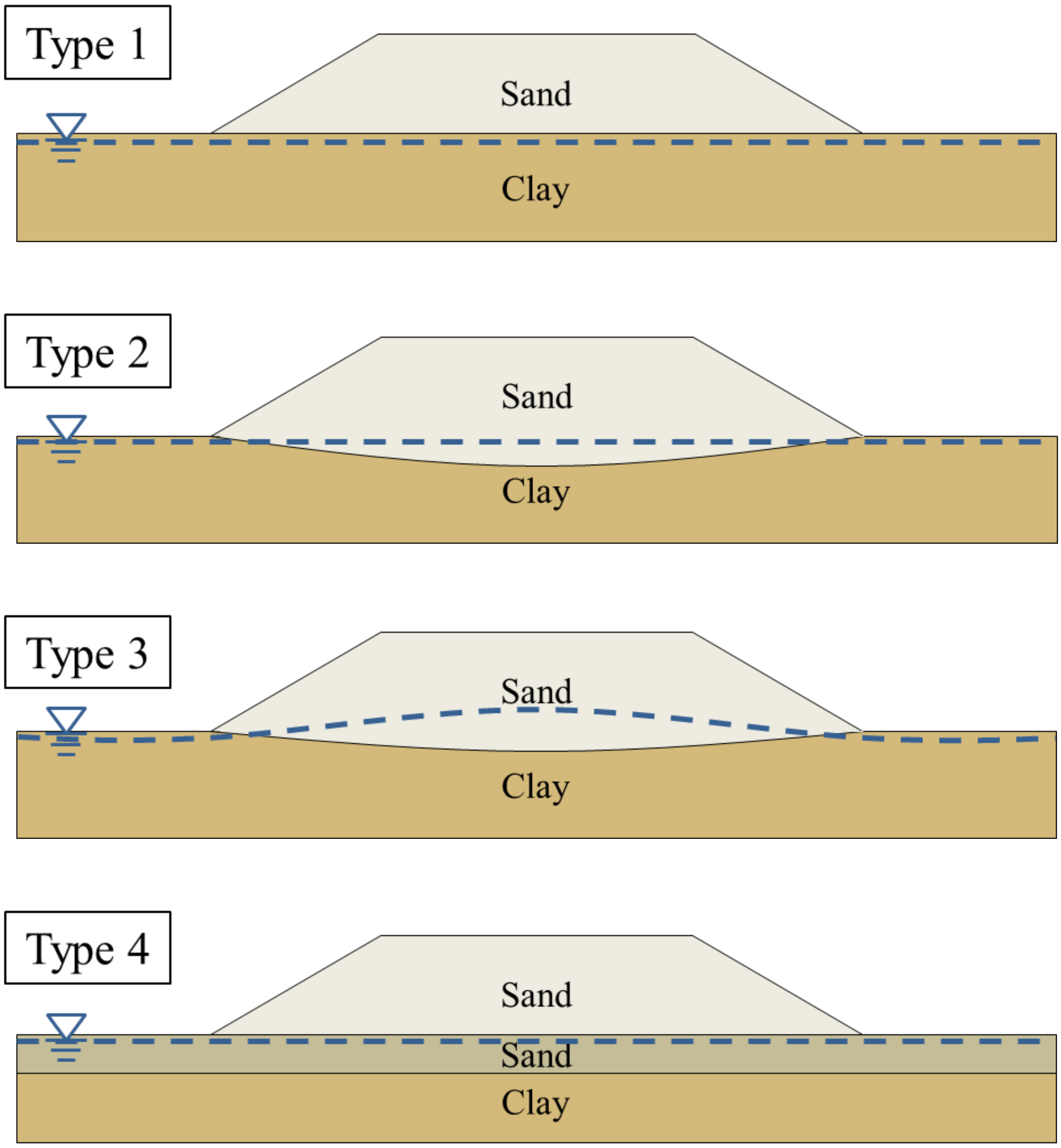
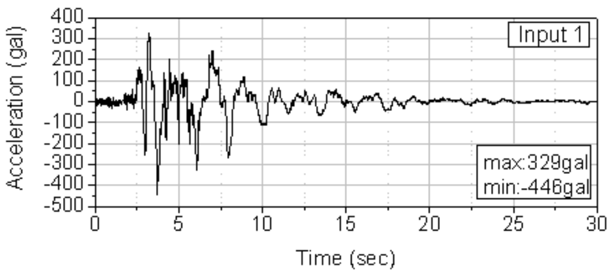
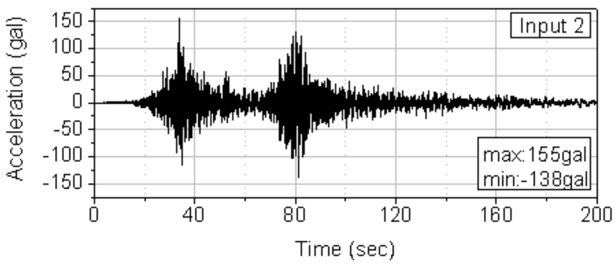


Fig.3 Soil profile and water table

In Figure 5, the vertical displacement-time profiles of the top of the embankment (Node 1978) and the horizontal displacement-time profiles of the toe of the embankment (Node 3178) are illustrated for all cases. The settlement of the top of the ground is maximum for Case 2-B. For the cases 2-A and 2-B, the maximum settlement of the top of the embankment and the maximum horizontal displacement of the toe of the embankments are obtained for Case2-B. For Case 2-A, the settlement of the top of the embankment is small and less than others.



Input 1
:Higashi-Kobe Ohashi,
1995 Hyogoken Nanbu
Earthquake (PWRI,1995)



Input 2:
MYGH06(at a depth of 80m)
-NS(Tajiri,KIK-net,
2011 of the Pacific
coast Tohoku Earthquake)

Fig.4 Input earthquake motions

Figure 6 shows the displacement distribution at the end of earthquake motions. For Case 1-A, the larger portion around the right toe of the embankments moves and it is seen that the displacement discontinuity can be seen below the ground level and in the clay layer, while in Case 1-B, the larger displacement is seen just around the toe of the embankment above the clay layer. Figure 6 indicates the distributions of displacement of Cases 2-A and 2-B. The largest displacement is seen in the central part of the embankment and below the top of the embankment for Case 2-B. Figure 7 shows the distribution of accumulated deviatoric plastic strain for Cases 1-A, 1-B and 2-A, 2-B. The accumulated deviatoric plastic strain is defined as:

$\gamma^p = \int (de_{ij}^p de_{ij}^p)^{1/2} ; de_{ij}^p$: Increment of deviatoric plastic tensor. For Case 1-A, we can see that the localized large strain beneath the river embankment, which is larger than the other cases, i.e., larger strain develops in the clay layers. In Figure 7 , we can see the larger plastic strain develops for Case 2-B in the saturated sand portion in the embankment as well as upper part of the embankment. The shear strain localized above the saturated region in the embankment and this trend is consistent with the observed failure pattern. Figure 8 shows the distribution of ESDR for Cases 2-A~2-B. ;

ESDR (Effective stress decreasing ratio: $ESDR \equiv \frac{\sigma'_{m0} - \sigma'_m}{\sigma'_{m0}}$)
.

Table 1 Material parameters

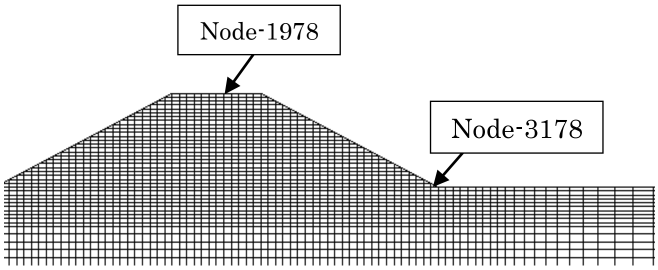
Parameter	**Sand**	**Clay**
Density ρ (t/m^3)	1.8 / 2.0	1.7
Water permeability k (m/s)	2.20×10^{-5}	5.77×10^{-10}
Initial void ratio e_0	0.8	1.25
Compression index λ	0.0250	0.3410
Swelling index κ	0.0003	0.0190
Normalized initial shear modulus G_0/σ'_{m0} (kPa)	761	75.2
Stress ratio at Maximum Compression M_m^*	0.909	1.24
Stress ratio at failure M_f^*	1.229	1.24
Quasi-overconsolidation ratio $OCR^*(=\sigma'_{mai}/\sigma'_{m0})$	1.0	1.0
Hardening parameter B_0^*, B_1^*, C_f	2000, 40, 0	100, 40, 10
Structure parameter $\sigma'_{maf}/\sigma'_{mai}$, β	0.5, 50	0.3, 3.6
Control parameter of anisotropy C_d	2000	-
Parameter of Dilatancy D_0^*, n	1.0, 4.0	-
Reference Value of Plastic Strain γ_r^{P*}	0.005	-
Reference Value of Elastic Strain γ_r^{E*}	0.003	-
Viscoplastic parameter m'	-	24.68
Viscoplastic parameter (1/s) C_1	-	1.00×10^{-5}
Viscoplastic parameter (1/s) C_2	-	3.83×10^{-6}
Hardening parameter A_2^*, B_2^*	-	5.9, 1.8
Strain-dependent modulus parameter α, r	-	10 , 0.4

Table 2 Analysis Cases

	Input1	Input2
Type1	*Case1-A*	*Case2-A*
Type3	*Case1-B*	*Case2-B*

For Case 2-B, we can see the liquefaction of the water saturated region in the embankment.

From the above discussions, it is worth noting that the water saturated region leads to the larger settlement of river embankment and the larger deformation/failure. This deformation behavior is consistent with the damaged embankments such as the embankments of Eai river in the Miyagi prefecture due the 2011 off the Pacific Tohoku Earthquake. From the numerical results of Case 1-A and Case 2-A, we can say that the earthquake wave form affects the deformation characteristics of the river embankment-subsoil layer system. Of course the amplitude of the earthquake is an important factor for the damage.



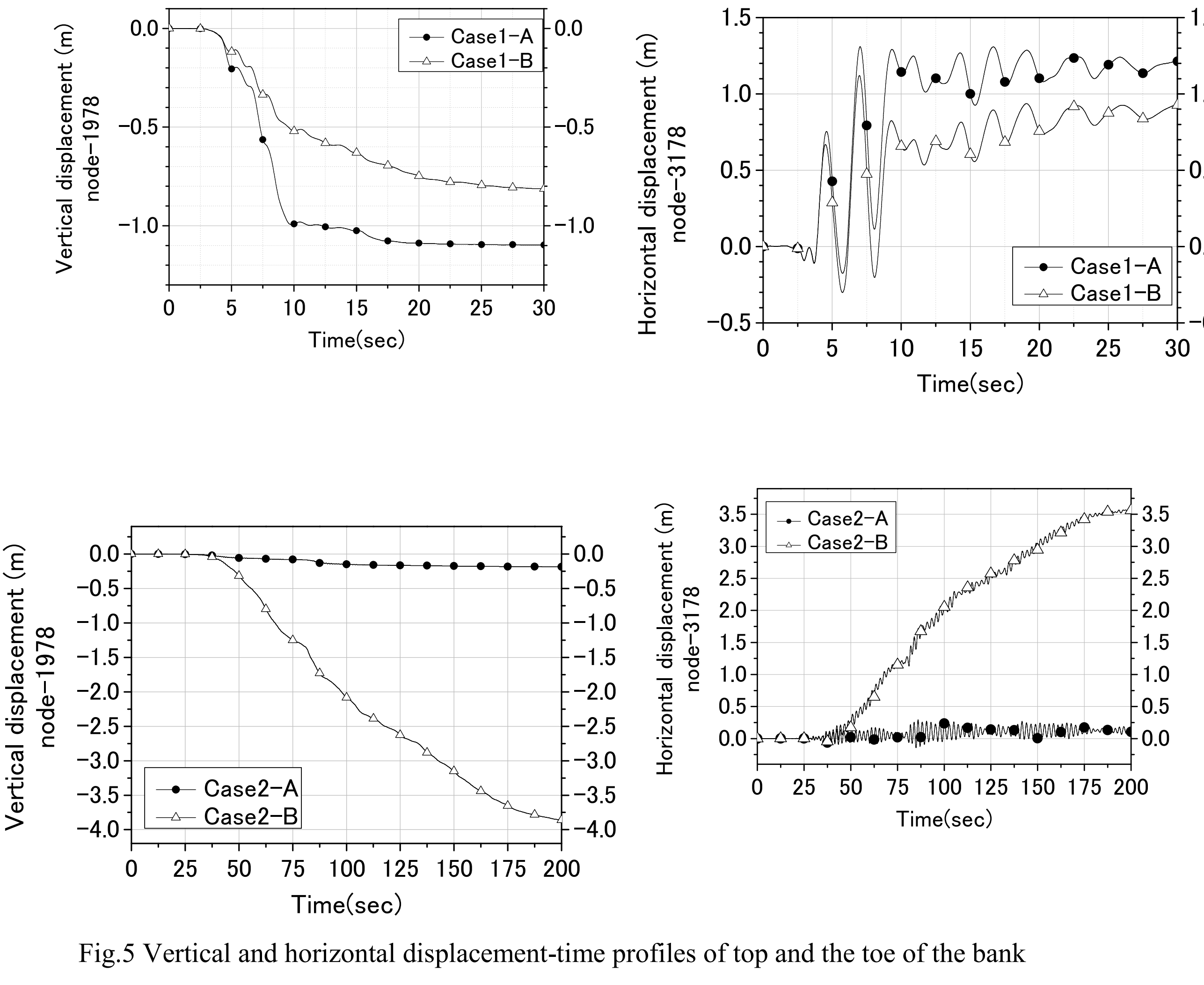
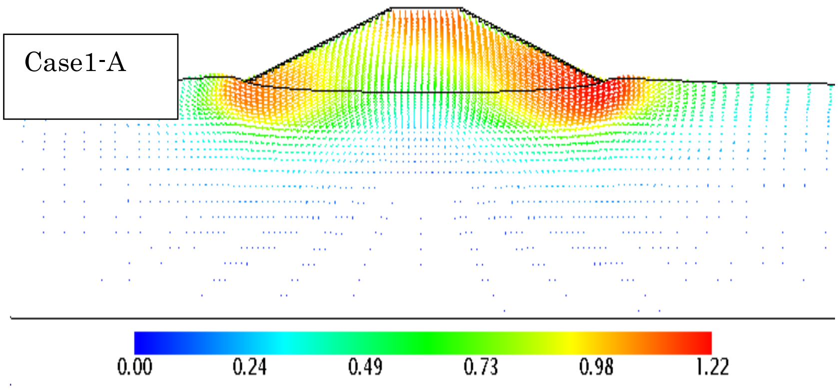
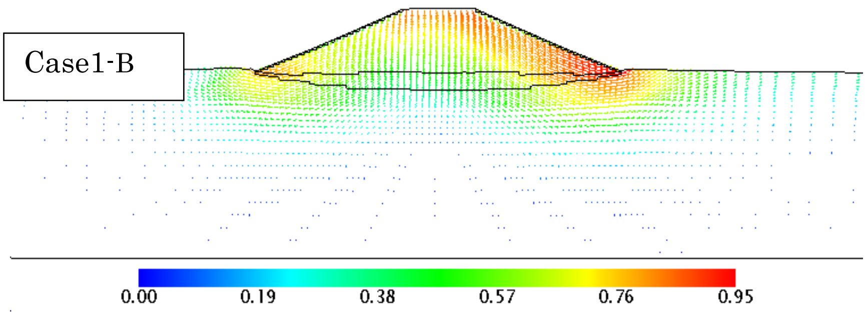
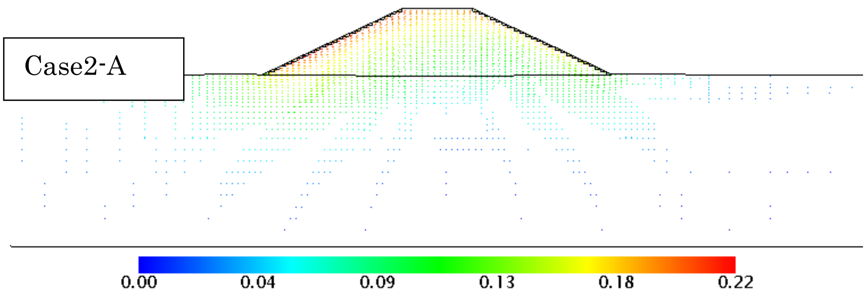


Fig.5 Vertical and horizontal displacement-time profiles of top and the toe of the bank


Case1-A
0.00
0.24
0.49
0.73
0.98
1.22


Case1-B
0.00
0.19
0.38
0.57
0.76
0.95


Case2-A
0.00
0.04
0.09
0.13
0.18
0.22

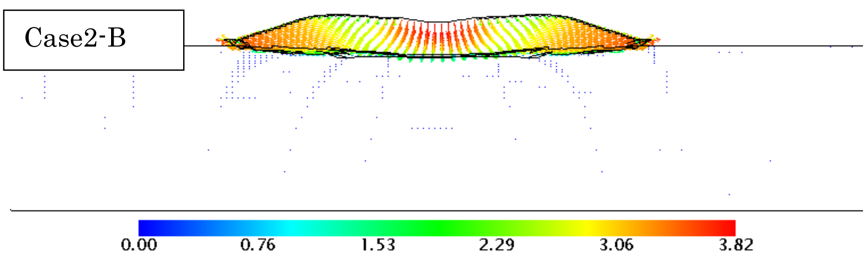

Case2-B
0.00
0.76
1.53
2.29
3.06
3.82

Fig.6 Displacement distribution

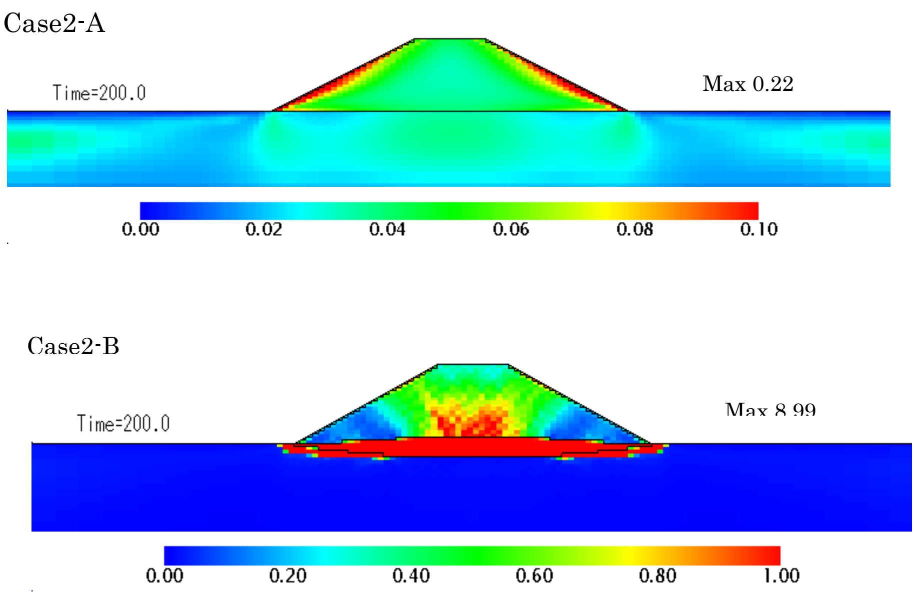


Fig.7 Distribution of accumulated plastic deviatoric strain

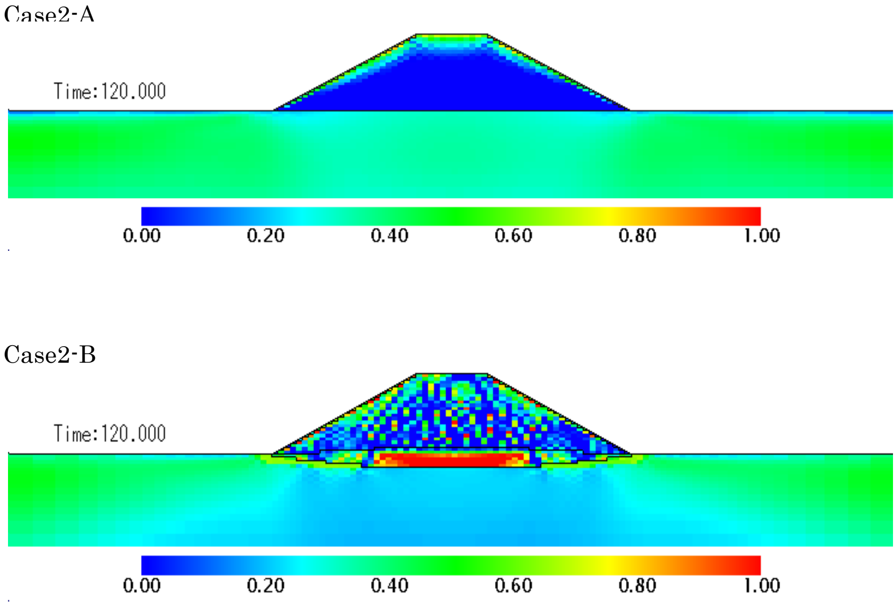


Fig.8 Distribution of effective stress decreasing ratio

From the investigation work of the damaged river embankments and the numerical simulation of river embankments with various subsoil profiles, we have obtained the following main conclusions:
By the detailed study of the heavily damaged river embankments, it has been found that the embankments on the soft clay deposit have been extensively collapsed due to the liquefaction. The feature of the damage is a liquefaction of the saturated region in the embankments downwardly bounded by the soft clay layers. From the numerical results, it has been found that the water saturated region in the embankments leads to the larger settlement of river embankment and the larger deformation/failure. This deformation behavior is consistent with the pattern of the damaged embankments due the 2011 off the Pacific Tohoku Earthquake. In addition, the earthquake wave form such as duration time affects the deformation characteristics of the river embankment-sub soil layer. Of course the amplitude of the earthquake is an important factor for the damage.

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