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NUMERICAL ANALYSIS ON MECHANISM OF DEWATERING AS A MITIGATION METHOD AGAINST LIQUEFACTION

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ABSTRACT: In recent years, liquefaction due to major earthquake caused serious damages to many infrastructures and houses around the world. In order to protect people's daily life and infrastructure from the disaster, development of effective and economical countermeasure against liquefaction that can be applied to existing houses is becoming increasingly important. Although many liquefaction countermeasures have been developed by many researchers, most of them require large construction machines and are costly, which limits their application to existing structures. For this reason, a liquefaction countermeasure, called as groundwater-level decreasing method, has been proposed in Japan. This method has already been put into practice and the construction of the countermeasure has finished several years ago. The purpose of this method is to change a liquefied layer to a non-liquefied layer by lowering the groundwater level. Yet the performance of this method has not been fully evaluated quantitatively. Therefore, in this paper, numerical analysis using FEM method was carried out to evaluate the liquefaction damage before and after the lowering of groundwater level. The calculation is conducted with 2D soil-water coupling finite element-finite difference (FE-FD) analysis based on a rotating-hardening elastoplastic constitutive model. From the analyses, it is found that the effective stress of the ground below under-groundwater level increases significantly because of the lowering of groundwater-level, resulting in an increase in resistance to liquefaction and mitigating the settlement damage of ground.

Keywords: Liquefaction, FEM, Countermeasure, groundwater-level decreasing method

1. INTRODUCTION

In recent years, the liquefaction occurred seriously in the world, e.g., 1995 Southern Hyogo Prefecture Earthquake, 2004 Mid Niigata Prefecture Earthquake, 2011 off the Pacific coast of Tohoku Earthquake, 2011 Canterbury earthquake, 2016 Kumamoto Earthquake, and 2018 Hokkaido Eastern Iburi Earthquake. In particular, the liquefaction damages in Tohoku Earthquake (2011) [1]-[2] were the heaviest recoded ever in Japan history. As shown in Fig. 1, one of the damage site, the liquefaction area covered 600 km along the Northeast coast of Japan and about 27,000 houses experienced severe damaged.

Therefore, development of effective and economical countermeasure against liquefaction for existing houses is very important and urgently needed. In this study, particular attention is paid to the performance of the groundwater-level decreasing method that has been already put into practical use as a countermeasure against liquefaction with numerical tests. In this method, continue drainage of groundwater is necessary so that the effective stress of ground can be increased and the excess pore water pressure can be dissipated quickly in a wide area with relative low cost. It is thought that these effects are effective not only for the large main shock, but also for multiple aftershocks in a short period of time.

The purpose of the research is to evaluate quantitatively the performance of the method that is still not enough at current stage. In this study, numerical analysis is conducted on the liquefaction damages of the ground in Ibaraki prefecture, Japan, dynamic FEM method considering the main shock and aftershocks in a unified way. The earthquake waves in the calculation were recorded in the Tohoku Earthquake (2011). In the analysis, a series of repeated dynamic-static analyses, considering not only the earthquake loading but also the static consolidation after each earthquake shock, are conducted in a sequential way just the same as the scenario happened in the Earthquake.

Fig. 1 Liquefaction damage in the 2011 off the Pacific coast of Tohoku Earthquake

2. ANALYSIS METHOD

The numerical analyses to evaluate the effect of a liquefaction countermeasure were conducted by a 2D/3D soil-water coupled finite element method program named as DBLEAVES [3] using based on the Cyclic Mobility model [4]. The applicability and the accuracy of the DBLEAVES has been firmly verified by shaking table tests for piles [5]-[8] and various liquefaction case histories [9]-[11].

Cyclic Mobility model is a kind of rotating-hardening elastoplastic model based on Cam-clay model [12]. It can consider properly the effects of stress-induced anisotropy, density and structure of soils in a unified way by introducing concept of subloading yield surface [13] and superloading yield surface [14], as shown in Fig. 2.

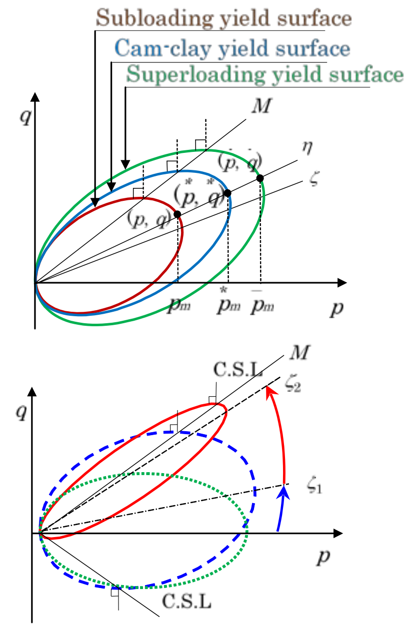


Fig. 2 Concept of Cyclic Mobility model [11]

The DBLEAVES can reproduce or predict accurately the overall mechanical behavior during and after the earthquakes, including the liquefaction and consolidation in repeated earthquake vibrations by describing properly the mechanical behaviors of soil subjected to monotonic/cyclic loading under drained/undrained conditions. In particular, the study of re-liquefaction using DAVLEAVES taking into account aftershocks [11], it was possible to reproduce the same phenomena as the observed phenomena, especially, a liquefaction happened easily by a small aftershock when the ground was not recovered from the damage by main shock and the range of liquefaction is expanded by aftershocks. For more detailed information about DBLEAVES and Cyclic Mobility model can be referred to references [3]-[4].

3. NUMERICAL ANALYSIS CONDITION

3.1 Investigated Site and Analysis Mesh for FEM

The investigated site, located at Ibaraki prefecture, experienced serious liquefaction damage during the 2011 off the Pacific coast of Tohoku Earthquake. Figure 3 shows the FEM mesh used in the calculation based on boring survey. The model ground consists of filling soil (Fs: 3.5 m), loose sand (As: 5.5 m) and dense sand (Ds: 11.0 m), and there is an embankment with a height of 1.0 m and a width of 60 m on the ground.

The ground area considered in the FEM analysis is 120 m in width and 20 m in depth, each mesh has width of 0.50 m and depth of 0.50 m. Here, the ground water level is set at -1.0 m of the ground level. In the case of dynamic analyses, an equal displacement boundary is adopted at side boundaries (x direction) to deal with the energy dissipation problem caused by artificial boundaries used in FEM. The bottom is assumed to be fixed in all directions.

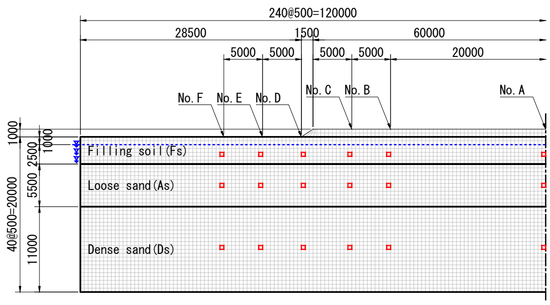


Fig. 3 FEM mesh for calculation

3.2 Earthquake Waves and Simulation Scenario

The earthquake motion in N-S direction recorded at Hasaki-2 923m below the ground surface at Ibaraki Prefecture in the 2011 off the Pacific coast of Tohoku Earthquake (Tohoku wave) is selected to be the input earthquake motion in analyses, as shown in Fig. 4. A maximum acceleration of the main shock was 0.62 m/s2 and that of aftershock was 0.94 m/s2. The interval between the main shock and aftershock was approximate 24 minutes.

By lowering the groundwater level, it is expected that the effective stress of the ground can be increased in addition to the excess pore water pressure (EPWP) being dissipated quickly. Therefore, the following four cases were investigated to clarify the countermeasure effects of the increase in initial effective stress and the effects of the early dissipation of EPWP, by lowering the groundwater level.

Case A (Water Level: G. L. -1.0m): This is a basic case for unimproved ground.

Case B (Water Level: G. L. -2.0m): In this case, the groundwater level is lowered by 1.0m but initial effective stress is kept the same.

Case C1 (Water Level: G. L. -3.0m): In this case, the groundwater level is lowered by 2.0m but initial effective stress is kept the same.

Case C2 (Water Level: G. L. -3.0m): In this case, the groundwater level is lowered by 2.0m while the initial effective stress is increased accordingly.

In all cases, the calculation is conducted using the same Tohoku wave: (1) main shock, (2) 1440 seconds consolidation, (3) aftershock, (4) consolidation until the settlement of the ground ceased completely (50 years later).

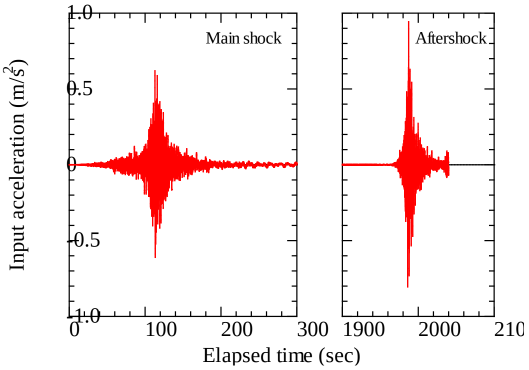


Fig. 4 Earthquake waves for calculation

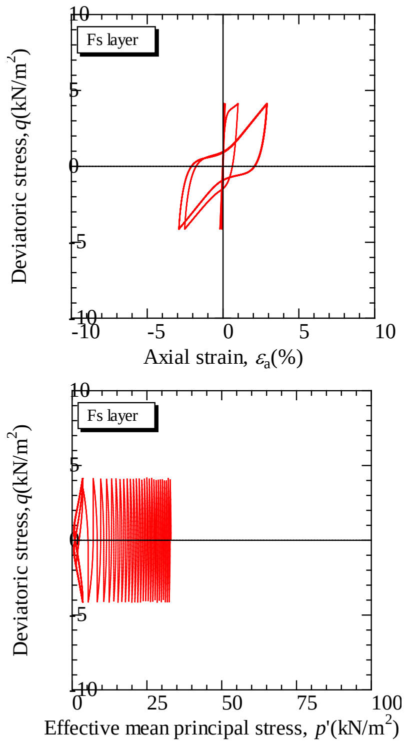
3.3 Material Parameters

The material parameters used in calculation are shown in Table 1. The parameters of the embankment on the ground are the same values as the filling soil. Here, the initial effective stress in each ground is given as the vertical stress in the central part of each ground with the coefficient of earth pressure at rest K0 of 0.5. Near the investigated site, standard penetration test was conducted, and it was possible to obtain a columnar section, N value and unit weight. However, data other than N value and unit weight (such as result of tri-axial test with undrain cyclic loading of soils and permeability test) were not available, some of these parameters were determined with reference to the standard penetration tests and those of Toyoura sand. Therefore, studies in this paper is a numerical experiment on a virtual ground rather than a simulation for liquefaction damage that actually occurred in the 2011 off the Pacific coast of Tohoku Earthquake .

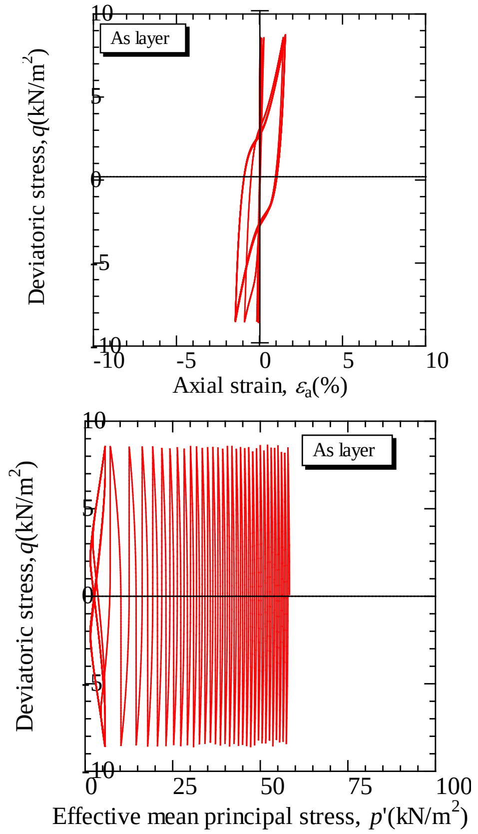
Table 1 Material parameters

	Filling soil	Loose Sand	Dense sand
Compression index λ	0.026	0.022	0.017
Swelling index κ	0.005	0.004	0.003
Stress ratio at critical state R_f	3.000	3.840	4.600
Void ratio e_0 (p'=98kPa on N.C.L)	0.550	0.550	0.470
Passion's ratio ν	0.300	0.300	0.300
Degradation parameter of over-consolidation m	0.100	0.100	0.100
Degradation parameter of structure a	2.200	2.200	2.200
Evolution parameter of anisotropy b_r	1.500	1.500	1.500
Unit weight γ (kN/m^3)	18.62	19.31	17.84
Permeability k (m/sec)	5.0E-5	5.0E-5	5.0E-5
Initial structure R^*_0	0.800	0.800	0.800
Initial degree of over-consolidation $1/R_0$	6.000	8.000	10.000
Initial anisotropy ζ_0	0.000	0.000	0.000

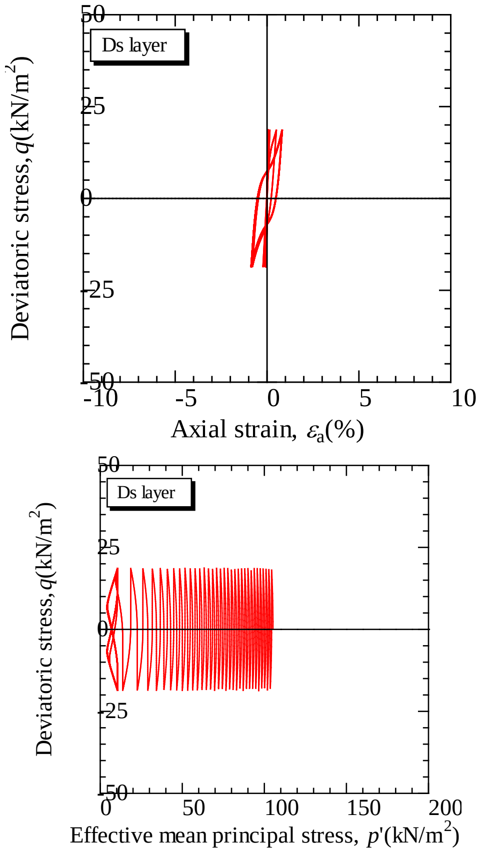
Figure 5 shows the simulation results of the element behavior in undrained cyclic loading test when the cyclic stress ratio is set to 0.10. From the results, it is known that the strain accumulates as the number of cyclic loading increases, and liquefaction accompanied by cyclic mobility occur in the filling soil and loose sand. However, liquefaction will not occur easily in the dense sand.



(a) Filling soil: Fs



(b) Loose sand: As



(c) Dense sand: Ds

Fig. 5 Simulated element behavior of soils

4. RESULT AND DISCUSSIONS

Figure 6 and Fig.7 shows the calculated excess pore water pressure ratio (EPWPR) at Point A (center of embankment) and Point F (10 m away from the toe of slope) in Case A. Fig.8 shows the distribution of EPWPR. Here, Case A is the basic case, and the measurement points (Point A to F) are shown in Fig.3. EPWPR is defined as the ratio of excess pore water pressure to the initial vertical effective stress. Therefore, EPWPR reaching 1.0 means that the soil is liquefied completely.

From the results, it is known that the liquefaction damage in non-embankment area is greater than that in embankment area. This is the effect of the initial effective stress due to embankment loading. In addition, it is also known that the liquefaction damage is expanding due to the aftershock. This result is clear seen in Fig. 8, that is, EPWPR increased greatly due to the aftershock.

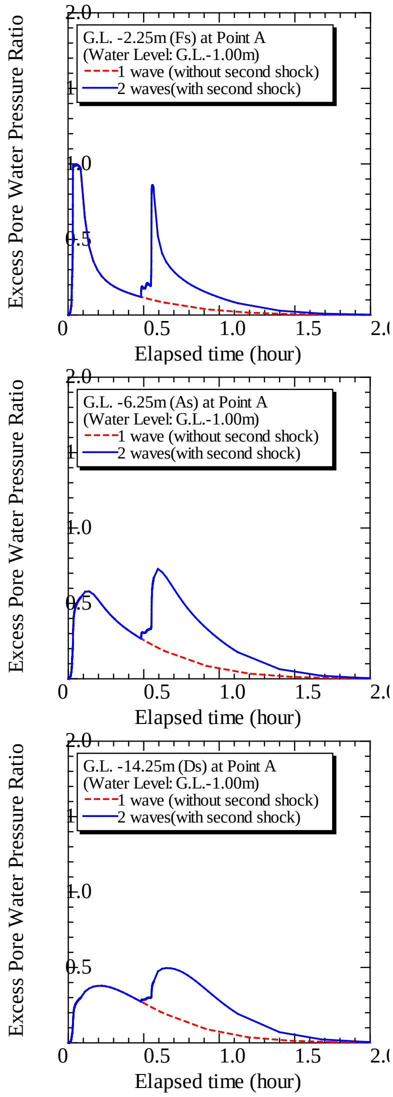


Fig. 6 Time history of EPWPR at Point A (center of embankment) in Case A

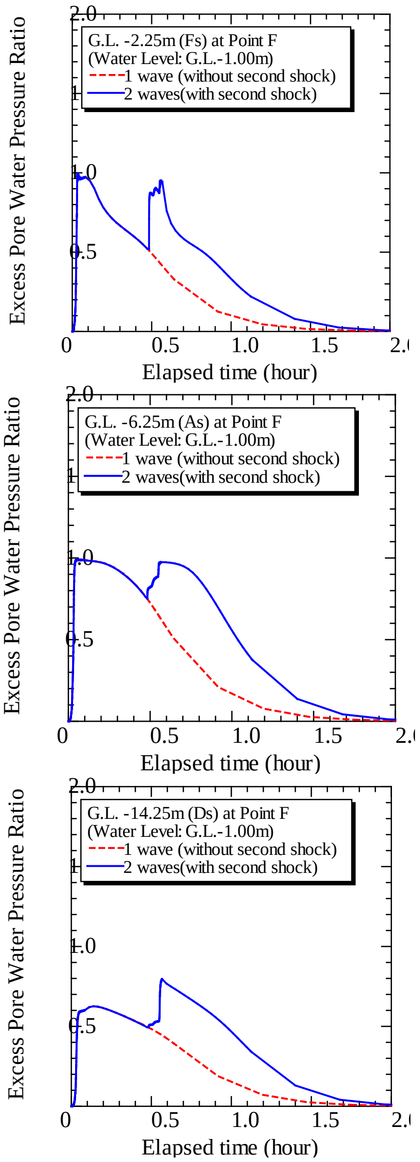


Fig. 7 Time history of EPWPR at Point F (10m away from the toe of slope) in Case A

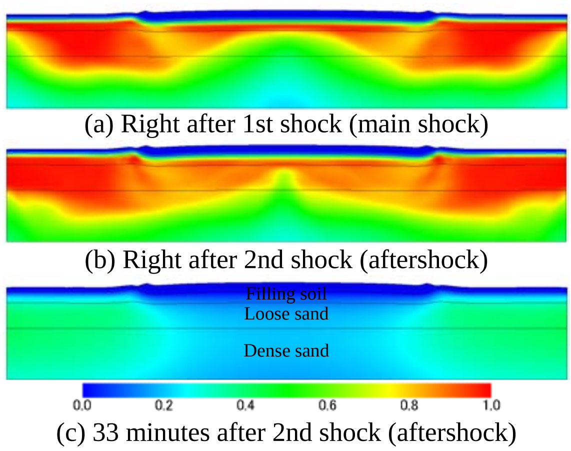


Fig. 8 Distribution of EPWPR in Case A

Figure 9 and Fig.10 shows EPWPR of loose sand at Point A and Point F. Furthermore, Figure11 and Fig. 12 shows the distribution of EPWPR right after 2nd shock and 33 minutes after the shock. From the results, it is known that EPWPR deceased due to the lowering of groundwater level, and that EPWP dissipated much faster.

Figure 13 shows the settlement of ground surface at Point A and Point F. From results, it is known that in the case of low ground water lever, ground surface sunk quickly and settlement got stable early. This is the reason because dispersion of EPWP is early when ground water lever is low.

As mentioned above, however, these cases have different groundwater depths, but have the same initial effective stress. Therefore, the countermeasure effect against liquefaction will be further enhanced by adding the effect of increasing the initial effective stress of lowering ground water level.

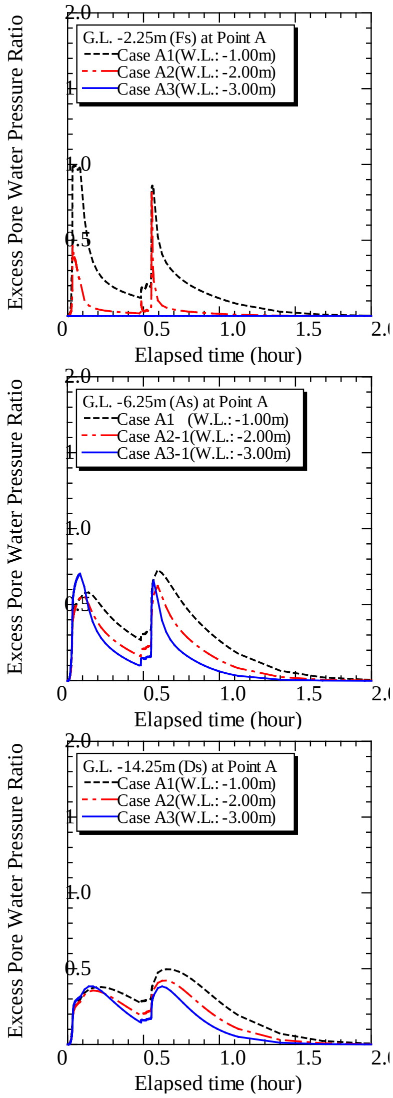


Fig. 9 Effect of groundwater level on EPWPR at Point A (center of embankment)

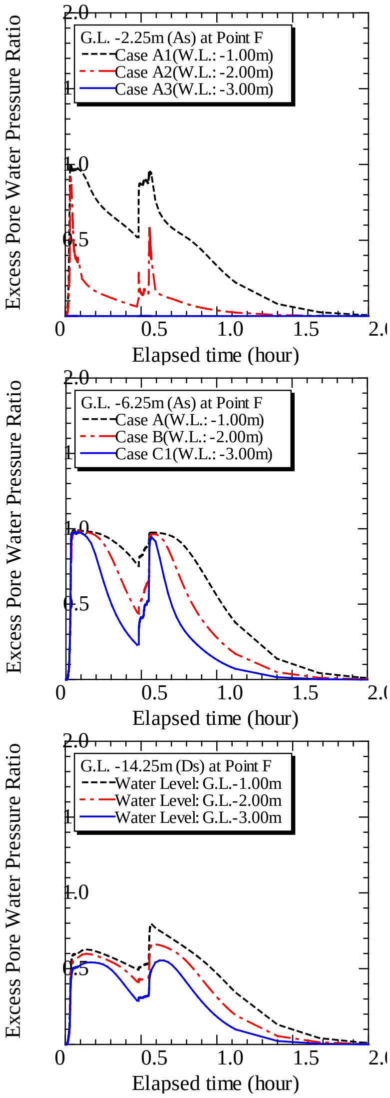


Fig. 10 Effect of groundwater level on EPWPR at Point F (10 m away from toe of the slope).

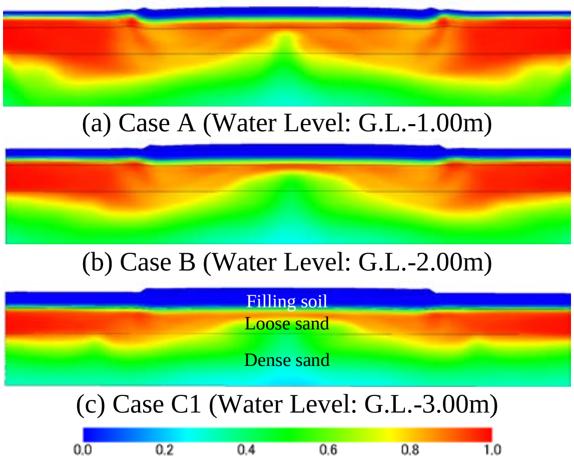


Fig. 11 Distributions of EPWPR right after 2nd shock (Comparison of groundwater level)

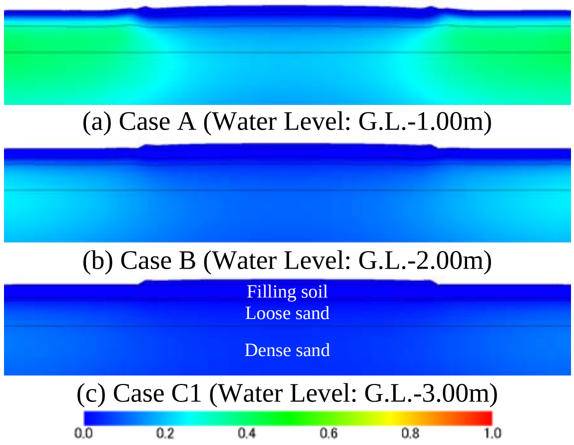


Fig. 12 Distributions of EPWPR 33 minutes after 2nd shock (Comparison of groundwater level)

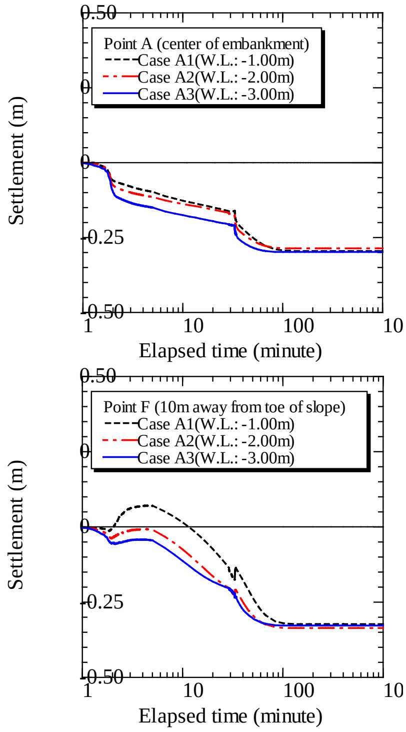


Fig. 13 Time history of settlement at Point A and Point F

Figure 14 and Fig. 15 shows a distribution of EPWPR in the Case C1 and C2. These cases have same groundwater depth in each case, but have the different initial effective stress. From the results, it is known that the countermeasure effect, such as suppression of excessive pore water pressure and early dissipation, is further enhanced by the increase of the initial effective stress compared to the case where only the groundwater level is lowered.

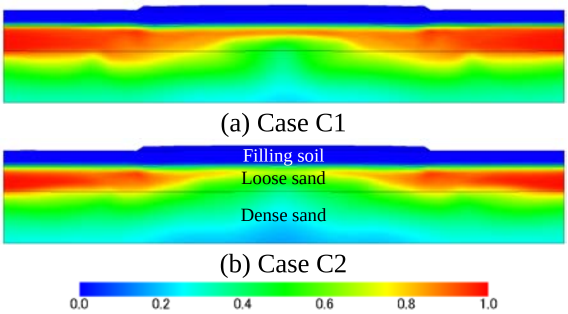


Fig. 14 Distributions of EPWPR right after 2nd shock (Comparison of initial effective stress)

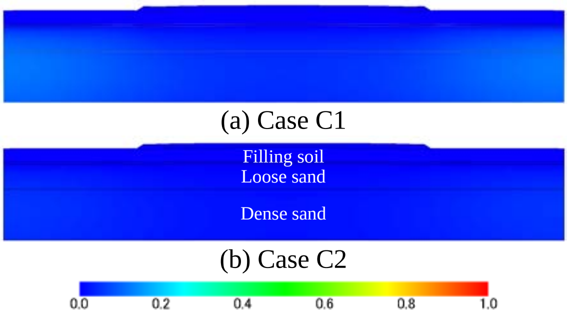


Fig. 15 Distributions of EPWPR 33 minutes after 2nd shock (Comparison of initial effective stress)

Figure 16 and Fig.17 shows distributions of displacement vector in Case A, C1 and C2. In Case A, it is known that the outer side of the embankment is greatly uplifted right after liquefaction, and then settlement due to consolidation with dissipation of EPWP. Therefore, it is clear that the ground deformation due to liquefaction is largely suppressed by the decrease of the groundwater level and the increase of the initial effective stress.

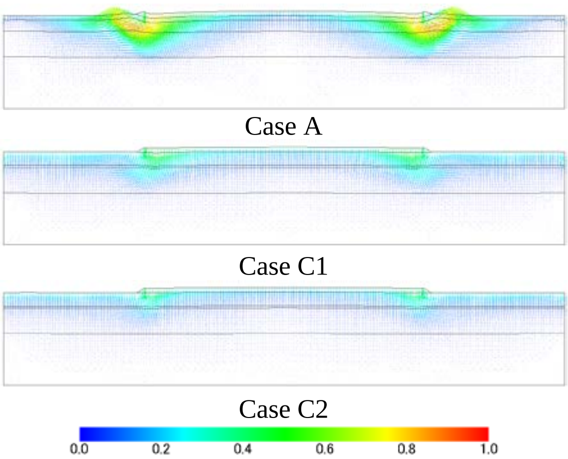


Fig. 16 Distributions of displacement vector right after 2nd shock (Comparison of ground water level and initial effective stress)

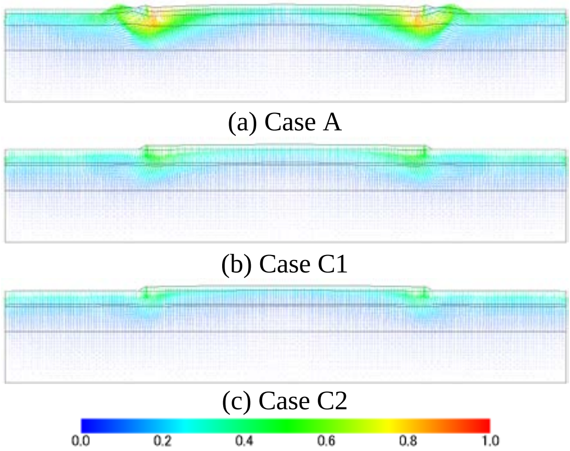


Fig. 17 Distributions of displacement vector 33 minutes after 2nd shock (Comparison of ground water level and initial effective stress)

5. CONCLUSIONS

In this study, 2D soil-water coupled finite element-finite difference analyses based on Ciclic Mobility model were conducted to evaluate the liquefaction damage before and after lowering the groundwater level. The following conclusions can be obtained:

1. According to the calculated results, even if the initial effective stress does not increase, liquefaction damage can be greatly reduced only by lowering the groundwater level with 1 to 2 m.

2. If the effective stress of the ground also increases in addition to the lowering of groundwater level, the effect of the countermeasure against liquefaction will be further enhanced.

3. Displacement of ground caused by liquefaction can quickly converged due to the lowering of groundwater level.

6. ACKNOWLEDGMENTS

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