

## COUNTERMEASURES AGAINST LIQUEFACTION-INDUCED LARGE SETTLEMENT OF RIVER LEVEE

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### ABSTRACT

The main plain in the Chubu region of Japan which is covered by loosely deposited sandy layers is surrounded by many wide rivers. A large settlement of the river levee is expected and worried due to liquefaction during an expected large earthquake. The Tonankai-Tokai coupled earthquake is targeted as the candidate earthquake attacking the Chubu region. In this study, effective stress based finite element analyses are carried out by program code "LIQCA" to predict settlements of river levees. Eight typical cross-sections are prepared as the target ones based on dominant factors about configurations and soil conditions. From the numerical results, it is found that there exist two distinct failure modes. One is named as "sliding failure mode" in which a large slip deformation appears especially around the both toe of the embankment. Another is named as "settling failure mode" in which the embankment sank into the liquefaction layer then it spread out to both directions. Countermeasures against liquefaction-induced large settlements are proposed based on the different failure modes.

Keywords: liquefaction, countermeasure, numerical analysis, river levee

### INTRODUCTION

Being situated on the boundaries between continental and oceanic plates and having many active faults throughout the islands, Japan is one of the most earthquake-prone countries in the world. Included in the plate-boundary-type earthquakes are large-scale earthquakes that occur nearly cyclically; large earthquakes have occurred in the Tokai, Tonankai, and Nankai areas with recurrence intervals of about 100 to 150 years. A magnitude-8.0-class Tokai earthquake can occur anytime soon, and the possibility of a magnitude-8.2-class Tonankai earthquake occurring within 30 years is estimated to be 60%. The damages caused by ground motions and tsunamis associated with such earthquakes are afraid.

In the Chubu region which is located in the center of Japan's main island, facing the focal regions of Tokai, Tonankai, and Nankai earthquakes, land areas below sea level are widely distributed in the lower reaches of the Kiso, Nagara, and Ibi Rivers (the Kiso-Sansen downstream area). Levees in the area have potential risks of liquefaction because they are constructed on the ground consisting of poor subsoil profiles, such as loose deltaic sand beds. Typical soil profile below levees is shown in Figure 1. In the worst case, a large tsunami could hit the area right after settlement of levees by an earthquake, and a great disaster such as long-term isolation of the area could occur.

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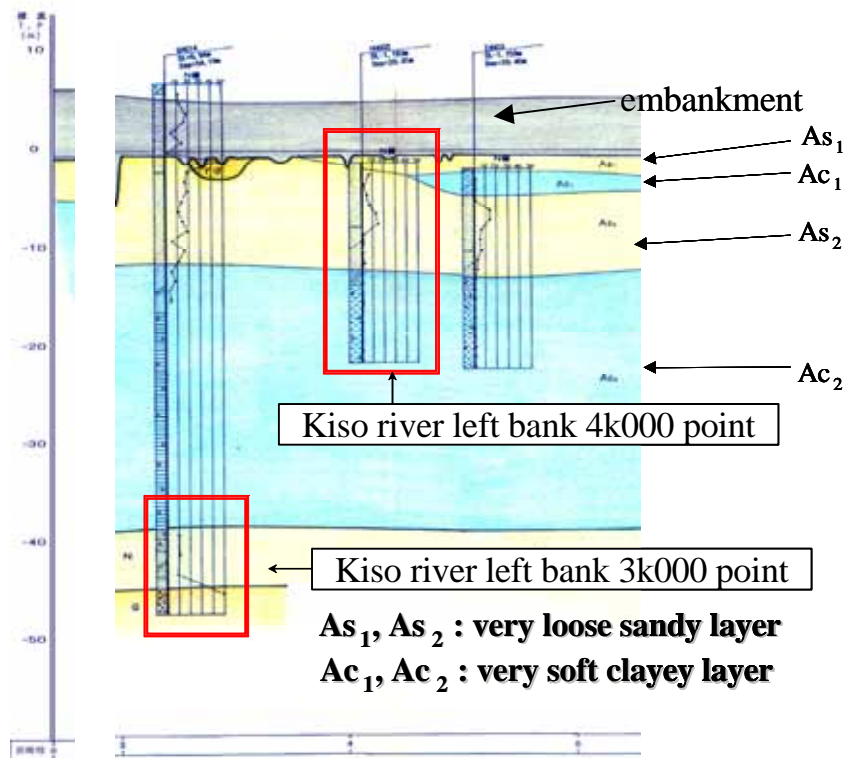


Figure 1. Typical soil profile below levees.

There are various methods to predict deformation of earth structures, such as river levees, during earthquake; the methods range from relatively simple ones to dynamic deformation analyses based on the finite element method. In the seismic evaluation of river levees in the Kiso-Sansen downstream area, it is necessary that the deformation can be predicted appropriately in consideration of the characteristics of levee foundation ground and the characteristics of the Tokai and Tonankai earthquakes, in particular large-scale, long earthquake duration. The Tonankai-Tokai coupled earthquake is targeted as the candidate earthquake attacking the Chubu region. In this study, effective stress based finite element analyses are carried out by program code “LIQCA” (2004) to predict settlements of river levees.

Eight typical cross-sections are prepared as the target ones based on dominant factors about configurations and soil conditions. Those factors are summarized as

- (1) thickness of liquefied layer (<10m, 10m<),
- (2) existence of clayey layer sandwiched in liquefied layer, and
- (3) flood channel width (<10m, 10m<).

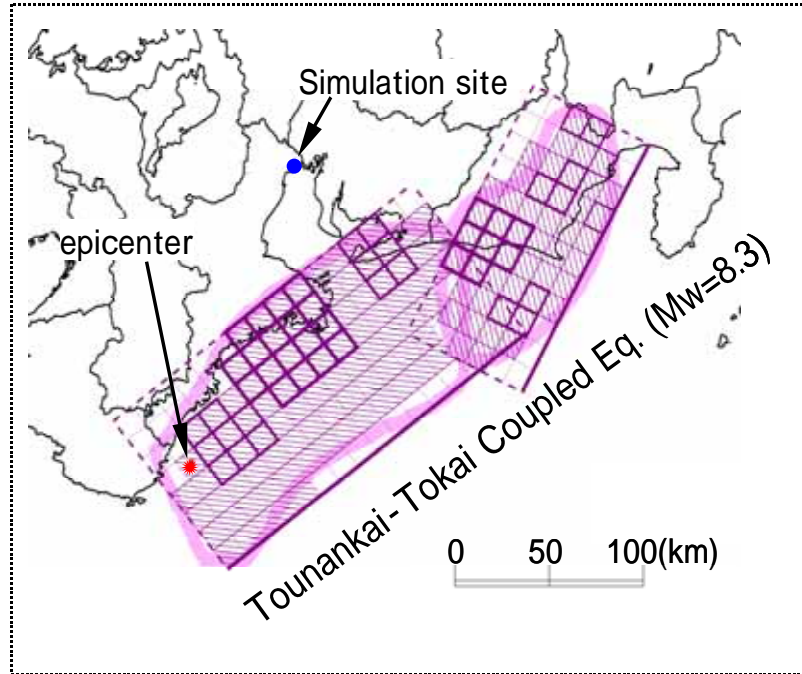
From the numerical results, it is found that there exist two distinct failure modes. One is named as “sliding failure mode” in which a large slip deformation appears especially around the both toe of the embankment. Another is named as “settling failure mode” in which the embankment sank into the liquefaction layer then it spread out to both directions. Countermeasures against liquefaction-induced large settlements are proposed based on the different failure modes.

## NUMERICAL SCHEME

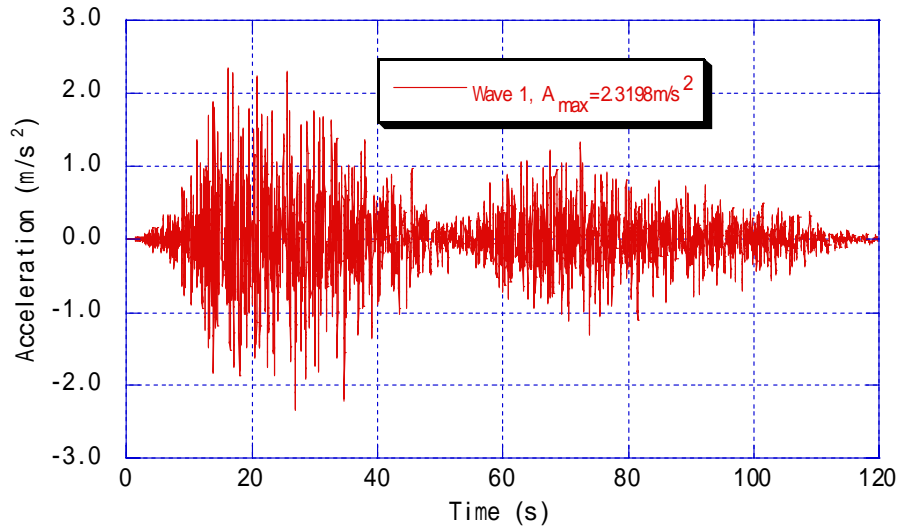
### Earthquake motion

Postulated Tonankai-Tokai coupled earthquakes were used for the investigation because they represent the severest earthquakes in the studied area, their occurrence is highly probable, and their tsunami

effects are feared. The fault area and failure process for the Tonankai-Tokai coupled earthquake is shown in Figure 2. The fault area is close to the big city Nagoya. Earthquake motion on the surface of bedrock was obtained by the strong motion prediction model, EMPR (Sugito et al., 2000). The expected acceleration input motion at the bedrock at Kiso river left bank 4k000-point (model No.8 in Table 1) is shown in Figure 3. It is found from this figure that the maximum acceleration is more than 200 gal ( $2.0 \text{ m/s}^2$ ) and the duration is more than 100 seconds.



**Figure 2. Postulated fault area and failure process.**



**Figure 3. Expected acceleration input motion at the bedrock.**

### Outline of LIQCA

The governing equations for the soil-water coupled problem are described based on Biot's two-phase mixture theory (Biot, 1941) and a  $u$ - $p$  formulation is adopted in the 2-dimensional analysis, where  $u$  stands for the displacement and  $p$  is the pore water pressure. Equations (1) and (2) corresponds the equation of motion and continuity equation for the Biot's two-phase mixture theory, respectively.

$$\rho \ddot{u}_i^s = \sigma_{ij,j} + \rho b_i \quad (1)$$

$$\rho^f \ddot{u}_{i,j}^s - p_{,ii} - \frac{\gamma_w}{k} \dot{\epsilon}_{ii}^s + \frac{n\gamma_w}{kK^f} \dot{p} = 0 \quad (2)$$

where  $\rho$  is the density of soils,  $\ddot{u}_i^s$  is the acceleration of the solid,  $\sigma_{ij}$  is the total stress,  $b_i$  is the body force,  $\rho^f$  is the density of fluid,  $p$  is the pore water pressure,  $k$  is the permeability,  $K^f$  is the bulk modulus of the fluid and  $\dot{\epsilon}_{ii}^s$  is the volumetric strain of solid. The finite element method (FEM) is employed for the spatial discretization of the equation of motion while the finite difference method (FDM) is employed for the spatial discretization of the pore water pressure in continuity equation. The validity of the proposed numerical method was verified by Oka et al. (1994) through a comparison of the numerical results and the analytical solutions for a transient response of saturated porous solids. As to the constitutive model for sand, a cyclic kinematic elastoplastic model (Oka et al., 1999) is used and the detailed description of the model can be referred to the reference.

### River levee models

Deformation of river levee induced by liquefaction is dependent on many conditions. In this study, it was assumed that the following three factors

- (1) thickness of liquefied layer (<10m, 10m<)
- (2) existence of clayey soil layer (Ac1) sandwiched in the liquefied layer, and
- (3) flood channel width (<10m, 10m<)

are dominant in liquefaction induced deformation of river levee, so that the river levees in the Kiso-Sansen downstream area were classified into 8-type models. Numerical case studies were carried out for these 8 models. The details of 8 models are listed in Table1.

**Table 1. Summary of numerical case study.**

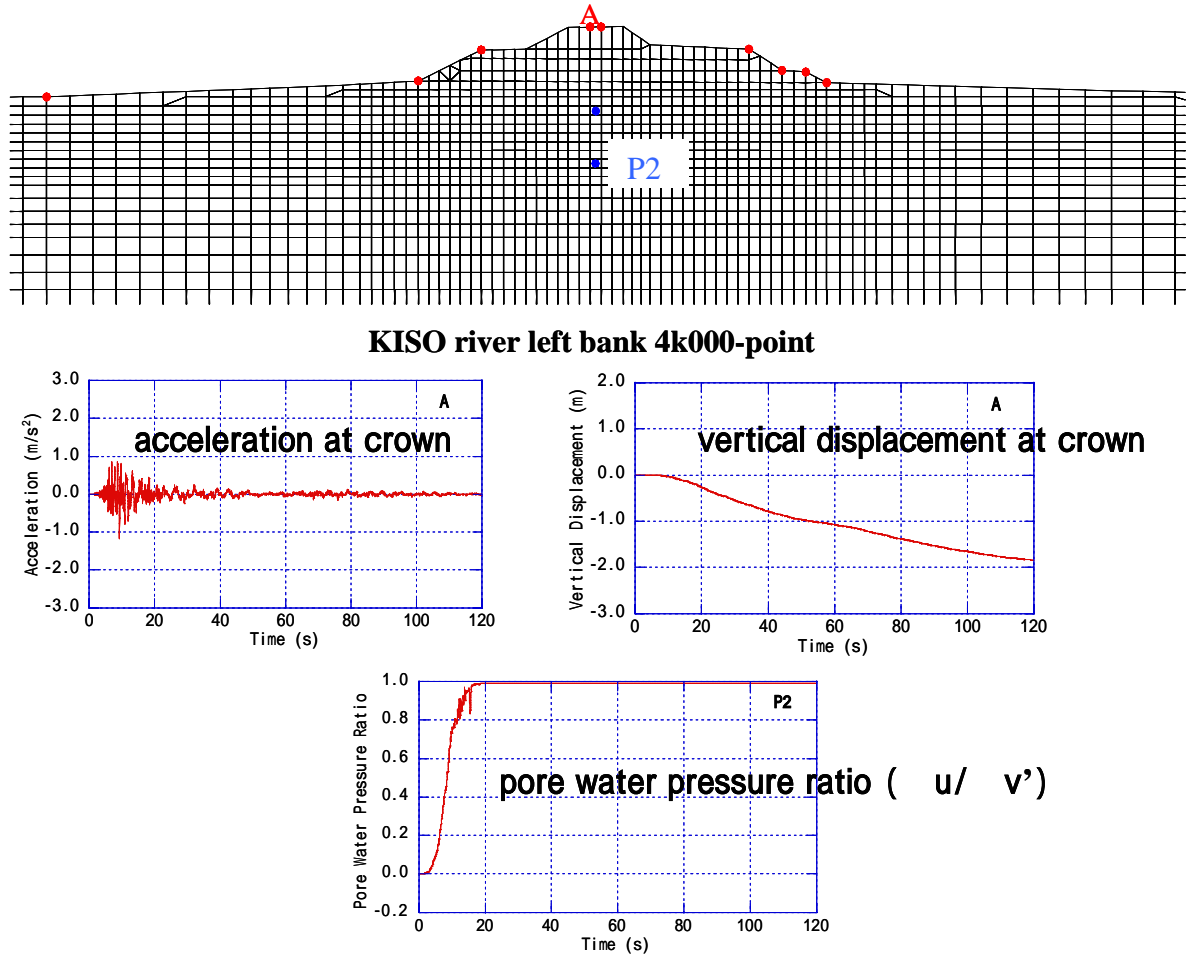
Thickness of liquefied layer (N > 20)	Existence of Ac1	Flood channel width	Model No.	Levee height (m)	Flood channel width (m)	Max. accel. at the bedrock (Gal)	Max. accel. (Gal)	Thickness of liquefied layer (N > 20) (m)	Mean N value of liquefied layer	Mean FL Value	permanent settlement (m)	Failure mode
10m	Exist	10m	1	6.2	6.1	215.1	130	6.0	8.1	0.59	2.1 (34%)* <sup>2</sup>	Sliding
		< 10m	2	4.5	11.1	228.3	177	4.0 (14.0)* <sup>1</sup>	21.4	1.38	2.0 (44%)	Settling
	Not Exist	10m	3	7.1	8.4	213.8	119	8.5	4.5	0.36	1.9 (27%)	Sliding
		< 10m	4	5.7	16.5	240.6	249	5.5	12.5	0.82	1.8 (32%)	Sliding
< 10m	Exist	10m	5	5.9	8.3	235.9	208	11.5	12.8	0.76	2.0 (34%)	Settling
		< 10m	6	4.3	11.5	240.6	80	15.0	8.4	0.36	1.1 (25%)	Settling
	Not Exist	10m	7	8.3	6.5	218.5	147	11.5	7.0	0.55	1.7 (20%)	Settling
		< 10m	8	4.3	12.5	232.0	116	12.0	5.7	0.42	2.0 (47%)	Settling

\*1 parenthesis indicates liquefied layer thickness which contains high N value (N > 20)

\*2 parenthesis indicates the ratio of settlement with respect to levee height

## NUMERICAL RESULTS AND DISCUSSIONS

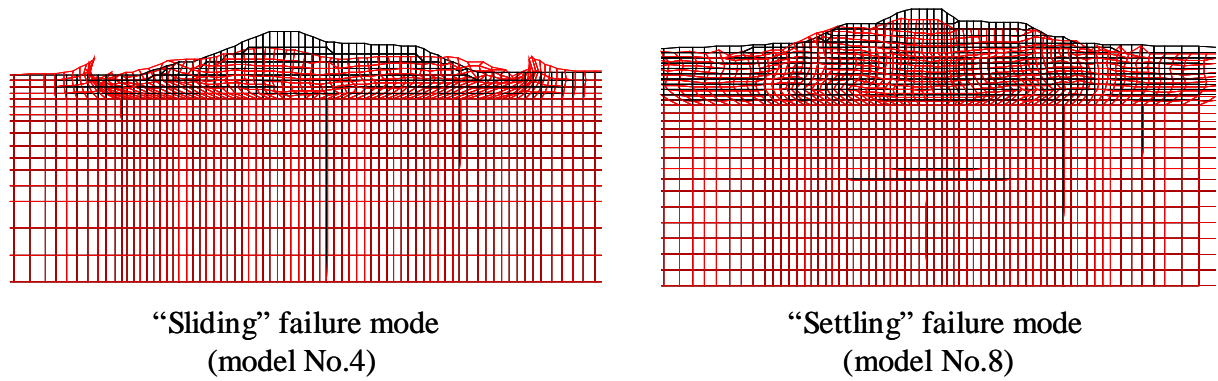
Numerical studies by the dynamic analysis (LIQCA) were carried out. In LIQCA analysis, some material parameters related to the elastoplastic constitutive model was adjusted by trial and error so that the model can simulate the target liquefaction strength. Other material parameters in LIQCA analysis were estimated from in-situ test data. The analyses were carried out under the plane strain condition. Numerical meshes were modeled up to the depth of bedrock which approximately corresponds to a bearing ground, whose shear wave velocity was set to be approximately 300m/s. The boundary conditions of right, left and bottom sides were fixed. The horizontal numerical area is sufficiently enough to avoid the effect of the reflection wave at the right and left boundaries. Since the earthquake waveform used as an input motion was assumed to be at the bedrock whose shear wave velocity was approximately 500m/s, the maximum acceleration amplification (Midorikawa, 1987) had to be done. The results of numerical case studies are also summarized in Table1.



**Figure 4. Numerical results for Kiso river left bank 4k000-point (model No.8 in Table 1).**

### Settlement mode of river levee

Typical numerical results with respect to acceleration time history at the crown of river levee, vertical settlement at the crown and the excess pore water pressure ratio ( $u/v'$ ) at Kiso river left bank 4k000-point (model No.8 in Table 1) are shown in Figure 4. It is found that the base sandy layer liquefied after 20 seconds since the earthquake begins. The shear wave does not propagate through the liquefied sandy layer and the obvious horizontal acceleration is not observed after 20 second. The settlement of the river levee starts after the liquefaction of the sandy layer and continues during the earthquake excitation for 120 seconds.

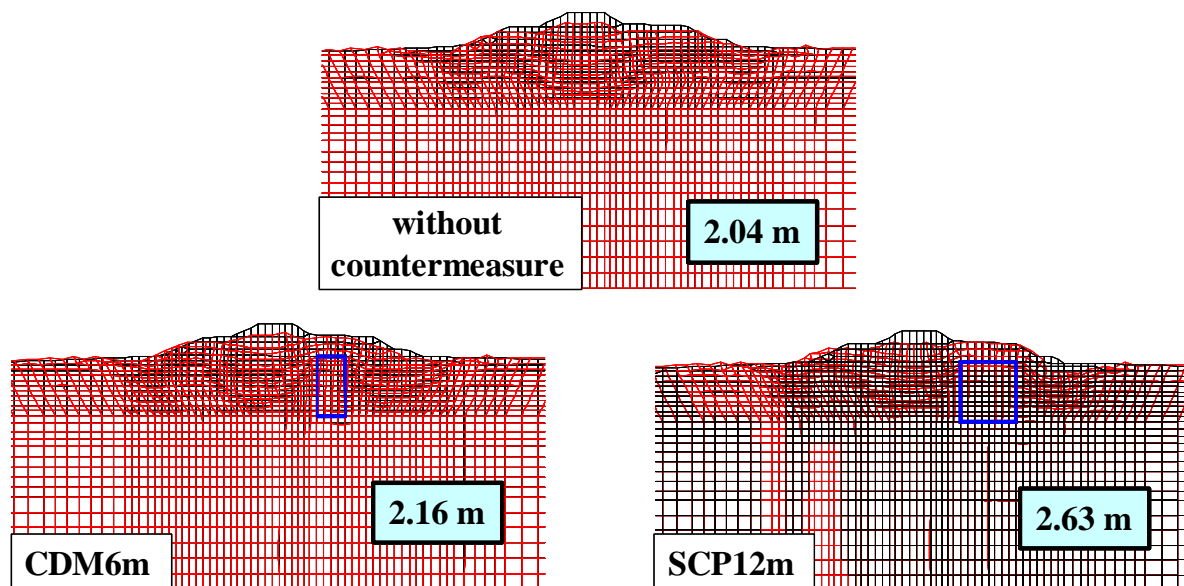


**Figure 5. Different failure mode after liquefaction.**

From the results of numerical case studies summarized in Table 1, one finds that the two distinct failure modes tend to be appeared in LIQCA analysis. One is named as “Sliding” failure mode that a large slip deformation appears especially around the both toe of the embankments. The other is named as “Settling” failure mode, which the embankment sinks into the liquefaction layer then it spreads out to the both boundary of the model. At the cross section which exhibits “Sliding” failure mode, high settlement is predicted by LIQCA almost regardless of the  $F_L$  value. Examples of both failure modes from LIQCA analysis are shown in Figure 5, which correspond “Sliding” (model-4 result) and “Settling” (model-8 result), respectively. In this figure, black lines represent the original mesh. On the other hand, red lines correspond to the deformed mesh after excitation. The “Sliding” failure mode seems to be appeared when thickness of liquefied layer is less than 10m. Other two conditions, existence of clayey soil layer (Ac1) sandwiched in the liquefied layer, and flood channel width ( $<10\text{m}$ ,  $10\text{m}<$ ), do not have major effects on the appearance conditions of “Sliding” failure modes.

#### Countermeasures against large settlement due to liquefaction

In order to retain the sufficient function of the river levee during the earthquake and following attack of Tsunami, it is necessary to prevent large settlement of the river levee by the appropriate countermeasures. In this study, the effect of the countermeasure against liquefaction-induced settlement is discussed based on the numerical simulations. Three distinct soil improvement techniques are employed in this study, which are Cement Deep Mixing Method (CDM), Sand Compaction Pile Method (SCP) and Gravel Drain Method (GD), respectively.



**Figure 6. Effect of CDM and SCP at onside only of the riverside.**



We expect “Settling” failure mode at Kiso river left bank 4k000-point (model No.8). To reduce the soil improvement cost, the effect of soil improvement by CDM and SCP at one side only of the riverside is firstly discussed. Figure 6 summarizes the effect of the CDM and SCP installed at riverside. In this figure, CDM6m stands for CDM with the improved width of 6m. SCP12m also means SCP treatment with the improved width of 12m. The values of final settlements at the crown and the deformed meshes are shown in figures. The final settlement at the crown in the case without countermeasure is 2.04 m. On the other hand, the settlement in the case with CDM6m is 2.16 m and

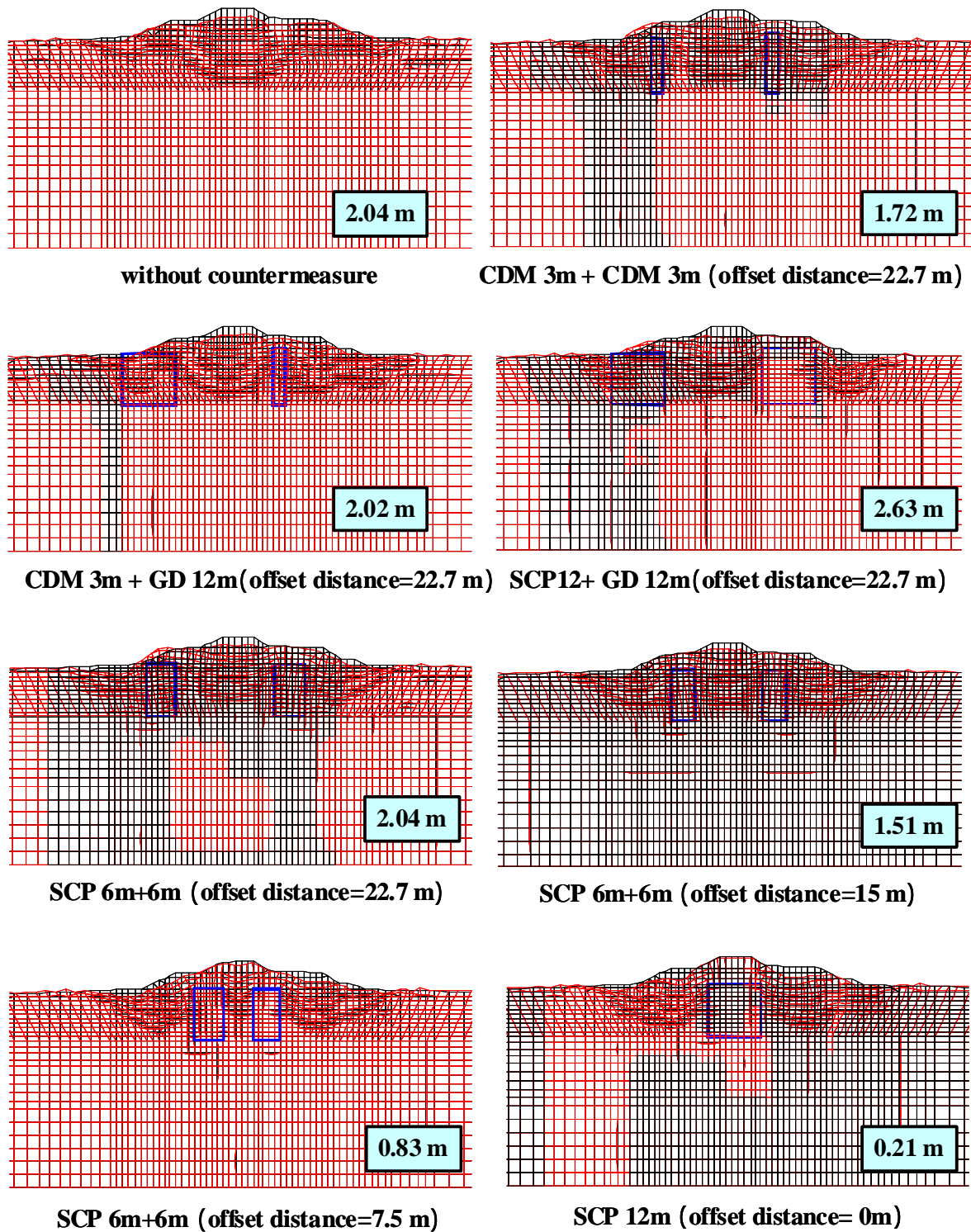


Figure 7. Effect of soil improvement at both sides of the river levee.

2.63 m in the case with SCP12m. The final crown settlements with countermeasures are larger than the case without countermeasure. It is found from the deformed mesh that the sliding mode is encouraged during a long period excitation. A large settlement is observed due to the sliding deformation toward dry land side. Therefore, the soil improvement at one side only is not effective to prevent large settlement due to liquefaction.

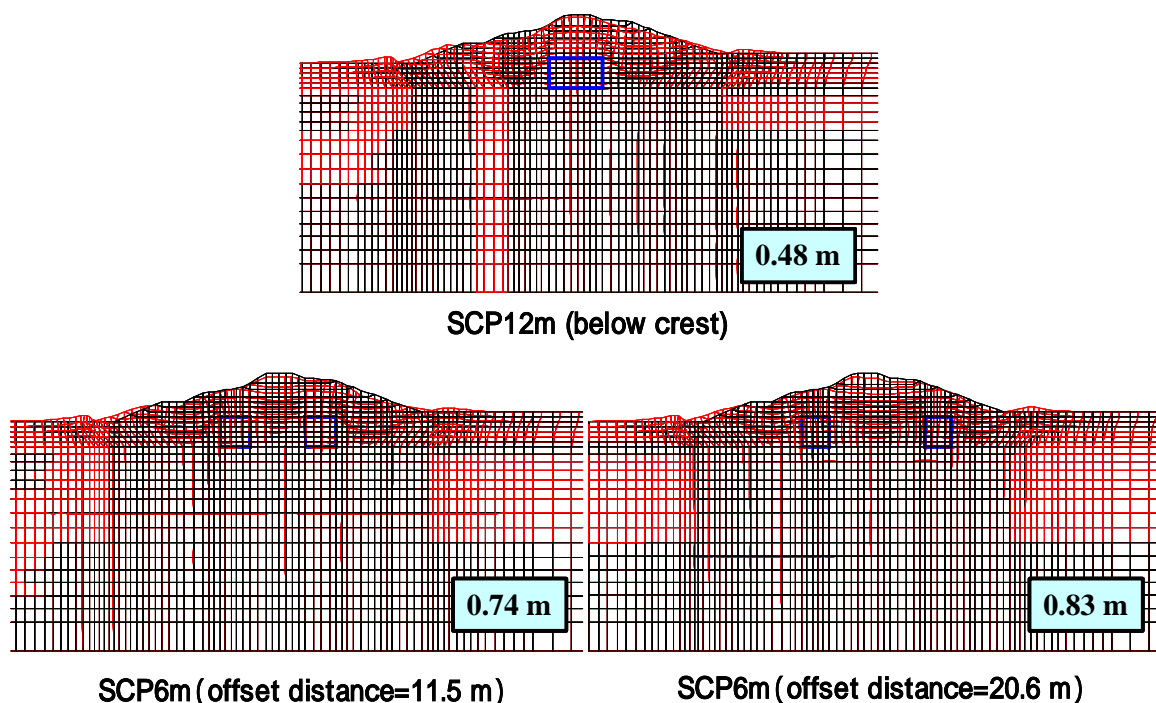
Secondly, the effects of three distinct soil improvement techniques installed at both sides of the river levee at Kiso river left bank 4k000-point (model No.8) where the failure mode is “Settling” are then discussed. The comparison of the final crown settlement for each case is shown in Figure 7. The soil improvement with relatively long offset length between the improvement areas at river side and at protected lowland side is found to be not effective to reduce the final settlement of the levee crown. If the offset length is enough long, the embankment of river levee sinks between the improved areas. At the same time, the propagated shear wave through the improved area induced the surplus settlement of the embankment due to the large horizontal excitation. On the other hand, if the offset length between the improved areas at both sides is reduced, the final crown settlement progressively diminishes.

It is concluded that at the cross-section in which the “settling failure mode” is predominant;

- 1) The very short offset distance of the improved areas is suggested to prevent the large settlement.
- 2) The improvement located immediately below the river levee crown is very effective.

Finally, at the cross-section in which the “sliding failure mode” is predominant, the influence of the offset length between the improved areas at both sides is examined. The final crown settlement at Ibi river right bank 10k600-point (model No.3 in Table 1) without soil improvement is 1.9 m. From Figure 8, it is found that at the cross-section in which the “sliding failure mode” is predominant;

- 1) The comparatively long offset distance of both improved areas on the both sides of the river levee crown can reduce the settlement significantly.
- 2) The improvement located immediately below the river levee crown is very effective.



**Figure 8. Effect of soil improvement at the cross section in which the “sliding failure mode” is predominant.**



## CONCLUSIONS

Large deformations in river levees in the Kiso-Sansen downstream area were analyzed comparatively by using the LIQCA for postulated Tonankai-Tokai coupled earthquakes. The river levees in the Kiso-Sansen downstream area were classified into 8-type models based on the thickness of liquefied layer, existence of clayey soil layer sandwiched in the liquefied layer and flood channel width.

Based on the thickness of liquefied layers, failure modes tended to be classified either “Sliding” or “Settling”. At the cross section which exhibits “Sliding” failure mode, high settlement is predicted almost regardless of the  $F_L$  value. Examples of both failure modes from LIQCA analysis are shown in Figure 5, which correspond “Sliding” (model-4 result) and “Settling” (model-8 result), respectively. The “Sliding” failure mode seems to be appeared when thickness of liquefied layer is less than 10m.

Countermeasures against liquefaction-induced large settlements are proposed based on the different failure modes.

- 1) At the cross-section in which the “sliding failure mode” is dominant, the comparatively long offset distance of both improved areas on the both sides of the river levee crown can reduce the settlement significantly.
- 2) On the other hand, at the cross-section in which the “settling failure mode” is predominant, the very short offset distance of the improved areas is suggested to prevent the large settlement.
- 3) The improvement located immediately below the river levee crown is very effective for both failure modes.

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