

Influence of the dominant period and duration of seismic motion on seismic damage of river levees

K. Nakaiⁱ⁾ and T. Nodaⁱⁱ⁾

i) Associate Professor, Department of Civil Engineering, Nagoya University, Furo, Chikusa, Nagoya 464-8603, Japan.

ii) Professor, Department of Civil Engineering, Nagoya University, Furo, Chikusa, Nagoya 464-8603, Japan.

ABSTRACT

In this paper, the effects of dominant period and duration of seismic motion on the seismic damage of river levees are numerically investigated. The results show that when the long-period component of the input seismic motion is dominant, not only liquefaction of sandy layers but also damage to clayey soil layers showed extensive seismic damage. In addition, since ground motions for design purposes are often specified by response spectra, the effect of duration is not strictly taken into account. Especially in the case of soft ground with strong elasto-plastic response, it is shown that the effect of duration of seismic motion is significant. Numerical analysis shows that it is important to take into account the seismic characteristics such as period and duration for detailed damage estimation.

Keywords: seismic response analysis, river levee, dominant period, duration of seismic motion

1 INTRODUCTION

In Japan, a country with a small land area, it is said that 50% of the population and 75% of assets are concentrated in flood-prone areas. Therefore, ensuring the integrity of flood protection facilities such as river levees, coastal levees, and drainage pump stations is a lifeline for these areas. However, the ground in plain areas is generally soft due to high groundwater levels and young sedimentation ages. Therefore, there is a high risk of liquefaction and other ground disasters during earthquakes. However, in the current seismic evaluation of river levees in Japan, (1) seismic damage of clayey soils is not adequately considered, even if the dominant soil is silt with relatively large grain size or soft with low N value, (2) the effects of complex wave propagation due to stratigraphic irregularities are not considered, (3) the effects of uncertainties such as heterogeneity of depositional conditions are not sufficiently considered, and (4) the effect of seismic motion duration has not been fully considered because the design motions used for seismic response evaluation are often specified in terms of acceleration response spectra. With recent fears of a massive earthquake, there is a need to accurately understand what will happen and what kind of damage will occur in the event of an earthquake. However, we do not know what kind of earthquake will occur as an external force. In order to accurately predict seismic damage, it is necessary to conduct seismic performance evaluation taking into account various possible external forces, understand actual damage, identify hazardous locations, and confirm the effectiveness of countermeasures.

In this paper, seismic response analysis was conducted for a actual existence river levee constructed on the Naka River in Tokushima, which is feared to be damaged by a Nankai Trough earthquake, and the effects of seismic motion characteristics (seismic motion duration and its period characteristics) on seismic damage were investigated numerically. The analysis code used in this study comprises a soil–water coupled finite deformation analysis code (Noda et al, 2008), incorporating elasto–plastic constitutive equations (Super/subloading Yield Surface Cam-clay model; Asaoka et al. 2002) to describe sand, intermediate soil, and clay in the same theoretical framework.

2 ELASTO-PLASTIC MODELING

The Naka River in Tokushima Prefecture, which is the subject of this study, is a typical delta topography and has extensive soft ground. It is located near the epicenter of the Nankai Trough earthquake, and there is concern about liquefaction damage in the event of an earthquake. In this study, we focused on the downstream area where soft ground is thickly accumulated. Figure 1 shows a finite element mesh created based on the site investigation results. The mesh is an enlarged view of the area around the embankment, and the analysis area is sufficiently large so that boundary conditions do not affect the analysis results. From the surface, buried soil (B), alluvial sand (As) and alluvial clay (Ac) are deposited, and the hard Pleistocene layer (D) is below these layers. Seismic evaluation was conducted in advance, and the embankment was raised and the ground was improved using a static compaction method near the

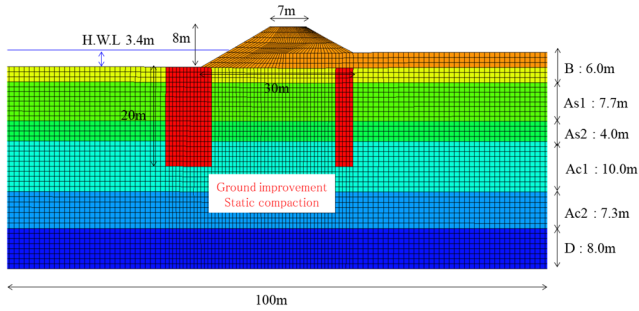


Fig.1 Finite element mesh.

Table 1 Physical properties of each soil layer.

	B	As1	As2	Ac1	Ac2	D
Soil layer thickness (m)	3.0	7.7	4.0	10.0	7.3	—
Average N-value	3.0	18.3	13.2	4.5	2.3	Over 50
Soil particle density (g/cm^3)	2.73	2.73	2.72	2.74	2.74	2.73
Fine particle content (%)	19.3	7.3	38.8	70.3	97.4	15.2
Mean grain size D_{50} (mm)	0.28	0.65	0.12	0.033	0.0063	4.99
Liquid limit w_L (%)	NP	NP	NP	37.3	50.1	30.2
Plastic limit w_p (%)	NP	NP	NP	23.1	26.9	15.8
Undrained shear strength c_u (kN/m ²)	—	—	—	70.8	82.4	—
Liquefaction strength R_{L20}	0.22	0.33	0.34	—	—	—

Table 2 Elasto-plastic parameters.

	B	As1	As2	Ac1	Ac2	D
Elasto-plastic parameter						
Critical state index M	1.20	1.13	1.22	1.41	1.48	1.15
Intercept of NCL at $p^*=98kPa$ N	1.67	1.65	1.64	2.10	2.80	1.72
Compression index λ	0.049	0.046	0.049	0.143	0.295	0.006
Swelling index $\bar{\kappa}$	0.0049	0.0046	0.0049	0.0014	0.0030	0.0006
Poisson's ratio ν	0.2	0.2	0.2	0.2	0.2	0.2
Evolution parameter						
Degradation index of structure a	3.84	7.81	3.16	0.45	0.23	6.2
Ratio between $-D_r^e$ & $ D_r^p $ c_s	0.94	0.99	0.92	0.41	0.54	0.98
Degradation index of OC m	0.33	0.14	0.42	4.88	11.27	0.18
Rotational hardening index br	2.38	6.91	1.78	0.09	0.03	4.89
Limit of rotational hardening m_b	0.94	0.17	0.98	1.00	1.00	0.51
Initial condition						
Stress ratio η_0	0.545	0.545	0.545	0.545	0.545	0.545
Degree of structure $1/R'_0$	3.0	2.8	2.9	4.4	4.3	1.2
Degree of OC $1/R_0$	27.7	32.0	28.4	3.5	1.2	770
Degree of anisotropy ϵ_0	0.0	0.0	0.0	0.0	0.0	0.0
Soil particle density ρ_s (g/cm^3)	2.71	2.72	2.72	2.71	2.71	2.70
Mass permeability index k (cm/s)	1.2×10^{-3}	6.3×10^{-3}	7.9×10^{-4}	2.3×10^{-7}	8.0×10^{-6}	1.0×10^{-7}

bottom of the embankment. Table 1 shows the physical properties of each layer. The average values for each layer are shown using data from several boreholes in the neighborhood. Focusing on the sandy layer, the upper As1 layer has a low fine-grained content, and the B layer has low liquefaction strength. Focusing on the clayey layer, Ac2 which is deposited deeper than Ac1, has a smaller N value with its higher fine-grain content. Table 2 shows the elasto-plastic properties used for the analysis. All parameters were determined based on the results of in-situ tests (refer to Fig. 1), and the ground improvement portion was reproduced by replacing the soil with dense sandy soil considering the actual improvement rate. The elements above the groundwater table were assumed to have zero water pressure around them to simply simulate unsaturated conditions (no

excess pore water pressure). Simple shear boundaries were set on both sides and a viscous boundary corresponding to $V_s=580m/s$ was set on the bottom as boundary conditions (Lysmer and Kuhlemeyer, 1969; Takaine et al. 2010). Seismic motions were input equally in the horizontal direction at all nodes at the bottom.

3 SEISMIC RESPONSE ANALYSES

3.1 Assumed Nankai Trough earthquake motion

First, seismic evaluation was performed in the event of assumed Nankai Trough earthquake. The input seismic motion is shown in Figure 2, which is the Nankai Trough earthquakes that are expected to occur in the vicinity of the analysis site. The left figure shows the time history of acceleration, and the right figure shows the Fourier amplitude spectrum. The data was released by the Cabinet Office in 2012. The maximum acceleration was $9.0 m/s^2$ and the duration was long (herein referred as Earthquake-A). Figure 3 shows the mean effective stress reduction ratio (herein called as MESRR) and shear strain distribution immediately after the earthquake. MESRR is an index obtained by dividing the excess pore water pressure generated during an earthquake by the initial mean effective stress, and takes a value between 0 and 1. In engineering terms, liquefaction is often indicated when the MESRR is 0.95 or greater. The MESRR of the B and As1 layers reaches

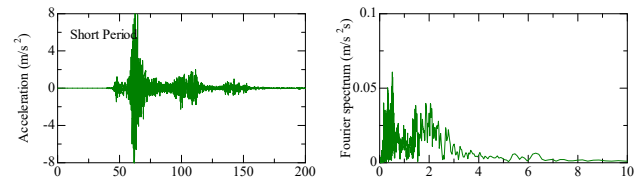
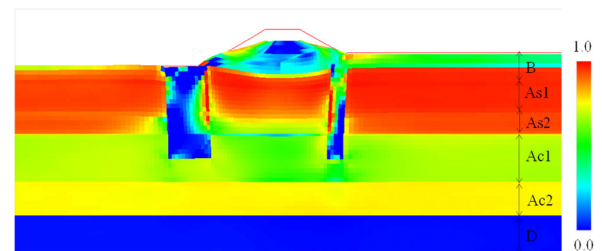
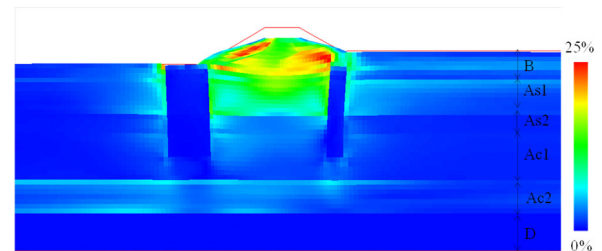


Fig.2 Earthquake-A.



(a) MESRR



(b) Shear strain

Fig. 3 Analysis results of Earthquake-A.

1.0, indicating that the surface sandy soil has liquefied. On the other hand, the deep clay layer does not lose its stiffness like the surface sandy soil, although there is a slight increase in the MESRR (decrease in effective stress) in the Ac2 layer. The shear strain shows that the lateral flow of the levee is suppressed by the improved embankment at the bottom of the slope, and the deformation of the foundation soil is greatly reduced, although the strain is predominant in the levee.

3.2 Influence of period characteristics of input seismic motions

The Fourier amplitude spectrum of earthquake-A used in 3.1 shows that the short-period component is dominant, and the slightly long-period component of more than 3 seconds is hardly included. In this section, we examine the effect of the long-period component of the earthquake motion on seismic damage. Figure 4 shows the long-period seismic motion data released by the Cabinet Office in 2015 for the Nankai Trough earthquake⁶⁾, which is also expected to occur around the analysis site. The data is mainly used for seismic evaluation of structures with large natural period, such as resonance of high-rise buildings and sloshing of oil tanks. The maximum acceleration is small (about 1.5 m/s²), but the long-period component of more than 2 seconds dominates (herein referred as Earthquake-B). On the other hand, earthquake B has almost no short-period component of less than 2 seconds. Therefore, we created the broadband seismic motion shown in Figure 5 (herein referred as Earthquake-C) by hybrid-synthesizing the two assumed Nankai Trough seismic motions, Earthquake-A and Earthquake-B, in a linear form with a connection period of 2 to 3 s.

Figure 6 shows the results of the analysis when Earthquake-B is input. Because of the small acceleration, the increase in the MESRR in the sandy soil layer is smaller than that of Earthquake-A. However, the MESRR in the deep Ac2 layer is not so large as that of Earthquake-B. However, when compared in the deeper

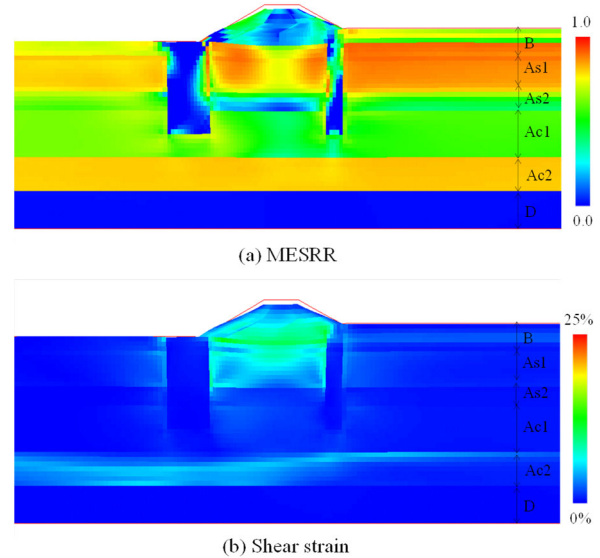


Fig.6 Analysis results of Earthquake-B.

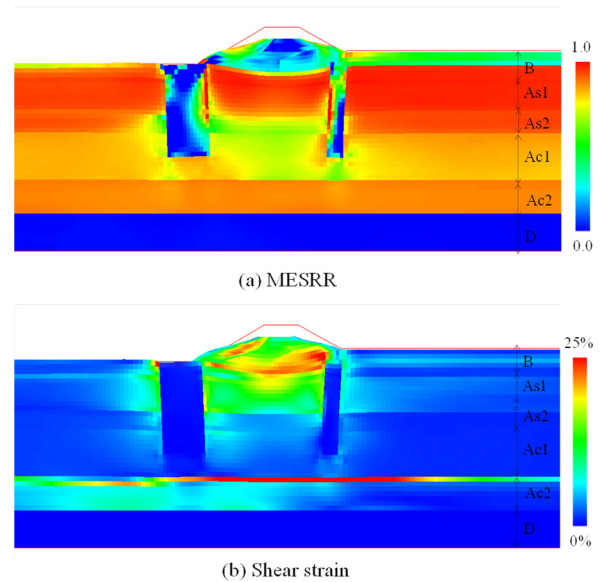


Fig. 7 Analysis results of Earthquake-C.

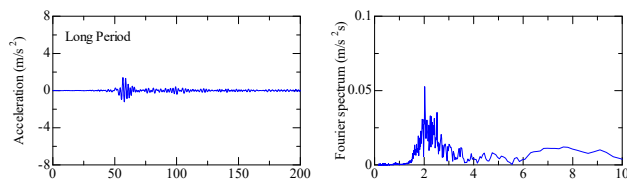


Fig.4 Earthquake-B.

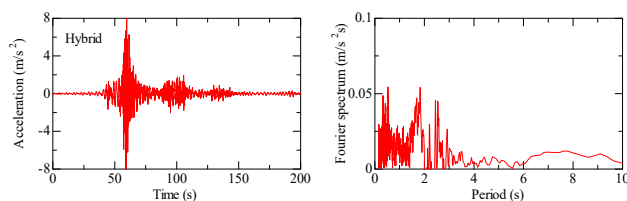


Fig. 5 Earthquake-C.

Ac2 layer, the MESRR is greater than Earthquake-A. The stiffness reduction in the ground is relatively greater in the Ac2 layer. The shear strain indicates that the sandy soil is not liquefied, so the deformation of the sandy soil is suppressed, but strain generation in the deep clayey layer is observed. It is generally believed that clayey soils are less susceptible to seismic damage than sandy soils. However, the strong shaking caused by Earthquake-B, which has a predominant long-period component, disturbed the soft clay and reduced its stiffness (Nakai et al., 2017). Figure 7 shows the results of the analysis for earthquake-C. In addition to the large acceleration level and long duration, the long-period component also causes very large shaking. Therefore, not only sandy soil but also clayey soil shows a large decrease in effective stress and stiffness. Since seismic

countermeasures for river levees generally target liquefied layers, ground improvement at this site was also carried out to prevent liquefaction of shallow sandy layers. Shear strain occurs over a wide area of the ground, especially in the clay layer below the improvement, where it becomes locally large and penetrates deep into the soil. The results of this analysis suggest that when soft clay layers are disturbed by seismic motion, there is a risk of large residual deformation at depth without sufficient countermeasures being effective. Although liquefaction damage of sandy soil tends to be the focus of attention when it comes to seismic damage, seismic damage has actually been observed even in clayey soil beds with relatively large grain size silt content or high water content and softness (Chu et al., 2010.; Sato et al., 2018.).

3.3 Influence of duration of input seismic motions

As described in Section 1, since the design ground motions for seismic response evaluation are often specified by acceleration response spectra, the effect of seismic motion duration has not been fully investigated. Therefore, we focused on the duration of seismic motion and examined its effect on the seismic damage of river levees. In order to examine the effect of duration, earthquake motions with the same acceleration response spectrum but different duration time were created. Figures 8 to 10 show the three input earthquake motions

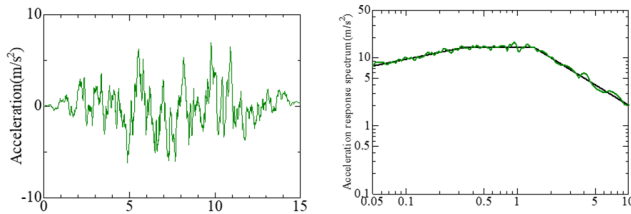


Fig.8 Earthquake-1.

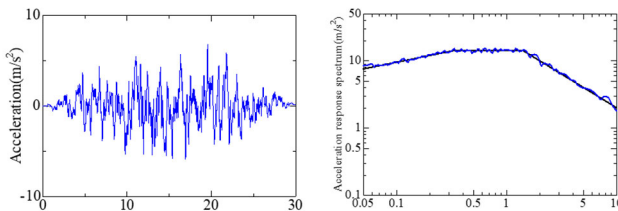


Fig. 9 Earthquake-2.

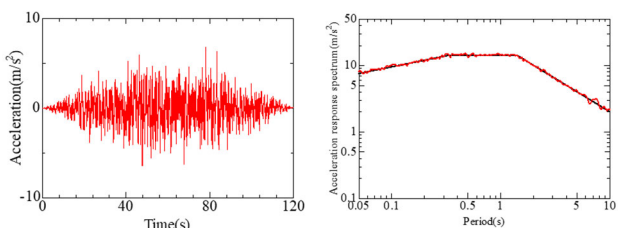


Fig. 10 Earthquake-3.

used in the analysis, which are referred to as Earthquake-1, -2, and -3, respectively. The left figure shows the acceleration time history and the right figure shows the acceleration response spectrum. These earthquake motions have different durations, which are adapted to the response spectra generally specified in the seismic performance evaluation of river levees. The envelope functions of the seismic waveforms were made to be similar, and the phase angles were given as uniform random numbers ranging from 0 to 2π . As shown in the seismic response spectra, all of the earthquake motions are broadband earthquake motions with a wide range of short- to long-period components.

Figures 11 to 13 show the analytical results for each earthquake motion input. The MESRR shows that the longer the seismic duration, the greater the effective stress reduction. In particular, the B and As1 layers, which are sandy soils, liquefy almost all the way to MESRR=1.0 in the case of earthquake-3. In addition to the sandy soil layer, the Ac1 and Ac2 layers, which are deep clayey soils, also show significant reductions in effective stress because they are suffered by broadband seismic motions. The shear strain indicates that the longer the duration of the earthquake, the greater the deformation, especially in the embankment area. The deformation is concentrated in the deep clay, especially at the boundary between the Ac1 and Ac2 layers, for all seismic motions. This is due to the disturbance of the soft clay by the long-period seismic motion.

Figure 14 shows the amount of horizontal displacement at the foot of the levee and the amount of settlement at the embankment crown. In terms of horizontal displacement, there is no significant difference in the maximum horizontal displacement in the initial phase of the earthquake, but the longer the duration of the earthquake, the greater the residual displacement. On the other hand, the settlement, which was once nearly converged, accelerates again around 10^5 s (about 1 day after the earthquake). Figure 15 shows the settlement by layer at the center of the top of the embankment at the time of earthquake-3. It can be seen that the delayed settlement occurs in the clay layer. If excess pore water pressure accumulates due to ground disturbance, consolidation settlement occurs with recovery of effective stress after the earthquake. Because clay layers have low permeability, there is a risk that ground deformation will continue over a long period of time if disturbed by an earthquake.

The above results indicate that the longer the duration of the seismic motion, the more severe the seismic damage becomes, even if the earthquake motion has the same response spectrum. This is due to the elasto-plastic response of the ground, such as liquefaction of sandy soil and disturbance of clayey soil.

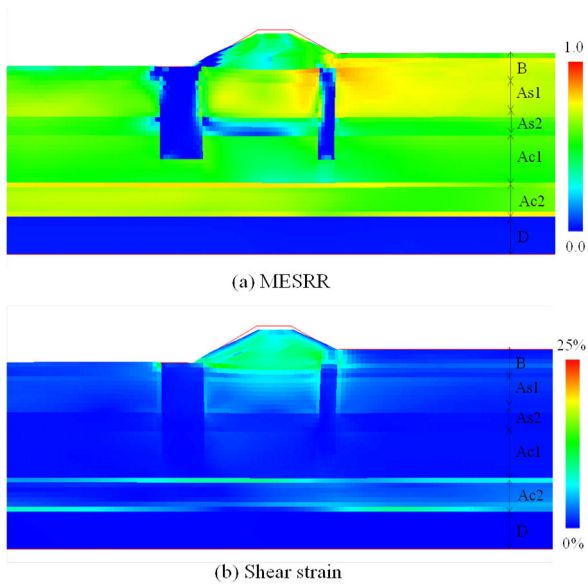


Fig.11 Analysis results of Earthquake-1.

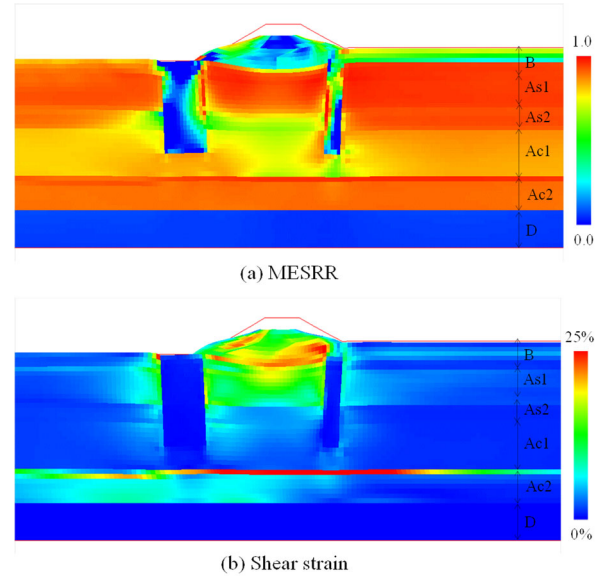


Fig.13 Analysis results of Earthquake-3.

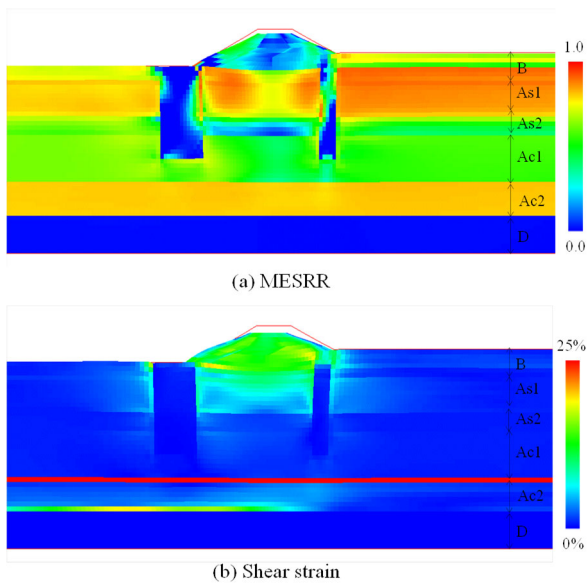


Fig. 12 Analysis results of Earthquake-2.

4 CONCLUSIONS

The effects of seismic excitation period and duration on the seismic damage of river levees are numerically investigated. The results show that when the long-period component of the input seismic motion is dominant, not only liquefaction of sand but also damage to clayey soil layers, which are conventionally considered to be less susceptible to seismic damage, is caused by strong shaking that disturbs the ground, resulting in extensive damage. In addition, the seismic response spectra are often used to specify the design ground motions for seismic evaluation of river levees. However, in the case of soft ground with strong elasto-plastic response, the duration of seismic motion has a significant effect.

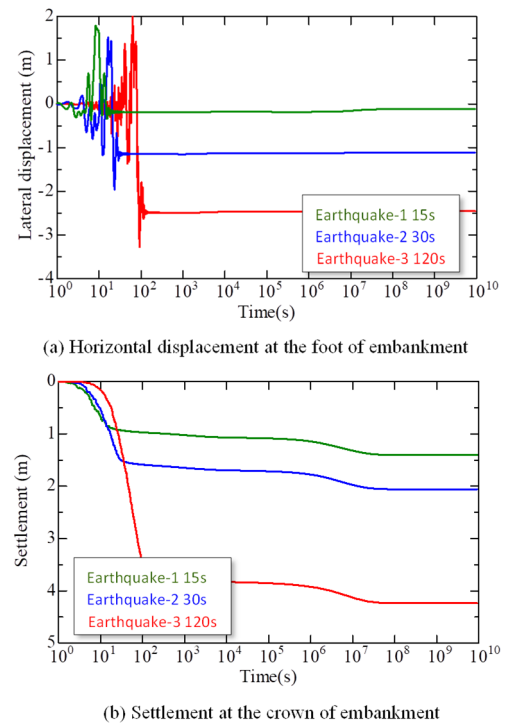


Fig. 14 Lateral displacement and settlement of the levee.

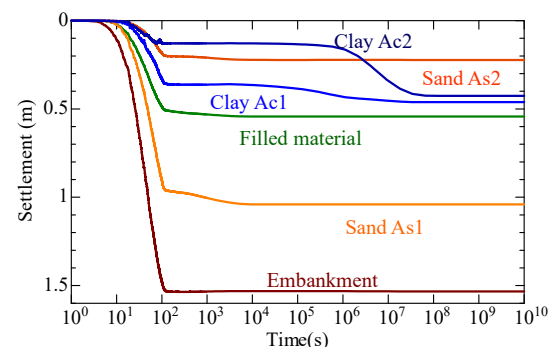


Fig.15 Settlement by strata in case of Earthquake-3.

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