A STUDY ON THE INFLUENCE OF BOUNDARY CONDITIONS ON THREE DIMENSIONAL DYNAMIC RESPONSES OF EMBANKMENTS

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ABSTRACT:

Seismic damages to embankments have sometimes been found to take place at locally-limited spots even though the foundation conditions are almost the same along their axes. The reason why local failures were caused is considered to their three-dimensional response during an earthquake. According to the shaking table tests on the three-dimensional response of embankments, the response at the crest was amplified locally even though the embankment base was shaken uniformly. The intervals of local failures at the crest depend on the frequency of input motion, the stiffness and the height of embankments.

This paper aims to clarify the influence of the boundary conditions on the seismic responses of embankments during earthquakes. A series of shaking table tests with model embankments were conducted under different boundary conditions. A series of numerical analyses were also conducted to examine the influence of boundary conditions of embankments. The results of numerical analyses were good agreements with the shaking table tests.

The test results showed that the response of a model embankment which ends were fixed is larger than that of free ends. Also, it was observed that the magnitude of response of former is about 1.2 times larger than the latter. When t the shear wave velocity of the boundary area was 1.5 times lager than the models embankment, the maximum response was almost the same as the one under the fixed boundary condition.

KEYWORDS:
Embankments, Three Dimensional Dynamic Responses, Numerical Analyses, Boundary Conditions

1. INTRODUCTION

Recently the seismic design has been improved from the traditional design method such as the seismic coefficient methods to the performance based design. In order to carry out the performance based design, it is requested to understand the seismic response of earth structures correctly and to reflect it to the design.

In seismic design of long structures such as embankments, the two dimensional seismic response of structures has been considered. However, Seismic damage to long structures has sometimes been found to take place at locally limited spots. For example, the locally limited damage for Kushiro river dike was reported during the Kushiro earthquake in 1993. Kano S., etc. (2007) carried out the small shaking table tests and concluded that the damage to the Kushiro river dike was caused due to the three dimensional seismic damage. They also derived the theoretical equation to calculate the intervals between the damaged points. And the intervals depend on the shear wave velocity of embankments, the height of them and the predominant frequencies of input motion. So the importance of the considering the three dimensional response is reported. They, however, carried out the shaking small table tests using the models which their lengths were less than 10 times as their heights. The influences of lengths of models and the boundary conditions on their three dimensional responses were not discussed in it.

Therefore this paper aims to discuss the influences of them on the three dimensional responses. A series of numerical analyses to calculate the seismic response was carried out. In this paper, a simple numerical analysis method that was developed by Ohmachi, T.and Tokimatsu, K. (1983) originally was used. To compare with the results of this numerical analysis, a finite elements method analysis was also carried out.

2. SEISMIC NUMERICAL ANALYSES

2.1 Simple numerical analyses

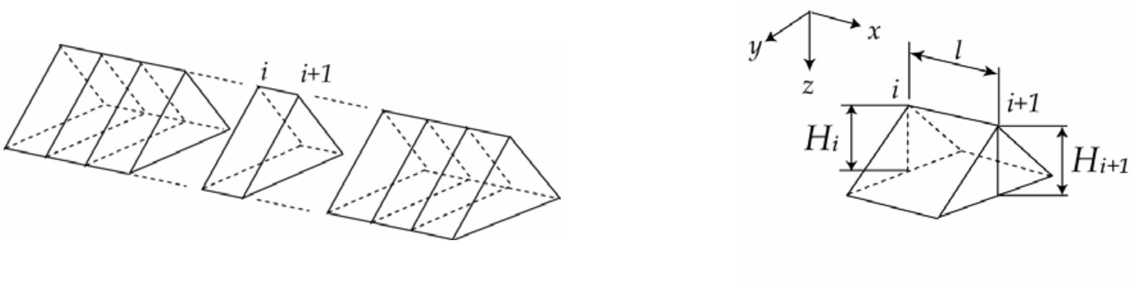
A simple numerical analysis carried out was developed by Ohmachi, T.and Tokimatsu, K. (1983) originally. In this numerical analysis, elements shape like triangular prisms as shown in Figure 1. The heights of the prisms are H_i and H_{i+1}, and the length of it is 1. The deformation shape of the neutral axis along the height is assumed by the shearing vibration theory as following equation (shown in Figure 1(b)).

$$f(x,z) = J_0\left({j_m z}/{H} \right) \tag{1.1}$$

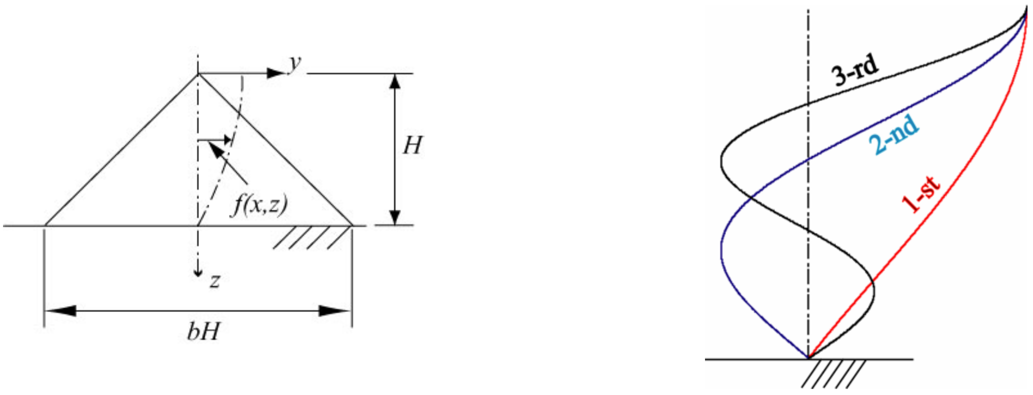
where $J_0(z)$ is the Bessel's function in 0 th, j_m is the m th number which satisfied $J_0(j_m) = 0$. When the deformation along the height is first mode, $j_m = 2.4084$.

Under the condition that the boundary is free, the results of the numerical analysis is the same value as the one of the two dimensional analysis. Under the boundary is fixed, the numerical analysis can be considered the three dimensional. In order to verify the validity of simple numerical methods, the elastic three dimensional finite elements analysis was also carried out.

Sinusoidal wave were used for input motion and the maximum acceleration of input motion was 200 gal. The predominant frequency of input motion was the same as the natural frequency of models.



(a) Elements for the simple numerical analysis



(b) Assumption of deformation along the model height

Figure 1 Models for the simple numerical analysis

2.2 Validity of the assumption of the deformation shape along the height

Figure 2 shows the deformation shapes along the height that was calculated using the Eqn. 1.1 and the two dimensional FEM. According to this figure, in the case of the steeper slope, it is found that the result of Eqn. 1.1 was different from the result of the 2D FEM. This difference can be thought to be caused by the influence of bending. In the cases of the gentler slope, results of former were almost the same as the 2D FEM.

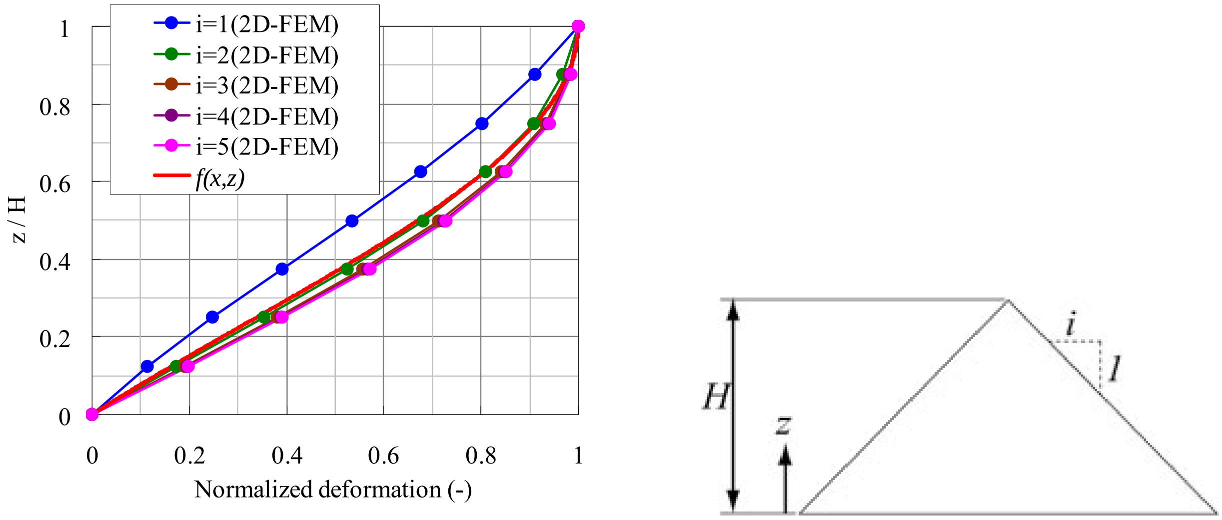


Figure 2 Deformation shapes of neutral axis along the height of models

2.3 Distribution of dynamic displacements at the crest along the model axis

Figure 3 shows distributions of the maximum dynamic displacements at the crest along the model axis during a shaking. It was found that the model responded uniformly along the model axis in the case of free boundary. And the displacements were the same as the results of 2-D FEM analysis. In the case of fixed boundary conditions, however, it was also found that the displacement at the crest was not uniform in the higher frequencies than the natural frequency of models. Furthermore it was clear that the displacements under the fixed boundary condition were larger than the one under the free boundary condition at the several points along the model axis.

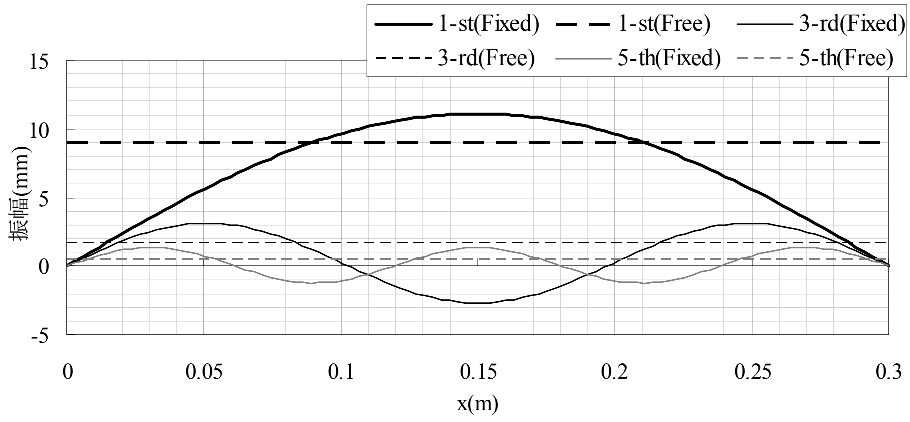


Figure 3 Distributions of the maximum dynamic displacements at the crest along the model axis

3. RESULTS OF NUMERICAL ANALYSES

Kano S. etc., (2007) studied the three dimensional responses of long earth structures using the shaking table. But in their study, the ratio between the model lengths (*L*) and model height (*H*) was less than 12 because of the limitation of shaking table size and the observation system. Thus, in this study, the numerical analyses with the longer models were conducted. The model height H was set to 8 m, the shear wave velocity of models V_s was set to 150 m/s and the damping ratio was set to 5 %.

As mentioned above, the results of the simple numerical analysis were good agreements with the FEM analyses in the case of the gentle slope models. Therefore, model slope gradient were set to 1:2.

3.1 Influence of the model length on its seismic response

Distributions of displacements at the crest are shown in Figure 4. The ratio between the model length and the model height (*L/H*) ranged from 1 to 300. In this figure, the area of 200m from the boundary was scoped. The results of 2D FEM was shown with dot line in the same figure. In the case that *L/H* was smaller than 10, it was found that the deformation shapes along the axis looked like a sinusoidal curves that both boundaries were nodal points and the maximum displacements appeared at the center of the models.

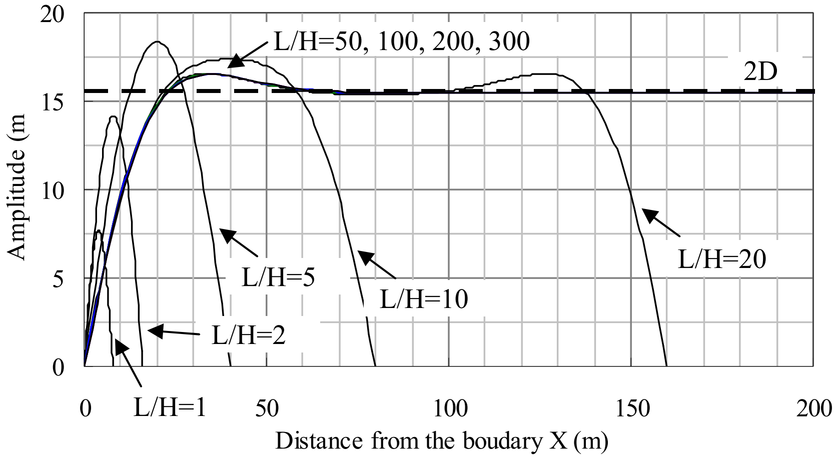


Figure 4 Distributions of the displacements at the crest

In the case that *L/H* was larger than 20, it was also clear that distributions of displacements were different from the results with model which the ratio is small. In that case, there were two peaks along the models and the .displacement at the center of models was the same to 2D FEM. In the case that *L/H* was larger than 50, the maximum displacement appeared only near the boundaries, the displacement near the center of models were almost uniform and the same as the results of 2D FEM. However, when the ratio ranged from 50 to 300, the maximum displacement points of models appeared only near the boundary and these maximum points located on almost the same point. This implies that the seismic responses near the center of the long earth structures are not amplified locally when they are long enough.

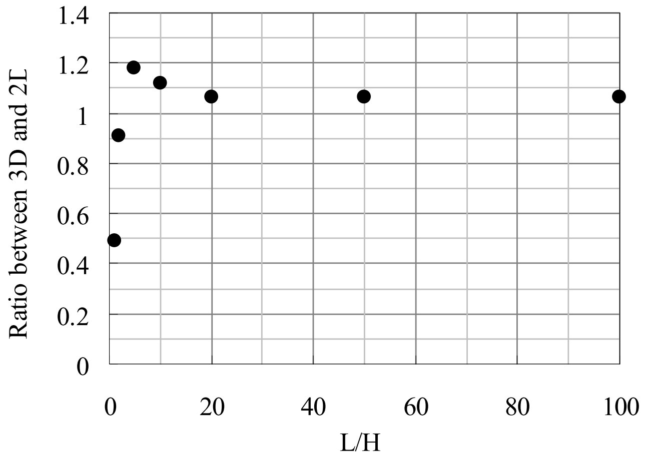


Figure 5 Relationships between the ratio of 3D/2D and the L/H

Figure 5 shows the ratio between the maximum displacements of the 3D simple numerical analyses and the one of the 2D FEM analyses, 3D/2D. According to this figure, the displacement at the crest became to maximum when the ratio, L/H was 5. The maximum displacement of the 3D numerical analysis increased to 1.2 times larger as the 2D FEM analyses. When L/H was larger than 50, the displacement of the 3D numerical analysis increased to 1.06 times larger.

3.2 Influence of the boundary conditions on the seismic responses of earth structures

In the preceding section, the seismic responses of long earth structures under the conditions of free boundary or fixed boundary were discussed. However, actually, there are not so many earth structures that the boundaries are fixed firmly except dams which stabilized to the rock ground.

The slope of management roads, the sluice gates and the foundations of bridge can be considered as the fixed boundary for the river dikes. These parts have the different shear velocity from the dikes and they should interrupt the seismic response of the dikes. Therefore the influences of the difference of rigidity of boundary were discussed in this paper.

As shown in Figure 6, the model embankment was constrained from both boundaries. The model lengths 40 m (L/H is 5) and the shear wave velocity of the models varied from 100 to 150 m/s The length of the boundary part was set to 2 m and the shear wave velocity ratios between the model embankment and the boundary are, α varied from 1 to 5. The outside of boundary part was free boundary condition. Thus the seismic responses at the crest should be the same as the results under the free boundary condition if the difference of the rigidity was no influenced on the seismic response.

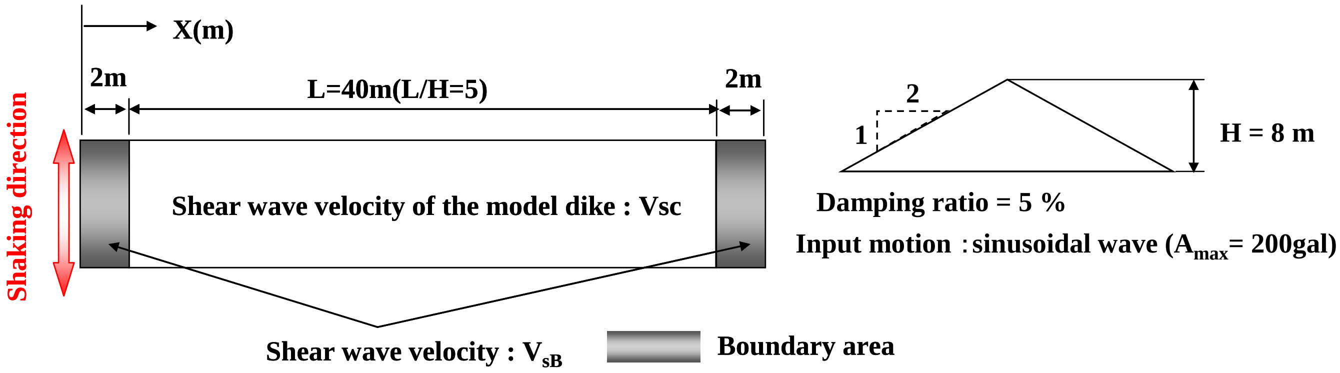
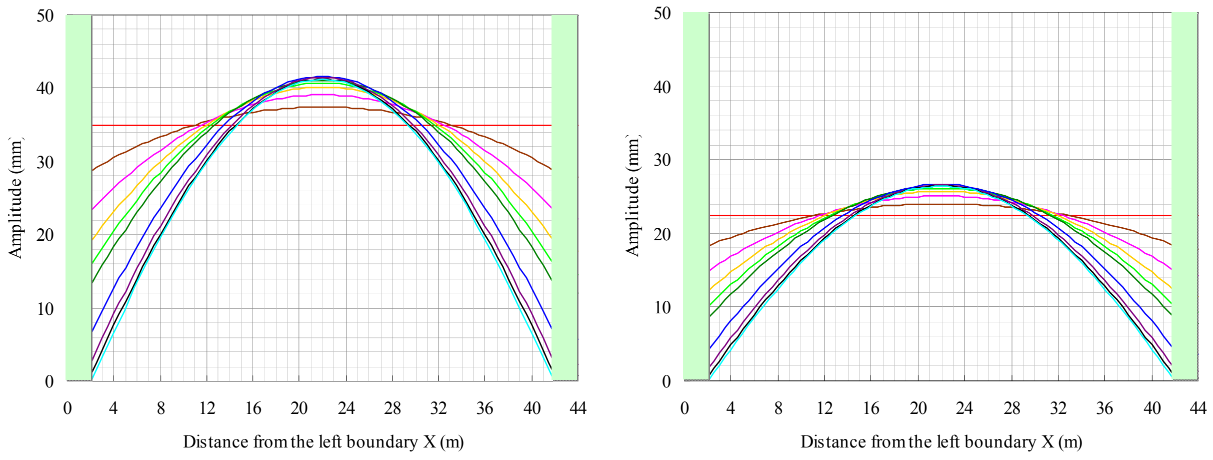


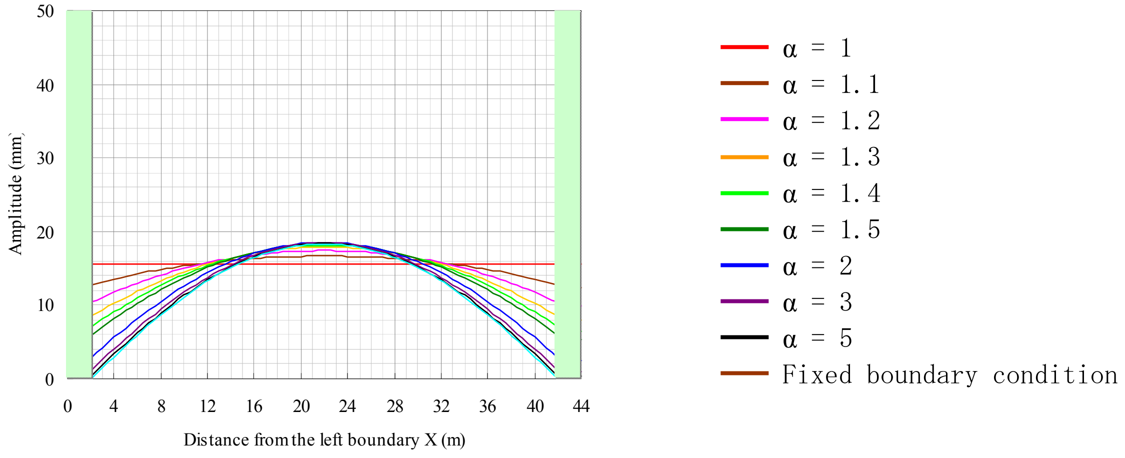
Figure 6 Sketch of the models in the numerical analysis

Figure 7 shows distributions of dynamic displacements at the crest in each analysis. The results with the homogenous model (α =1) under the free boundary condition and the results under the fixed boundary conditions are also shown in Figure 7. It is found that the dynamic displacements near the boundary area were decreased when the rigidity of the boundary area was larger than the model embankment even though the boundary was under the free condition. The deformation shape of the model looked like a half sinusoidal curve which the boundaries were nodal points. And the maximum displacement along the model embankment became larger than the homogenous model. The larger the rigidity difference between the model embankment and the boundary area became, the larger the maximum displacements became. When the shear wave velocity of the boundary area was 5 times as fast as the model dikes were, the dynamic displacement of the model dike became the same as the one under the fixed boundary condition. This tendency was observed in every case.

Figure 8 shows the relationships between α and H. Concerning the maximum displacement along the model embankment, the maximum displacement in the case of α = 1.5 was almost the same as the results of the fixed boundary condition.



(a) Shear wave velocity at the center is 100 m/s (b) Shear wave velocity at the center is 125 m/s



(c) Shear wave velocity at the center is 150 m/s

Figure 7 the distribution of dynamic displacements at the crest in each analysis (L/H = 5)

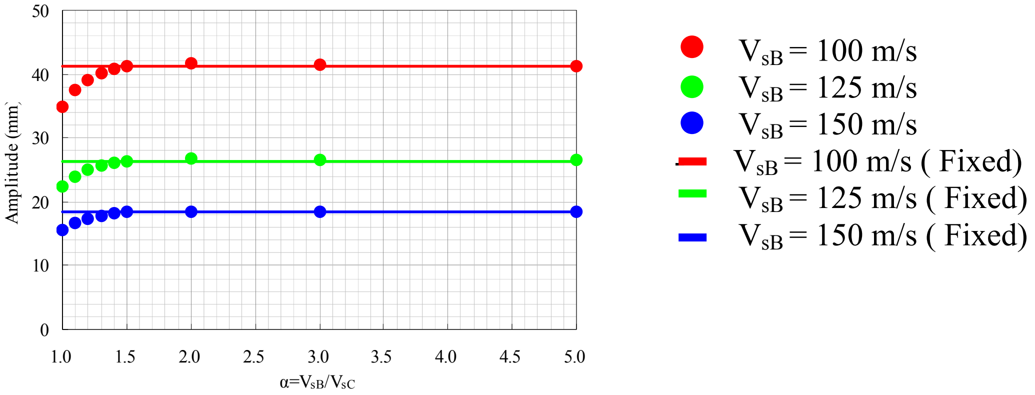
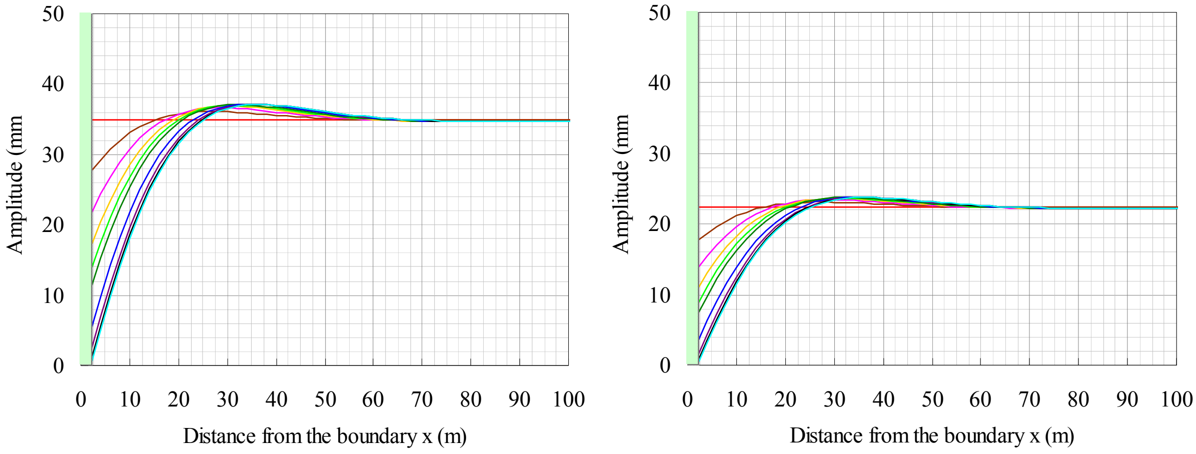
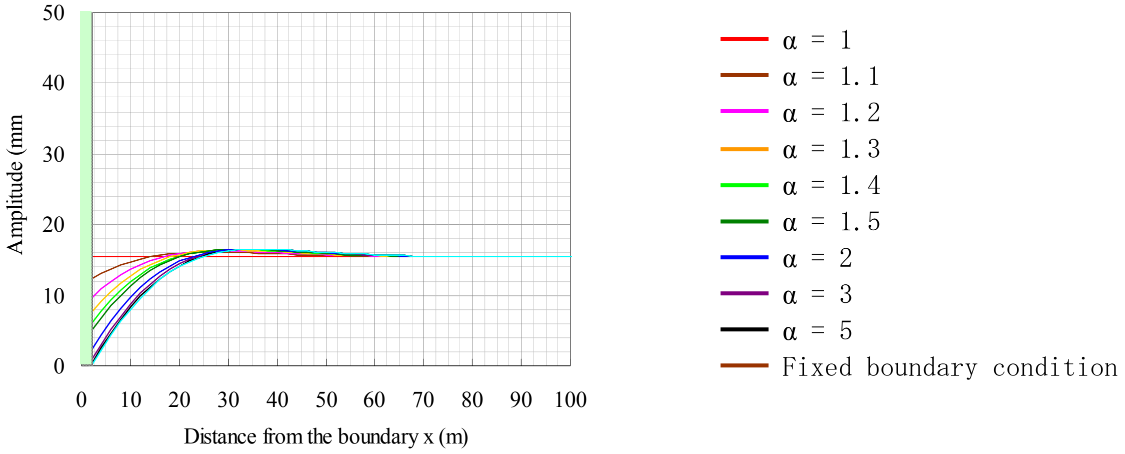


Figure 8 Relationships between the maximum displacement and α

A series of numerical analyses with the long model that its L/H was 100 were also conducted. The results of the numerical analyses were shown in Figure 9. When the model embankment was long enough, the seismic responses at the center of the model became uniform and were almost the same as the free boundary condition. Therefore, the area near the boundary was shown in this figure.



(a) Shear wave velocity at the center is 100 m/s (b) Shear wave velocity at the center is 125 m/s



(c) Shear wave velocity at the center is 150 m/s

Figure 9 Distribution of dynamic displacements at the crest in each analysis (L/H = 100)

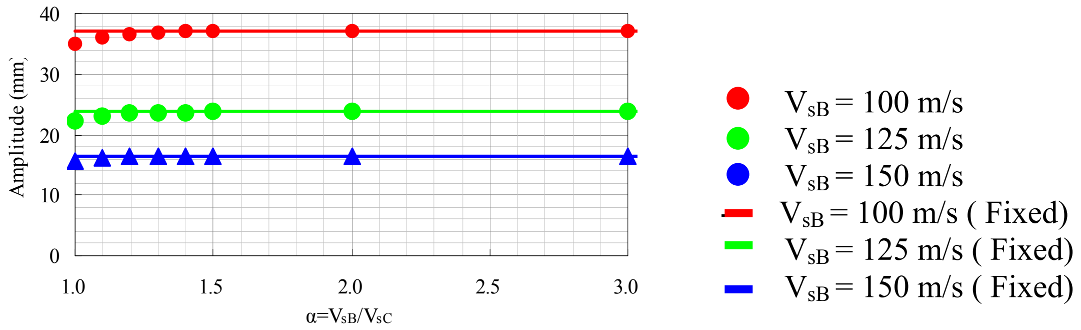


Figure 10 Relationships between the maximum displacement and α

According to this figure, it was found that the seismic response near the boundary was increased larger than near center of the model because of the influence of the constraining at the boundary. And it was larger than the results of the 2D numerical analysis. It was also found that the larger the difference of the rigidity between the model and the boundary area was, the larger the seismic responses near the boundary area were.

As shown in Figure 10, when the shear wave velocity of the boundary became the 5 times faster than the model's one, the seismic response of the model was almost the same as the model under the fixed boundary condition like the short model. The maximum displacement was almost the same as the model under the fixed

boundary condition when the shear wave velocity of the boundary area was 1.5 times larger than the model.
As mentioned above, when the shape of cross section of earth structures and their material properties along the axis are uniform, the seismic responses along their axes become uniform and the seismic responses can be calculated by the two dimensional numerical analysis. However, when there is something to constrain the seismic responses of earth structures, the seismic responses of earth structures are increased at the locally limited spots and the maximum responses become larger than the calculated value by the 2D numerical analysis. In general, considering the existing earth structures, earth structures that the shape of their cross sections and their material properties are uniform along their axes are few. For example a pier of a bridge, a sluice gate, a slope for the maintenance road etc., there is something to constrain the seismic responses of earth structures in the structures. Therefore it is necessary to consider the three dimensional response in the seismic design of long earth structures.

4. CONCLUSIONS

This paper aims to study influences of boundary conditions for seismic responses of earth structures. In order to understanding influences of the boundary conditions, a series of numerical analyses were conducted. The simple numerical analysis that were developed by Ohmachi T. and Tokimatsu K. (1983) was sued. To compare with this, the two dimensional finite element method analyses were also conducted. Conclusions obtained from this study are as follows,
1) The simple numerical analysis method used in this paper was useful when the slope of a model embankment was gentler than 1:2.The seismic response of the model which slope is gentler than 1:2 along the height can be calculated by Eqn 1.1.
2) The seismic response of the model embankment under the fixed boundary condition was larger than the one under the free boundary condition. The results under the free boundary condition was almost the same as the two dimensional FEM analysis.
3) In the case that the ratio between the length and the height (*L/H)* was smaller than 10, it was found that the deformation shapes along the axis looked like a sinusoidal curves that both boundaries were nodal points and the maximum displacements appeared at the center of the models.
4) In the case that *L/H* was larger than 20, the distributions of displacements along the model axis were different from the results with model which the ratio is small. In this case, there were two peaks along the model axis and the .displacement at the center of models was the same to 2D FEM. In the case that *L/H* was larger than 50, the maximum displacement appeared only near the boundaries, the displacement near the center of models were almost uniform and were the same as the results of 2D FEM.
5) When the shear wave velocity at the boundary area was 1.5 times larger than the models embankment, the maximum displacement was almost the same as the one under the fixed boundary condition. When the shear wave velocity at the boundary was 5 times larger, the deformation shape was almost the same as under the fixed boundary condition.
6) When there is something to constrain the seismic response of the earth structures, the seismic responses of earth structures are increased at the locally limited spots and the maximum response becomes larger than the calculated value by the 2D numerical analysis. Therefore it is necessary to consider the three dimensional response in the seismic design of long earth structures.

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