# Shake-Table Tests and Simulation Analyses on EPS Fill for Road Widening

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## Abstract
The wall to restrict EPS (expanded polystyrene) fill for road widening is changing from the conventional retaining wall type to simple self-sustaining wall type using H-steels. In recent years, studies are underway on methods to further simplify the structure of the retaining wall by utilizing the self-sustainability of EPS itself. However, since the sizes of EPS fill structures for road widening are increasing, it is essential to verify their behaviors during earthquakes. To achieve this objective, dynamic tests on EPS fill for road widening were conducted using a large shake table, and the test results were examined by simulation analyses. The tests and analyses showed that 1) EPS fill, even if not restricted by walls or anchors, can remain self-sustainable and prevent the loss of the function of roads constructed on it, although small residual deformation may occur, and that 2) residual deformation can be minimized if anchors are provided at proper locations. These results revealed that the retaining wall structure for EPS fill for road widening can be simplified.

**Keywords:** expanded poly-styrol (EPS), shake-table test, aseismic performance of EPS fill, anchor, retaining wall type.

## 1. Introduction
Since the introduction of the EPS method, establishing a seismic design method for structures formed by EPS has been an urgent issue in Japan, which is one of the earthquake-prone countries. Although the seismic design method was created after active studies by various research organizations, the Hyogoken-nanbu Earthquake (a strong inland earthquake) in 1995 raised a major problem about the safety of EPS fill during such a large earthquake. Previously, shake-table tests on EPS fill for road widening considered bw embankments with heights from 4 to 5 m, and focused on the verification of the dynamic behaviors of EPS fill without taking into account the effects of the retaining wall provided in from of it. In recent years, many tall EPS fill structures for road widening with a height of about 15 m are being constructed, and the types of the front retaining walls vary depending on the site conditions. However, it is difficult to accurately predict the earthquake response of the whole structure of EPS fill. In recognition of this, the authors not only studied the static characteristics of high EPS fill (including stress transfer and load distribution during construction), but also conducted large shake-table tests and simulation analyses to verify how the dynamic behavior of tall EPS fill is affected by the retaining wall and by the anchors. The tests and analyses yielded fundamental data with which to develop a new type of retaining wall which can utilize the self-sustainability of EPS and which allows easy and cost-effective construction. This study was jointly conducted by the Civil Engineering Research Institute of Hokkaido and the EPS Development Organization.

## 2.Outline of shake-table tests
### 2.1. Test specimens and test cases
Specimens with a scale of 1/5 and using D-20 type EPS as shown in Figure 1 were used in the shake-table tests. Steel plate 2 cm in thickness, corresponding to the intermediate slabs, were provided at 60 cm vertical

intervals. A surcharge during construction (including the weight of pavement) was set to 150 kN/m2. Friction between materials (i.e. between EPS layers, between EPS and concrete layers, and between EPS layers and the soil embankment behind them) was also considered. In order to verify the effects of the retaining wall type and anchors, six cases as shown in Table 1 were tested.

### 2.2. Shaking conditions

The shaking conditions for shake-table tests are shown in Table 2. In step 1, sine waves with a maximum acceleration of 50 gal were used as the seismic input motions to obtain the natural frequency of specimens, while in steps 2 and 3, random input waves were used to investigate the dynamic response characteristics during large earthquakes. The random waves for the tests were created by modifying actual seismic waves in such a way that they would correspond to the three standard acceleration response spectra shown in Figure 2: the spectra in this figure are given in the Specifications for Highway Bridges: Part V, Seismic Design. In addition, since the tests used 1/5 scale specimens, the scale for the time axis was also set to 1/5 based on the law of similarity.

### 2.3. Reproducibility of shake-table tests

#### 2.3.1 Reproducibility of the acceleration of random input waves

In the shake-table tests, the specimens were vibrated by giving them displacements converted from the random input waves (displacement control method). Therefore, the authors checked whether the characteristics of the original random input waves can be reproduced by the displacement control test method. As shown in Table 3, the maximum acceleration obtained from the shake-table test for each case was close to the maximum acceleration of the original random input waves.

#### 2.3.2. Deformation of EPS due to vibration

Tests on Case 1 and Case 6, both using models without anchors for restricting the movement of EPS, showed that residual deformation would occur at the bottom of EPS fill under large seismic forces, but failure of EPS fill would not be caused. This indicates that EPS fill can remain self-sustainable even if anchors are not provided. On the other hand, as shown in Photograph 1, models with anchors (Cases 2 to 5) showed no residual deformation and remained stable even when subjected to large forces. This indicates that anchors are quite effective for maintaining the stability of EPS fill during large earthquakes.

#### 2.3.3. Relationship between the predominant response frequency of EPS fill and the acceleration of the input ground motions

Figure 3 shows how the predominant response frequency changes depending on the input acceleration. As shown in the figure, the predominant response frequency is between 1.3 and 2.0 Hz, regardless of the type of embankment structure. Models without anchors for restricting EPS showed large predominant frequencies. On the other hand, the predominant frequencies for models with anchors were about 1.3 Hz. In addition, as shown in Figure 4, the magnification of response for models with anchors ranged from 1.5 to 2.0 for level 2 earthquakes.

#### 2.3.4. Effects of the structure type of EPS fill on the reaction force at the fill bottom during earthquakes

Figure 5 shows the relationship between the structure type of EPS fill and the increase of the reaction force at the bottom of EPS during earthquakes. This figure indicates that 1) anchors can reduce the overturning moment during earthquakes, and this decreases the ground reaction acting on the bottom surface of EPS, and 2) the overturning moment can be reduced if the number of the layers of anchors is increased. With respect to the structure of the retaining wall in front of EPS fill, it was revealed that the type in which the wall is rigidly fixed to the foundation soil (the type in which the H-steel is embedded into the foundation soil) is effective for restricting the displacement of EPS.

#### 2.3.5. Relationship between the acceleration of input ground motions and the forces acting in anchors during earthquakes

Figure 6 shows the relationship between the acceleration of input ground motions and the ratio of the forces acting in the anchors at the elevations of the intermediate slabs to the forces acting in the anchors at the elevation of the top slab during earthquakes. As shown in the figure, the ratio among the forces in the top, medium, and bottom anchors was 1:0.2:0.05 regardless of the magnitude of the acceleration of the input ground motions.

## 3. Simulation analysis

Simulation analysis for each model shown in Figure 1 was conducted to check whether shake-table tests can reproduce the dynamic behaviors of EPS fill during earthquakes.

### 3.1 Analysis conditions

Figure 7 shows the entire analysis flow, including the simulation analysis. DINAS, a finite element analysis program, was used for simulation. The features of this program are as follows:

• Being a program based on the nonlinear analysis method, it can analyze dynamic behaviors by direct integration.
• It can calculate residual deformation during an earthquake.
• It can consider separation and slip failure during an earthquake.

DINAS (two-/three-dimensional coupled-foundation-to-structure dynamic response analysis system) is a general-purpose program which can analyze the coupled vibration of the structure and foundation soil. If the nonlinear characteristic of the tangential stiffness and vertical stiffness of joint elements are taken into consideration, dynamic response analysis can verify the interaction between fill materials and the soil embankment behind them, and reproduce the phenomenon in which the EPS fill materials repeatedly come into contact with and apart from the surface of the slope of the soil embankment. The constraint conditions at boundaries for dynamic response analysis were rigid fix at the bottom of EPS and roller support at the side. In addition, joint elements were used between EPS fill materials and the slope surface of the soil embankment to consider the separation and slippage of EPS fill materials. A sequential method based on direct integration by the Newmark's ß-method was used for analysis, and the analysis interval was set to 0.025 seconds.

#### 3.1.1. Analysis model

As shown in Figure 8, an analysis model accurately reproducing the specimens for shake-table tests was prepared. For test cases with the retaining wall, H-steels, and anchors, five models as shown in Table 4 were prepared.

#### 3.1.2. Properties used for analysis

The basic material properties used for analysis are shown in Table 5. The properties in the table were determined based on previous study results. An equivalent linear model was used for the part formed by EPS to consider the non-linearity, while a rigid body model was used for the soil embankment part. With respect to the types of elements, beam elements were used for the wall, and strain elements for EPS fill materials. In addition, the modulus of deformation in the shearing direction for joint elements at the slope surface and at the bottom was set to one tenth the initial shear modulus of elasticity of EPS fill materials, which is the value normally used.

### 3.2. Discussion on simulation analysis results

Simulation analysis was conducted to check whether its results were in agreement with shake table test results described in the former clause. The simulation analysis showed the following results:

1) Reproducibility of wave forms of response acceleration of EPS fill

A simulation analysis taking into consideration the response characteristics of EPS fill was conducted to check whether it could reproduce the wave forms of response acceleration at the top of EPS fill for case 1 (without restriction for EPS fill materials) obtained from the shake-table tests. Figures 10 to 12 compare the representative wave forms of response acceleration obtained from the shake-table tests and simulation analysis. As shown in these figures, the input ground motions and the wave forms of response acceleration obtained from the tests and from the analysis were fairly in good agreement with each other. In the simulation analysis, the damping factor of EPS fill materials was changed depending on the input acceleration. This means that the dynamic behaviors of EPS fill can be accurately reproduced by simulation analysis, if its internal damping which changes depending on the input acceleration is considered. For cases other than Case 1 (i.e. cases with restriction for EPS fill materials), the wave forms were not affected by the response of EPS materials, and the test and analysis results with respect to the wave forms of the response acceleration showed good agreement with each other, since the EPS materials in these cases were restricted and behaved monolithically with the soil embankment behind.

2) Response characteristics of EPS fills

Figure 13 shows the representative results obtained from shake-table tests for Case 1 (case without restriction for EPS fill materials) with respect to the transfer function for the wave forms of horizontal response acceleration at the front top and at the bottom of the EPS fill. As shown in the figure, the predominant frequency for the first vibration mode obtained from the test was almost the same as that obtained from the analysis. With respect to cases other than Case 1, the predominant frequency was not affected by the response of EPS fill, and test and analysis results showed simillar values (1.5 to 2.5 Hz), since the EPS fill materials were restricted and behaved monolithically with the soil embankment behind. Since an embankment formed by EPS is structurally different from normal embankments which are built by spreading and compacting soil in layers, its natural period is generally calculated by the following method in which its shape is taken into consideration.

• Calculation of the natural period of an embankment formed by EPS

Natural period: T

$$T = 2\pi \cdot \sqrt{\frac{W \cdot H}{E \cdot a \cdot b \cdot g}\left\{4\left(\frac{H}{a}\right)^2 + 1 + \frac{12}{5}(1+\nu)\right\}}$$

where

W is surcharge;

E and $\nu$ are the modulus of elasticity and the Poisson's ratio of EPS, respectively;

g is gravity acceleration;

H is the height of the embankment formed by EPS; and

a and b are the length and the width of the structure, respectively.

Using the above equation, the natural period for the model used in the shake-table tests (T) was calculated to be 0.46 seconds (frequency: 2.20 Hz). Where the vibration acceleration level was low, the natural period (natural frequency) was about this value. If the vibration acceleration was large, however, the natural period increased and the natural frequency decreased. This tendency agrees with the results shown in Figure 3.

3) Effects of the structure type of EPS fill on the reaction force at the fill bottom during earthquakes

Figure 15 compares the simulation analysis results for each case with respect to the internal stability of EPS fill at the bottom (width: 20 cm for test specimens and 1.0 m for the actual structure) during earthquakes. As shown in the figure, the increase of stresses for EPS restricted with H-steels and anchors was considerably smaller than that for EPS without restriction. As shown in Figure 16, this tendency was due to the response characteristics of the EPS fill structure, especially the vertical movement. The analysis conditions for each case were the same as those shown in Table 4. Tests and simulation analysis under these conditions showed that if proper measures to restrict the movement of EPS (such as the use of anchors) are taken, the rocking mode (which is one of the response characteristics of top-heavy structures) is prevented and this reduces the vertical movement of EPS and thus increases the stability at the bottom of EPS during earthquakes. A further study revealed that the increase of stresses at the bottom of EPS can be considerably decreased if the number of layers of anchors is increased or if the wall made of H-steel is sufficiently embedded into the foundation soil.

4) Relationship between the forces acting in anchors during earthquakes and input acceleration

Figure 17 shows the relationship between the input acceleration and the ratio of the forces acting in the anchors provided at the levels of the intermediate slabs to the forces acting in the anchors at the level of the top slab during vibration. As shown in this figure, the simulation analysis results were in good agreement with the shake-table test results. This finding provides useful information for preparing design methods for anchors capable of withstanding large seismic forces.

## 5. Conclusion

The following findings were obtained from the shake-table tests and simulation analysis for EPS fill for road widening:

• EPS fill for road widening, even if not restricted with a retaining wall, can remain self-sustainable even during large earthquakes, and the road constructed on it can remain in a serviceable condition.
• The stability of EPS fill for road widening during earthquakes is greatly improved if H-steels and anchors to restrict its movements are provided at proper locations. For an embankment formed by EPS fill materials which is a top-heavy structures, anchors provided at the level of the top slab can improve the stability of the entire EPS fill structure and reduce the residual deformation due to earthquakes. This means that anchors are more effective for improving the stability of EPS fill during earthquakes than the front retaining wall.
• The ground reaction of EPS fill at the bottom is greatly improved if H-steels and anchors are provided.
• Simulation analysis can accurately predict the natural period, response characteristics, and internal stresses of EPS fill, if the analysis model is properly produced.

The above findings indicate that if proper measures (e.g. installation of anchors in the soil embankment) are taken, EPS fill for road widening can maintain its stability even when struck by large earthquakes. With respect to the retaining wall in front of EPS fill, a simple structure suffices if it will not cause large forces in the entire body formed by EPS.

In future studies, the authors will research the proper structure for the front retaining wall that takes into account the behaviors of EPS fill during earthquakes, by considering not only the above findings and on-site test results, but also such factors as cost-effectiveness, construction easiness, and durability.

## References

1. EPS Development Organization: The EPS Method - Super Lightweight Banking Using Expanded Poly-styrol (EPS), Rikoh Tosho Co., Ltd.
2. Soil Dynamics Division, Construction Method and Equipment Department, Ministry of Land, Infrastructure and Transport: Study on the Aseismic Performance of EPS Fill, Technical Memorandum of PWRI No. 2946

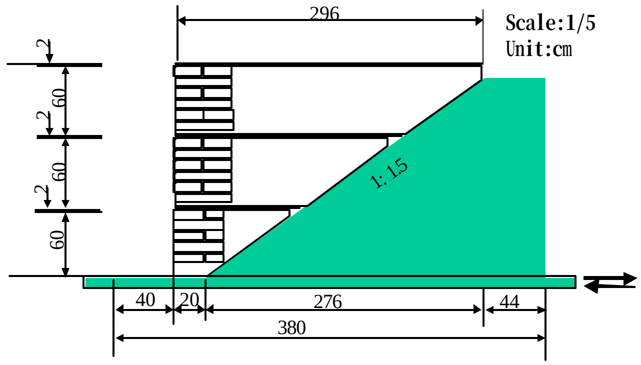



**Table 1　Test Model Table**

**Fig.1 Image of filling up EPS**

| Test Case | Wall | Anchor |
|---|---|---|
| Case1 | Nil | Nil |
| Case2 | Nil | Top slab only |
| Case3 | Placed, lower part open | Top slab only |
| Case4 | Placed, lower part fixed | Top slab only |
| Case5 | Nil | Top slab intermediate slabs (upper and lower) all placed |
| Case6 | Placed, lower part open | nil |

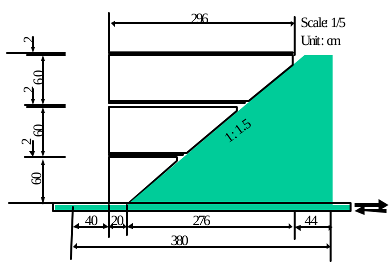
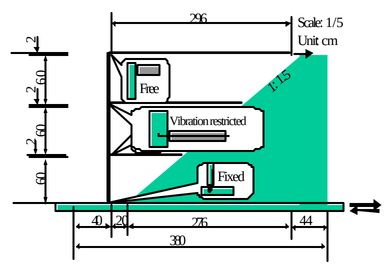
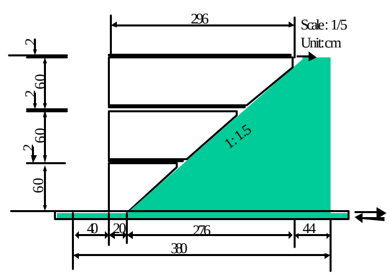
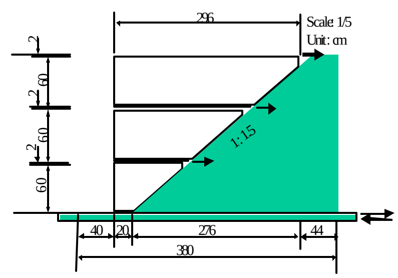
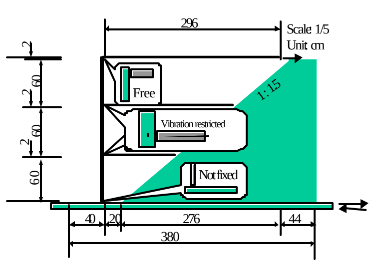
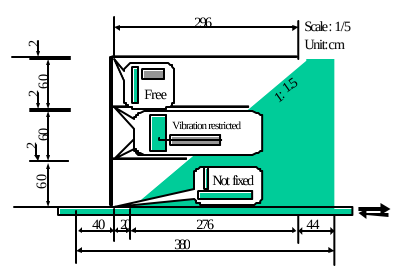
| Test Case | Simplified illustration | Test Case | Simplified illustration |
|---|---|---|---|
| Case1 |  | Case4 |  |
| Case2 |  | Case5 |  |
| Case3 |  | Case6 |  |

**Table 2  Shaking condition in this experiment**

| Step | Input wave | | | Purpose | Remarks |
|---|---|---|---|---|---|
| **1** | Sine Curve | 0.5~ 15Hz | | Basic data for specific frequency of the fill | About 50gal |
| 2 | Random wave | Level 1 seismic motion | | Kind ? ground | 1968 Hyuganada-oki Earthquake, modified |
| 3 | | Level 2 seismic motion | Type ? seismic motion | Kind ? ground | 1994 Hokkaido-toho-oki Earthquake, modified |
| | | | | Kind ? ground | 1994 Kushiro-oki Earthquake, modified |
| | | | Type ? seismic motion | Kind ? ground | 1995 Hyogoken-nanbu Eearthquake, recorded at Kobe Maritime Weather Bureau |
| | | | | Kind ? ground | 1995 Hyogoken-nanbu Eearthquake, recorded at JR Takatori Station, modified |

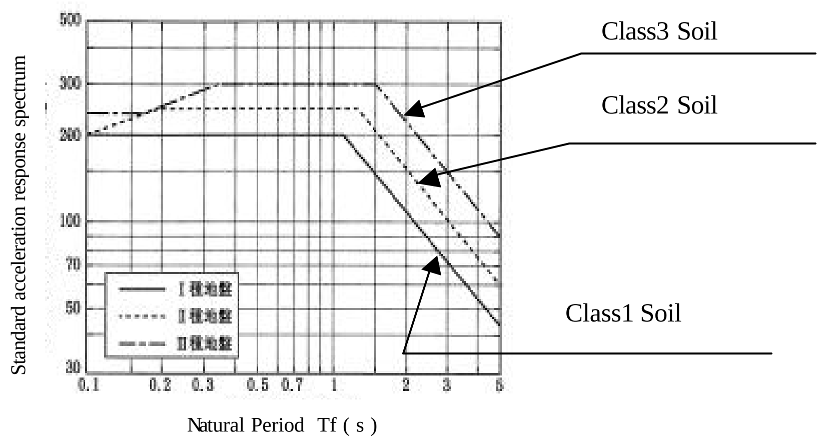
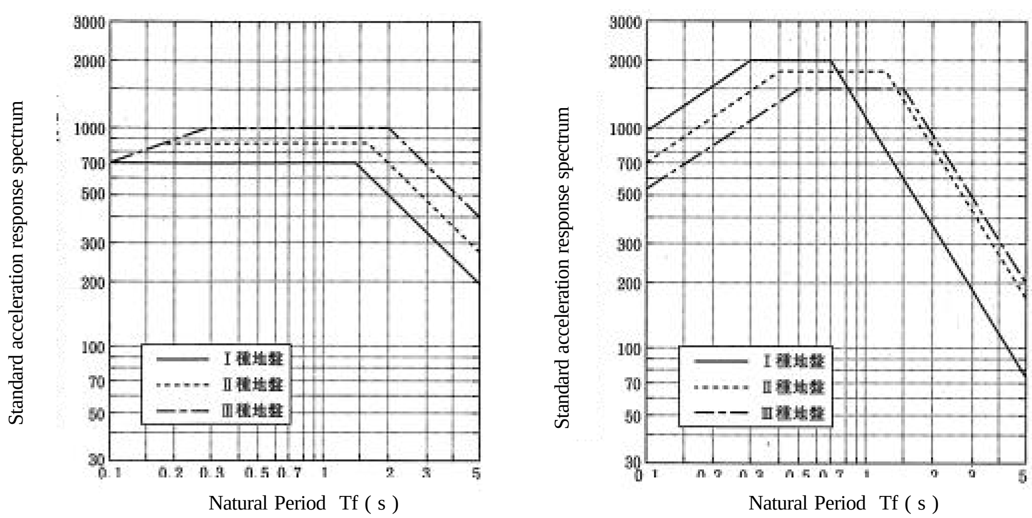



**Fig.2(1)  Standard acceleration response spectrum(Level 1 earthquake)**




(a) Type ?    (b) Type ?

**Fig.2(2)  Standard acceleration response spectrum(Level 2 earthquake)**

**Table 3 Reproducibility of shake-table tests using randam input ground motion**

(Comparison between the maximum acceleration of the shake-table and the maximum acceleration of the input ground motion)

| Classification of input ground motion | | Soil Classification | Random input waves | | Maximum response acceleration of the shaletable(gal) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Name of input waves | Maximum Acceleration (gal) | Case1 | Case2 | Case3 | Case4 | Case5 | Case6 |
| Level -1 | | ? | Hyuganada-oki(1968) Modified | 118 | 128 | 131 | 122 | 128 | 123 | 134 |
| Level - 2 | Type-? | ? | Hokkaido -toho-oki(1994) modified | 364 | 376 | 362 | 354 | 358 | 392 | 382 |
| | | ? | Kushiro-oki(1993) Modified | 438 | 579 | 443 | 445 | 439 | 426 | ? |
| | Type-? | ? | Kobe(1995) Kobe-Maritime-Modified | 812 | 785 | 875 | 839 | 814 | 821 | ? |
| | | ? | Kobe(1995) JRTakatori -Modified | 686 | ? | 713 | 641 | 682 | 684 | ? |

**Photo 1 The condition in the experiment end**

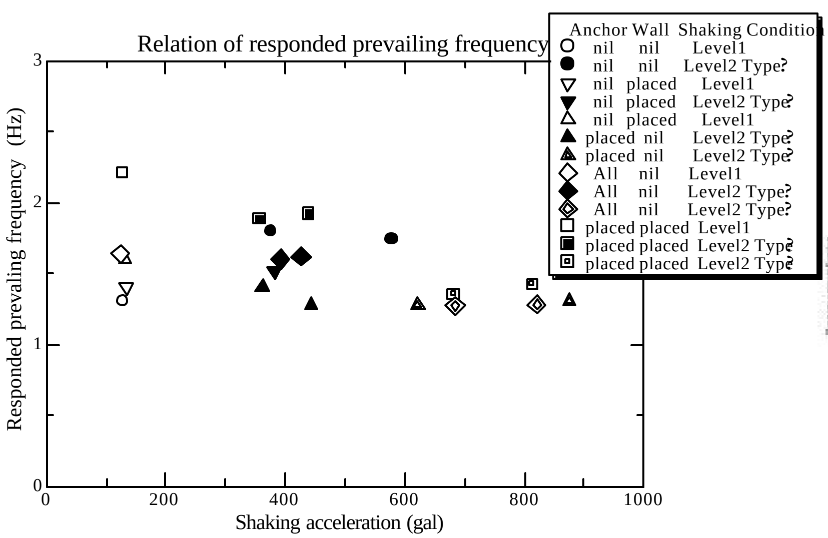



**Fig 3 Relation between Responded Prevailing Frequency of EPS-Fills and Shaking Acceleratiojn**

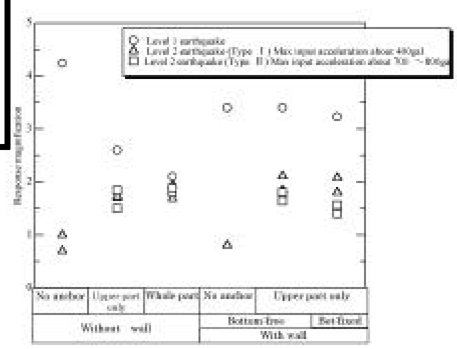



**Fig 4 Relationship between Magnification of Acceleration Response of EPS Fills and Structure Type**

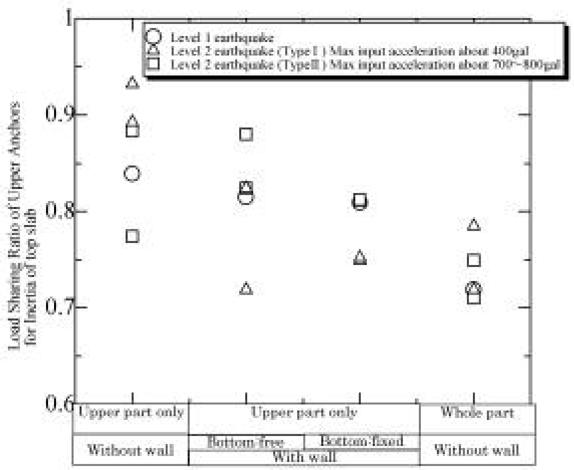



**Fig 5 Relation between Stress Increase at EPS Bottom Part at Earthquakes and Structure Type**

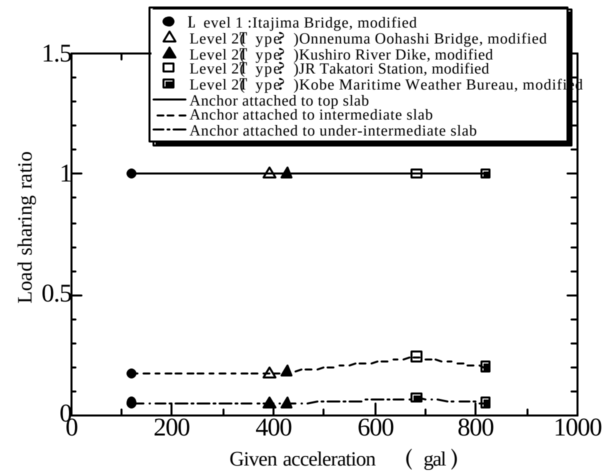



**Fig 6 Relation between Load Sharing Ratio of each Anchor and Shaking Acceleration**

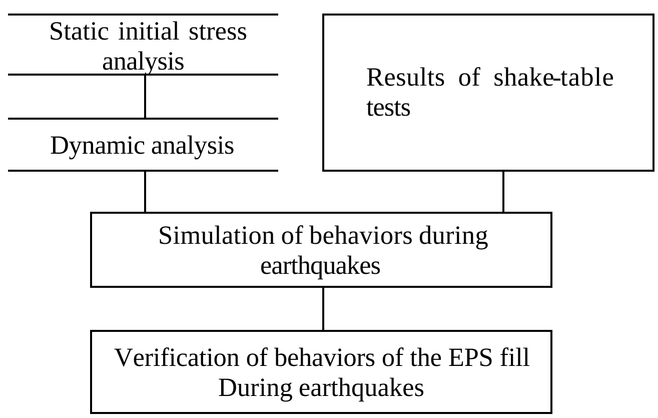



**Fig 7 Simulation Flow**

**Table 4 Analysis Model**

| Model | Retaining Wall | Bottom end of H-steel | Anchor | Remarks |
|---|---|---|---|---|
| 1 | Not Provided | Not applicable | Not Provided | |
| 2 | Not Provided | Not applicable | Provided only at top slab level | |
| 3 | Provided | Not fixed | Provided only at top slab level | |
| 4 | Provided | Enbedded into foundation soil(rigidly fixed) | Provided only at top slab level | |
| 5 | Not Provided | Not applicable | Provided at each slab level | |

**Table 5 Material properties used for simulation analysis**

| Material | Unit weight ? ( kN/m$^3$ ) | Shear modulus of elasticity $G_0$ (kN/m$^2$ ) | Poisson's ratio ? | Damping factor h | Cross sectional area A ( m$^2$ ) | Moment of inertia ? ( m$^4$ ) | Remarks |
|---|---|---|---|---|---|---|---|
| EPS | 0.2 | 2500.0 | 0.075 | Varying | - | - | |
| Layer spread on EPS | 24.25 | 1.087E+07 | 0.167 | 0.05 | - | - | |
| Top Slab | 78.5 | 8.077E+07 | 0.300 | 0.03 | 0.092 | 2.860E-05 | |
| Intermediate Slab | 78.5 | 8.077E+07 | 0.300 | 0.03 | 0.032 | 2.730E-06 | |
| Soil embankment | 100.0 | 1.00E+12 | 0.300 | 0.01 | - | - | |

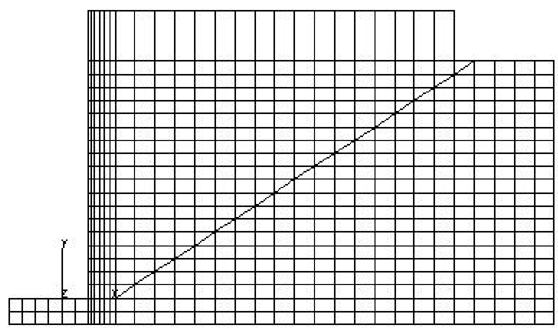


**Fig.8 Experimental model**

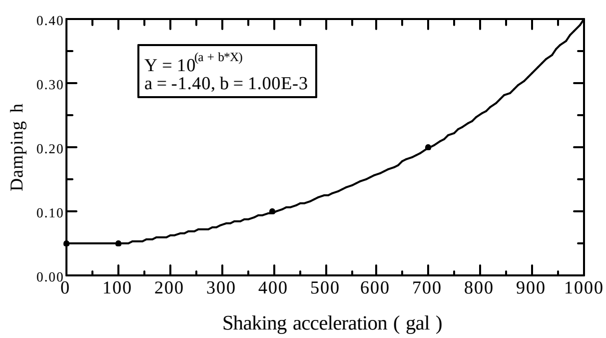



**Fig.9 Relationship between Shaking Acc. and Damping**

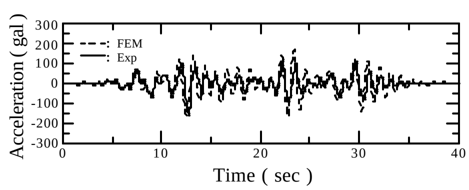
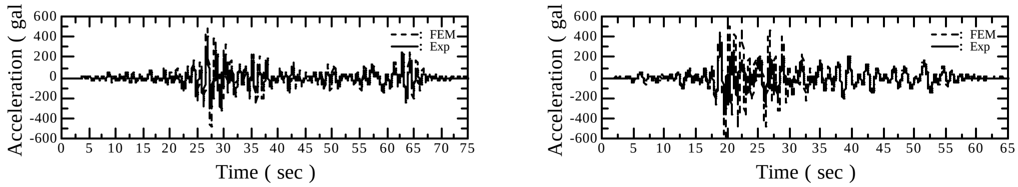



**Fig.10 Wave forms of response Acc.(Case 1,Level 1 earthquake: Itajima Bridge,modified)**




(1) Onnetou Oohashi Bridge, modified (2) Kushiro River Dike, modified

**Fig.11 Wave forms of response Acc.(Case 1,Level 2 earthquake: Type？ )**

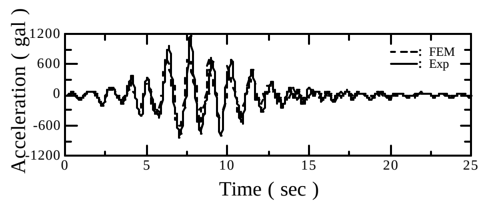
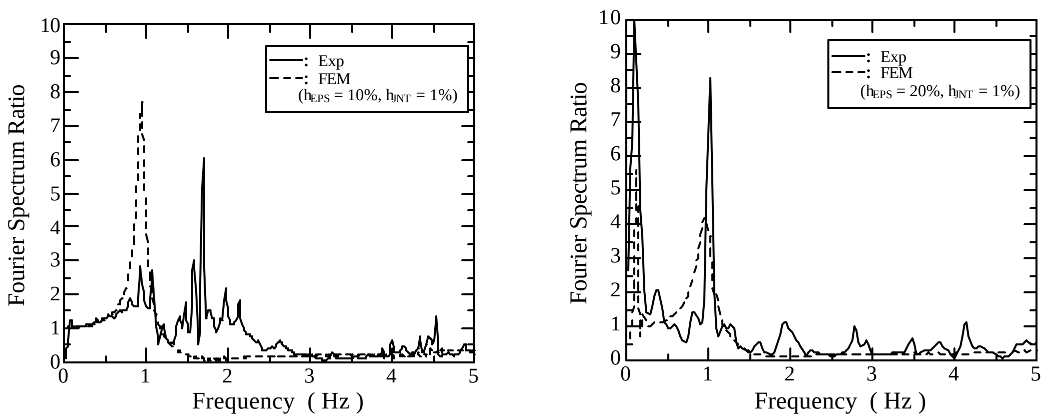



**Fig.12 Wave forms of response Acc.**
**(Case 1, Level 2 earthquake: Type？ ;KOBE Maritime Observatory, modified)**




(1) Onnetou Oohashi Bridge, modified (2) KOBE Maritime Weather Bureau, modified

**Fig. 13 Fourier Spectrum Ratio (Case 1； Level 1 or Level 2(Type？ ))**

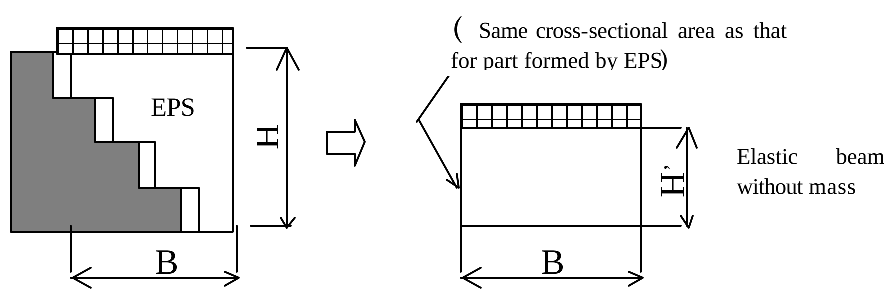



**Fig.14 Equivalent model for slope section created by a simplified method**

(EPS Development Organization: The EPS Method –Super Lightweight Banking Using Expanded Poly-styrol(EPS), Rikoh Tosho Co.,Ltd.))

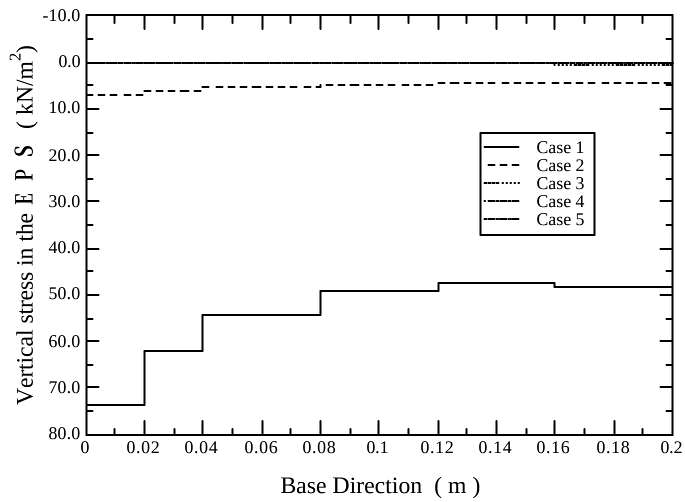



**Fig. 15 Increase in stress during earthquakes at the bottom surface of EPS for each case**
(FEM analysis results, Level 2 earthquake (Type？ )KOBE Maritime Observatory, modified)

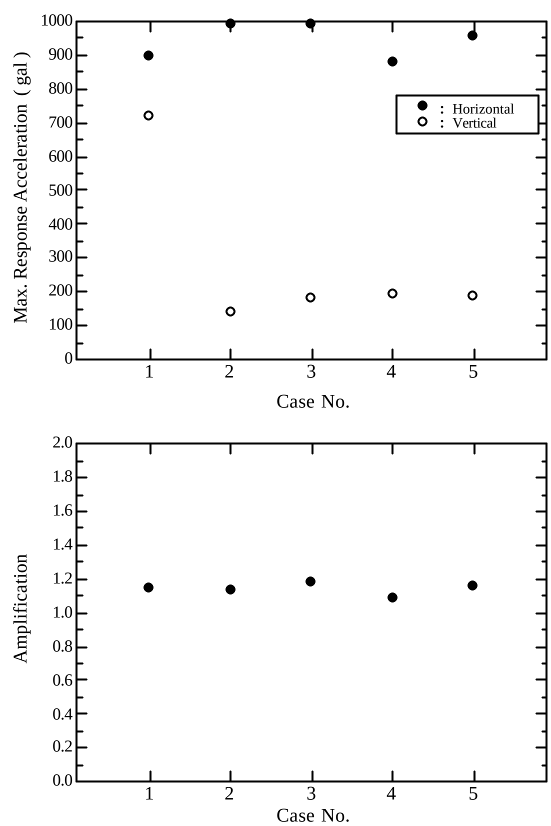



**Fig.16 Characteristics of acceleration response at the top of EPS fills for each case**
(FEM analysis results, Level 2 earthquake (Type？ );KOBE Maritime Observatory, modified)

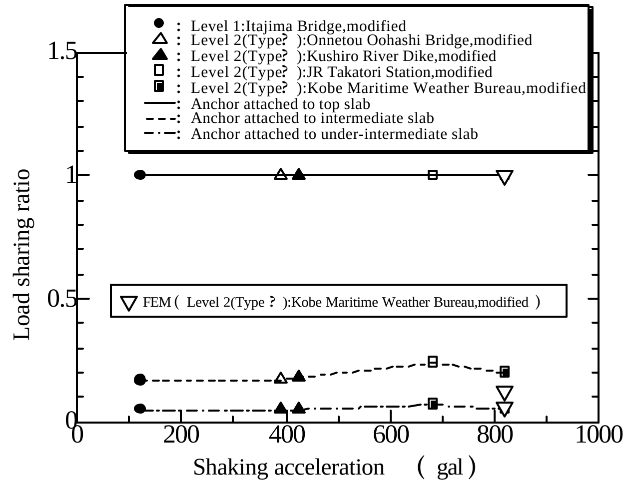



**Fig.17 Relation between Load Shaking Ratio of each Anchor and Shaking Acceleration**