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An Expanded Polystyrene Foam (EPS) Road Robust to Successive Great Kumamoto Earthquakes in 2016

K. Yasuhara[1], H. Tsukamoto[2], K. Taneichi[2], T. Konami[3], and T. Kubota[2]
[1]*EPS Development Organization (EDO), Tokyo, and Ibaraki University., Ibaraki, Japan*
[2]*EPS Development Organization (EDO), Tokyo, Japan*
[3]*Okasan Livic Co. Ltd., Tokyo, Japan*
E-mail: kazuya.yasuhara.0927@vc.ibaraki.ac.jp

ABSTRACT: This paper describes a case in which no complete demolishment was observed in a geofoam (expanded polystyrene foam EPS) embankment. Used for local roads situated over active faults at a mountainous site in Mashiki Town, Kumamoto, Japan, the EPS withstood two successive strong earthquakes that struck Kumamoto and Oita prefectures in 2015. The EPS blocks of this EPS embankment were markedly shifted sideways both horizontally and vertically because earthquake-caused landslides occurred behind the EPS fills. Nevertheless, only a part of the EPS embankment collapsed, causing no damage to the temple nearby. Thereafter, the road surface was remediated temporarily immediately after the earthquakes and was maintained for the opening of traffic. This case demonstrates that EPS presents great benefits: most importantly, the partly collapsed EPS road was put into practical use as a temporary road supporting the daily life of local residents. This report describes an engineering perspective of why the road was not collapsed completely. Future issues to be considered by local governments and engineering institutions are explained for the preparation of great earthquake countermeasures.

KEYWORDS: Earthquake, Geofoam block, Local road, Reuse, Stability.

1. INTRODUCTION

In 2016, two successive gigantic earthquakes struck the Kumamoto area of Japan, damaging numerous private residences and infrastructure over a wide area. Furthermore, local roads were damaged, including mountainous local roads with expanded polystyrene foam (EPS), sometimes called Geofoam, for civil engineering embankment applications in the Mashiki area near the earthquake epicenter. The EPS blocks in this road embankment were shifted sideways horizontally by 80 cm and vertically by 50 cm because of landslides that occurred behind the EPS fill during the successive great earthquakes. Fortunately, although part of the EPS embankment collapsed, it did not fail completely. Therefore, the road surface was remediated by the Kumamoto Prefecture government temporarily immediately following the two earthquakes. The road was maintained as it was for the opening of traffic. This case proves that EPS can provide great benefits: most importantly, the collapsed EPS road was put into practical use as a temporary road supporting the daily life of local residents in Mashiki Town. This paper introduces damage features of this EPS embankment and presents an engineering perspective of why the road did not collapse completely. Future issues to be considered not only by local governments but by engineering institutions are explained to facilitate the preparation of countermeasures against future earthquakes.

2. 2016 KUMAMOTO EARTHQUAKE

On April 14, 2016, an extremely strong earthquake struck the Kumamoto area in the Kyushu district in southern Japan (Figure 1). The earthquakes had magnitudes of 6.2 and 7.0, roughly equivalent to the Izmit Earthquake that occurred in Turkey in 1999 in terms of the following points.

i) The damage was caused mostly by the active faults.
ii) Numerous residences were damaged.
iii) Many residence foundations were on soft and weak ground, which consisted of volcanic-origin cohesive soils (Yasuhara, et al., 2018).

Nevertheless, the two earthquakes also present great differences. A characteristic feature of the Kumamoto Earthquake is that two large-scale earthquakes occurred successively within 28 hr. Moreover, about 5000 large and medium aftershocks occurred continually during the subsequent four months of April–July.

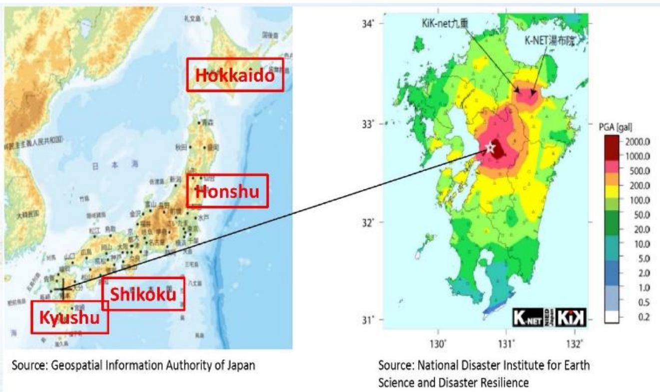


Figure 1 Kumamoto location stricken successively by two earthquakes in 2016

3. GEOTECHNICAL ASPECTS OF DAMAGED FEATURES

Generally speaking, older wooden houses in rural regions and steep slopes in mountainous areas often have less resistance if struck twice in succession by large-scale earthquakes. In fact, in Mashiki in Kumamoto near the epicenter, many residences collapsed, in addition to such important monuments as a national treasure: Kumamoto castle. Furthermore, roads through the area collapsed; thereby traffic became impossible. Mountainous slopes also collapsed. Numerous landslides occurred. Because this area is located on the Median Tectonic Line passing through the Japanese archipelago, many faults in the area induce movement and shredding of embankments and retaining walls that line roads and rivers (see Figure 2).

From geotechnical engineering points of view, the damage can be characterized as explained below:

1) Landslides and liquefaction occurred respectively in volcanic mountainous and plain sites (Figures 3, 4 and 5).
2) Both gentle and steep embankments of residential areas founded on volcanic ash cohesive soil deposits flowed and collapsed during the period of maximum seismic intensity, measured as 7. Residences with retaining walls were most severely damaged.
3) Volcanic ash soil is an important keyword associated with geo-disasters.

4) Rich groundwater of Kumamoto plain played an important role in exacerbating damage to earth structures and foundations.

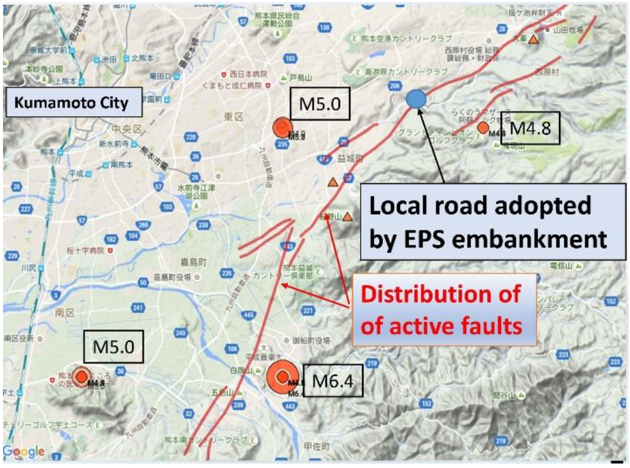
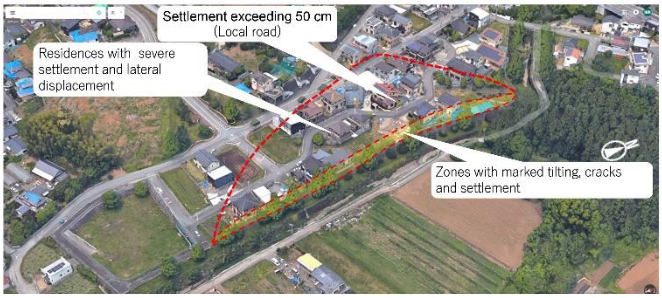
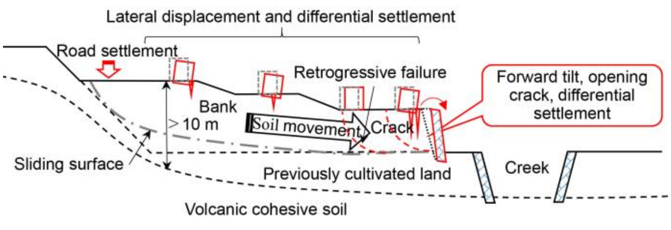


Figure 2 Location of EPS embankment for a local road (Prefectural road called "Route 28") on active faults



(a)



(b)

Figure 3 A damage feature in 2016 Kumamoto earthquake: (a) Damaged residences and adjacent retaining walls and (b) Sketch of the damaged embankment for residences

Figure 4 Large-scale landslide in the Minami Aso village

One example of damage to residential areas is shown in Figure 3(a). A key sketch is presented in Figure 3(b). The authors inferred at least two reasons to explain how and why severe damage was induced by the earthquake, as described below.

i) Soil embankments used as residential foundations lost strength and stiffness, leading to collapse, severe settlement, and deformation
ii) Predominant nonlinearity and amplification of ground motion degraded the stiffness and strength of volcanic ash cohesive soils, leading to large lateral displacement

Several grabens of approximately 50 m width occurred in the Aso Volcano caldera. However, the mechanism for this event remains unclear. It is now under investigation (Yasuda et al., 2018).

Figure 5 Land subsidence caused by grabens 9 at Aso

4. EPS ROAD IN KUMAMOTO–MASHIKI AREA

The EPS road in the Kumamoto–Mashiki area introduced herein presents an incredible sight. The Mashiki area has many mountains, among which many villages are connected by a single road. If these roads were closed, it would take hours to take negotiate a detour.

The Mashiki road with EPS reinforcement described herein was planned through steep slopes comprising tuffaceous sand from pyroclastic flow deposits mixed with breccia and pepper just beside a temple and tomb. This kind of material readily causes falling rocks, which influence infrastructure to some extent. Available information suggests some reasons for local government adoption of EPS embankments for local roads at this mountainous site (see Figure 6).

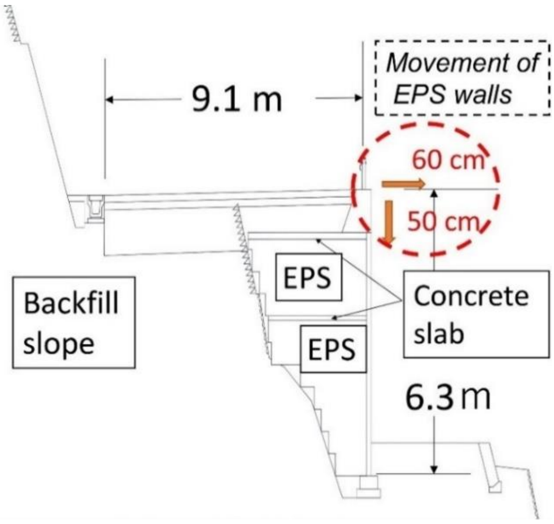


Figure 6 Original configuration of EPS embankment in 1998

i) maintaining safety against fallen stones from steep slopes
ii) saving excavation
iii) avoiding usage of large construction machinery at the steep mountainous site

5. COLLAPSED EPS EMBANKMENT

Figure 7 shows damage features at the road reinforced with EPS in images taken from various angles. Although the mountainous steep slope behind the EPS embankment collapsed and the retaining wall protected the foundation from collapse, the road was not completely destroyed, as stated previously.

The protective wall on the vertical surface of the EPS road was damaged as the ground moved because of the two successive earthquakes. The EPS blocks were shifted by landslides from the back. They protruded out at the front of roads with EPS (Figure 8). Nevertheless, the EPS blocks were mutually supportive and maintained the form of the embankment. Joint metal binders (JMB) linking EPS blocks moved, but they kept the EPS blocks mutually connected (Figure 8). A concrete slab in the embankment between EPS blocks broke: a large crack of 1 m width appeared on the road surface (Figures 9 and 10). However, the road level remained even; it did not fail completely. In fact, the roads were temporarily opened for traffic after the earthquakes to support the daily lives of local residents. In addition, the partly damaged EPS road was able to minimize the effects on the neighboring temple.

Figure 7 Damage features of local road (Route 28) with EPS embankment

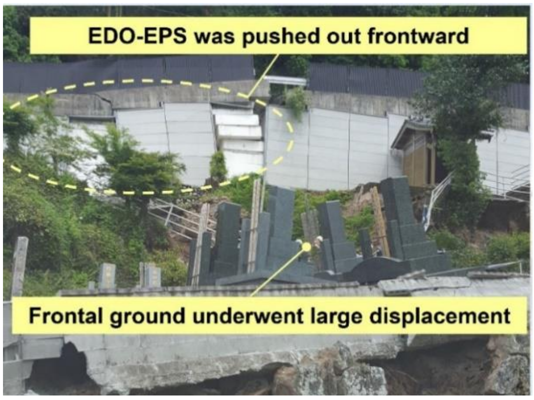


Figure 8 Damage to the frontal side of the road

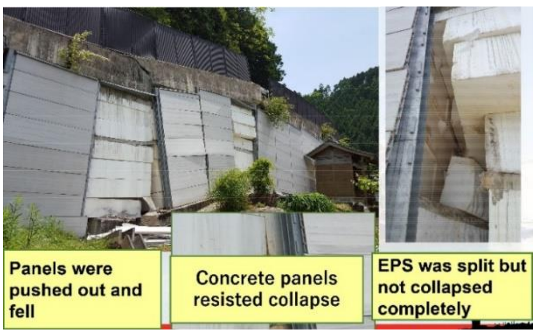


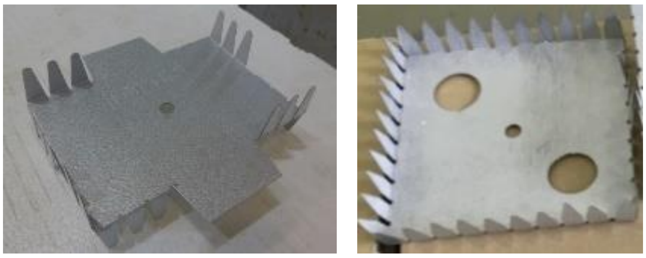
Figure 9 Details of damaged EPS frontal side of road

Figure 10 Damage of road surface

In conclusion, the reasons that the EPS embankments remained stable even under the two subsequent severe earthquakes despite being situated upon the active fault are the following:

i) Because of the super-lightweight of EPS, the seismic earth pressure was reduced.
ii) Adequate function of interaction of the respective EPS blocks was exerted.
iii) The JMB linking the respective blocks functioned properly.
iv) Concrete slabs were effective for maintaining the evenness of the underlying concrete slab.

Among the reasons stated above, the most important factor is the role of JMB, as shown in Figure 11. Experiences for local roads during the Kumamoto earthquake examined in this case study indicated that conventional binders like those shown in Figure 11(a) are not sufficiently strong to resist strong earthquakes of M7 although the EPS embankment for local roads avoided complete failure. Therefore, the conventional binders are expected to be converted to new ones like that shown in Figure 11(b). This is described further in the following chapters.



(a) (b)

Figure 11 Metal joint binder connections of EPS blocks: (a) present type and (b) newly developed type

6. POST-EARTHQUAKE AND FUTURE REMEDIATION

6.1 Temporary Post-earthquake Remediation

The damaged road was the only mode of transportation for daily life for these mountain residents. If the roads were closed by restoration work, then the daily life activities of area residents would be impossible. Moreover, more than a year might be necessary to recover from landslides behind the EPS embankment and to repair the deformed EPS embankment. For these reasons, the possibility of using the partly collapsed road as a temporary Kumamoto-Mashiki road was discussed. The council deliberated the question at length in regional assemblies. Eventually, it was decided to re-open the road conditionally, with the following limitations.

1) The road width is restricted to one lane, as was shown in Figure 7, with a speed limit.
2) The road shall be closed during heavy rains.
3) Traffic is restricted immediately after the earthquake.
4) To support daily life for local residents, roads opened for traffic under the following conditions after temporary remediation against unexpected events by placement of large sand bags resisted against severe weather (Figure 12).

Figure 12 Placement of anti-weathering sand bags

6.2 Permanent future remediation

Principally, the local government plans to carry out the following.

i) Reversion to the original state, perhaps using EPS but with no consideration of active fault effects.
ii) Permanent remediation work will be finished before 2020. Until then, roads shall remain closed.

Currently, a revised design for this road is in progress (see Figure 13). The design method is to reconstruct the new EPS embankment after stabilizing the rear slope with anchors (Figure 14). However, no technical measures against future earthquakes will be undertaken for permanent remediation.

7. ISSUES LEFT FOR FURTHER DEVELOPMENT

Based upon Kumamoto earthquake experiences in which an EPS embankment was adopted at the local area at Mashiki of Kumamoto Prefecture, the EPS Development Organization (EDO) in Japan has decided to explore further advanced studies of technical improvement for increasing the earthquake resistance of EPS embankments. Further required studies have been underway. More are planned as explained below.

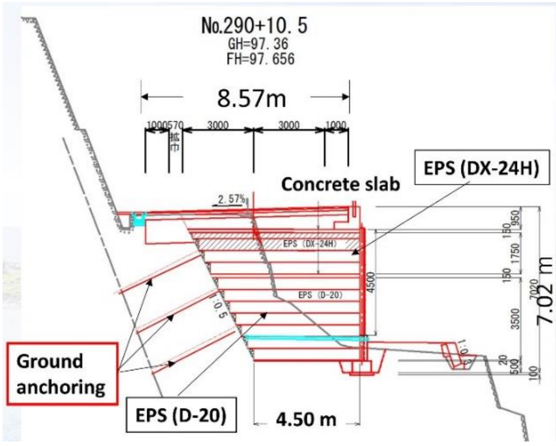


Figure 13 Proposed road remediation using EPS

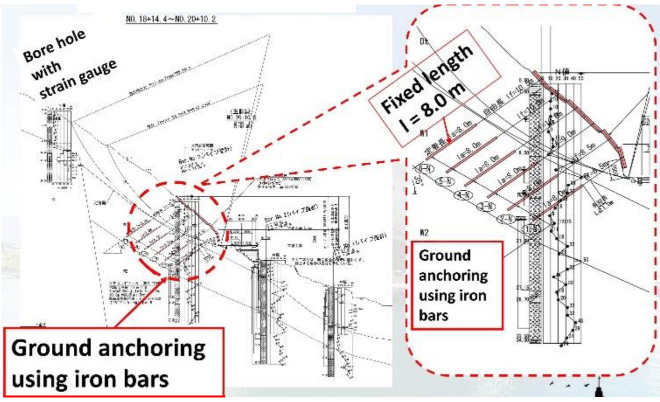


Figure 14 Details of anchoring for backyard steep slopes

7. 1 Joint Metal Binder Improvement and its Effects

Conventional JMBs are rectangular with asymmetrical spikes, but eccentric motion from seismic forces might affect the mutually connected EPSs. For this reason, the shape should be changed to a square, as was shown in Figure 11, but with an increased number of spikes. Direct-shear box tests were conducted by attaching old and new JMBs to EPS blocks. Results confirmed that the newly developed JMB has 1.5 times the shear strength of the conventional JMB (Taneichi et al., 2018a).

Shaking table tests were carried out under the scaled-down 1/5 model EPS embankment to verify that the newly developed JMBs are available for increasing seismic resistance against the forces of great earthquakes. Effects of the numbers and positions of JMBs will be confirmed using model shaking table tests conducted with support from the geotechnical laboratory of The University of Tokyo (Taneichi et al., 2018b).

7.2 Assessing EPS Embankments under Great Earthquake Forces Using Full-scale Tests

Successive to the shaking table tests on full-scale EPS embankments conducted in 1997 (Tsukamoto, 2011), shaking table tests on the new

EPS model embankment of 8 m height, 5 m length, and 3 m width (Figure 15) were conducted in 2018 at a large facility under the auspices of National Research Institute for Earth Science and Disaster Resilience (NIED), Japan.

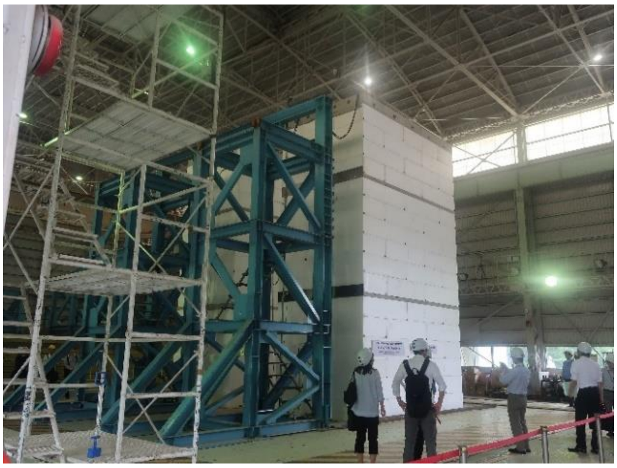


Figure 15 Scene of full-scale model tests of an EPS embankment

Although EDO is planning to present details of the tests within 2019, a characteristic aspect of this new full-scale test was to investigate the effects of new JMBs for improving EPS embankment stability. The following are newly devised points that differ from the earlier experience in 1997.

i) New JMBs were adopted (Figure 11).
ii) Layout effects of new JMBs were compared (Figure 16).
iii) Metal L-hooks were supplemented to resist rocking motions between EPS blocks and concrete slabs (Figure 17).

(a)

(b)

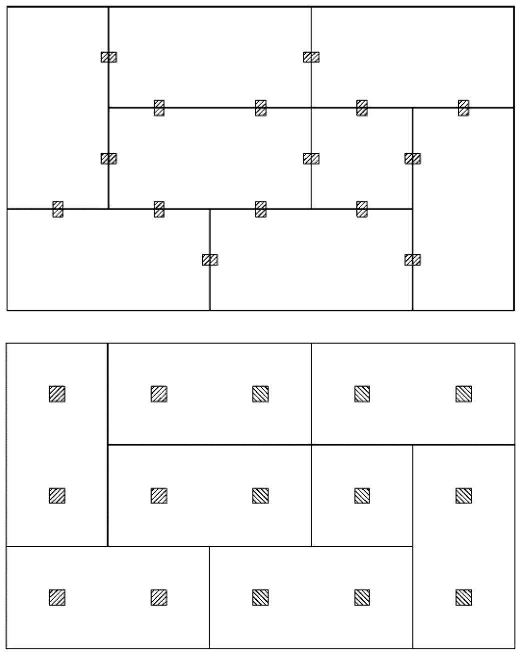


Figure 16 Two JMB layouts: (a) Conventional layout and (b) New layout

Unfortunately, the laboratory model tests (Taneichi et al., 2081b) revealed greater deformation in the case of the new layout than in the case of the conventional one, as shown in Figure 18.

To avoid rocking deformation of EPS structures, the following devices were additionally undertaken.

i) The hybrid layout shown in Figure 19 was adopted.
ii) Metal L-hooks were set between EPS blocks.

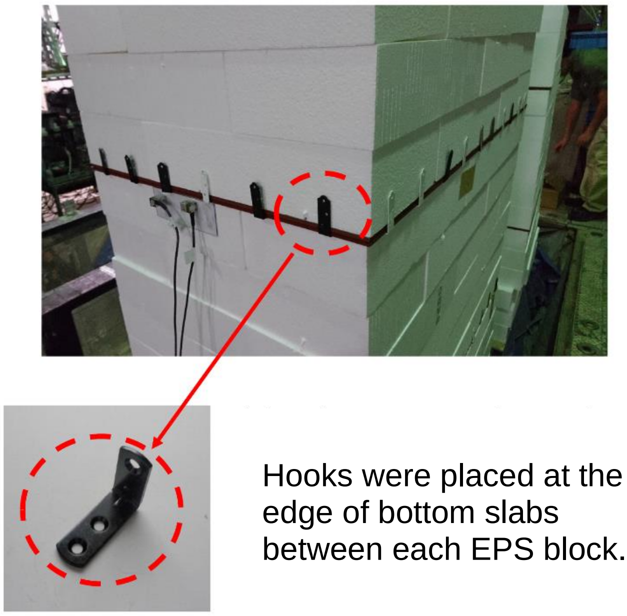


Figure 17 Metal hook placement

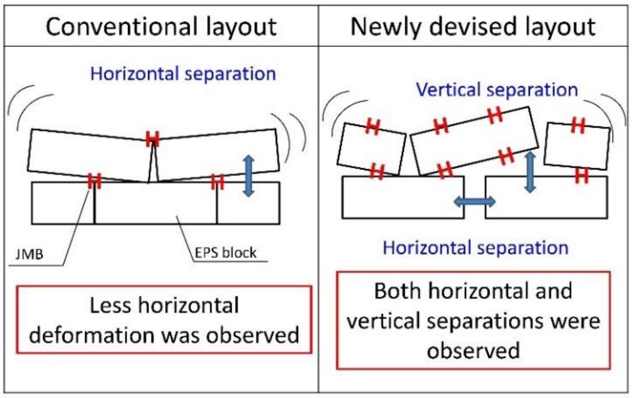


Figure 18 Rocking motions of conventional and new layouts

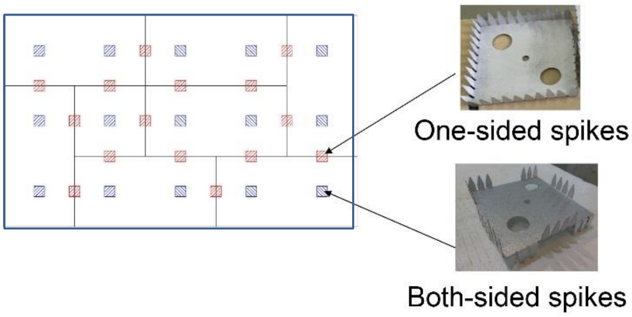


Figure 19 Hybrid layout of JMB

Results of small-scale shaking table model tests (Nishi et al., 2018) conducted using the two additional devices above are shown below.

i) JMBs with one-sided spikes form a lateral connection of EPS.
ii) JMBs with two-sided spikes form a vertical connection of upper and lower EPS blocks and thereby restrain vertical shear deformation.
iii) Metal L-hooks decrease EPS structure rocking motions during earthquakes.

In addition to the small-scale shaking table tests, full-scale tests were conducted. Interpretation of test results is underway. In Figure 20, we describe only typical results from tests undergoing the acceleration waves shown in Figure 21.

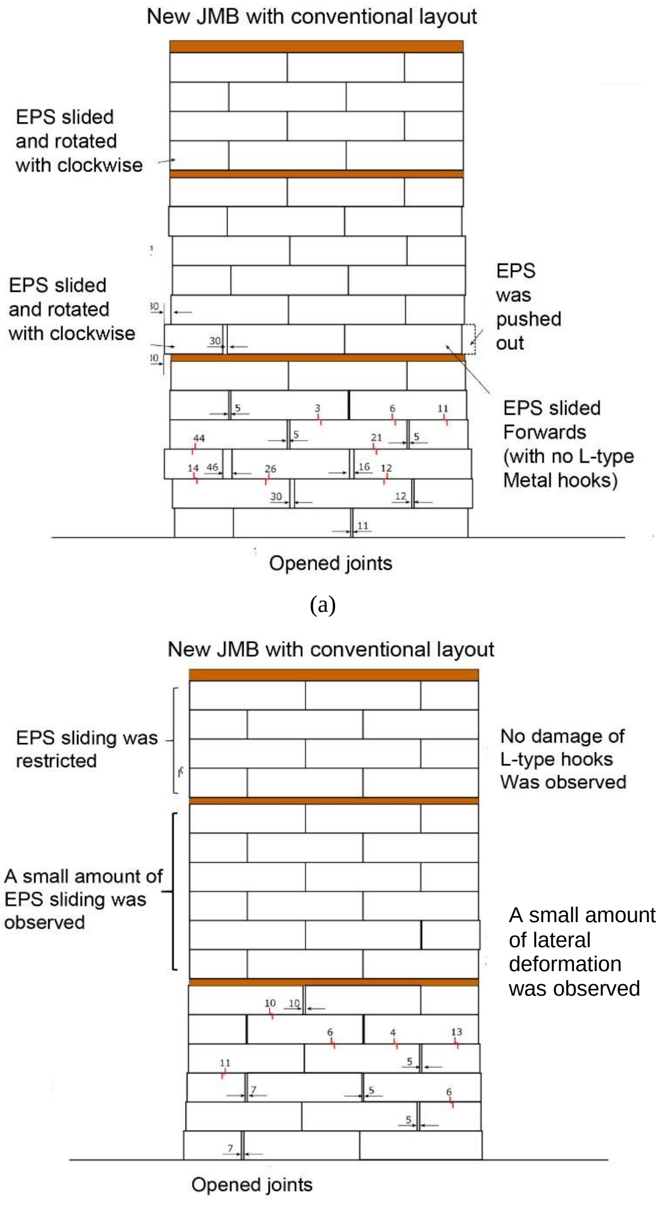


Figure 20 Typical results of full-scale shaking table tests for EPS embankment: (a) Conventional layout and (b) Hybrid layout

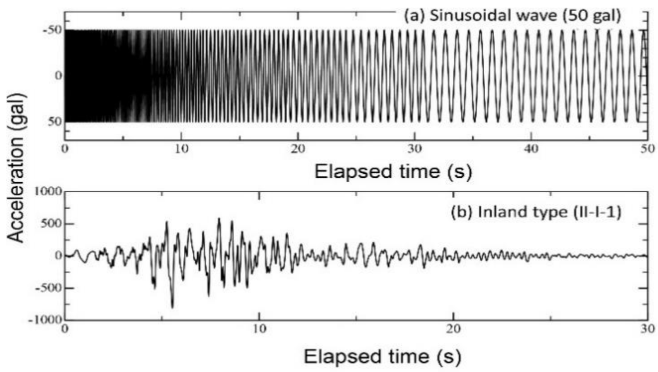


Figure 21 Acceleration records used for full-scale shaking table tests

Test results were obtained with and without L-hooks installed for increasing stability against earthquakes having the acceleration waves depicted in Figure 21. It might be readily apparent from Figure 20 that using metal L-hooks in the hybrid layout of JMB is useful for maintaining EPS embankment stability during earthquakes.

7.3 Design Specifications

Based on these experiment results, Japan's MLIT has requested that EDO establish a new design system for the use of EPS embankments as a countermeasure against large-scale earthquakes. This work has currently been ongoing.

8. CONCLUSIONS

1) From this case study of this road situated on active faults, the following are lessons learned of an EPS road embankment that did not collapse completely.
   i) Joint metal binders (JMBs) mutually connecting EPS blocks worked effectively, even during strong successive earthquakes.
   ii) Although the concrete slabs between EPS blocks were cracked by the drastic embankment deformation, they maintained the road surface evenness after undergoing damage.
2) Based on results obtained from both small-scale and full-scale shaking table tests, the EPS embankment can become more robust against earthquakes when adopting such additional devices as metal L-hooks, improved JMB, and a hybrid JMB layout.

9. ACKNOWLEDGMENTS

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