29 Mar 2001, 4:00 pm - 6:00 pm

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Hemanta Hazarika
Maizuru National College of Technology, Japan

Juichi Nakazawa
Maizuru National College of Technology, Japan

Hiroshi Matsuzawa
Oyo Corporation Ltd., Japan

Dawit Negussey
Syracuse University, Syracuse, NY

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Hemanta Hazarika & Juichi Nakazawa
Maizuru National College of Technology
Kyoto 625-8511, Japan
Hiroshi Matsuzawa
Oyo Corporation Ltd., Chubu Branch
Nagoya 463-0078, Japan
Dawit Negussey
Syracuse University,
Syracuse, NY 13244-1190, U.S.A.

ABSTRACT

A numerical analysis was carried out for a rigid retaining wall experiencing earthquake loading. The seismic forces acting on the wall was determined by simulating both sinusoidal load as well as the earthquake time history of an actual earthquake. At first considering that the backfill consists purely of sandy soils, the failure zone and the resulting earth pressure were calculated. After observing the failure zone of such backfill, the domain is substituted by lightweight Expanded Polystyrene (EPS) geofoam. The effect of replacing the sand with such lightweight materials on the developed seismic thrust is then examined. The results show that the use of the EPS geofoam as a replacement renders as much as 50% to 60% reduction of the seismic thrust.

INTRODUCTION

The Hyogo-ken Nanbu earthquake in Japan (January, 1995), and more recently the devastating earthquakes in Turkey (August, 1999) and Taiwan (September, 1999) serve as a stark reminder to both the research and the planning communities the enormity of damage caused by such earthquake, and their repercussions on social and economic fronts. Retaining structures are integral part of any infrastructure system, which are vulnerable to catastrophic failure during earthquakes. They frequently represent the key elements of port and harbors, transportation system lifelines, and other constructed facilities Thus, in seismically active zones frequented by strong earthquakes, adequate design of retaining structures assumes significant importance. The prerequisite for such design is, indeed, the proper estimation of the seismic earth pressure through comprehensive analysis taking into consideration the soil properties, the construction condition and the other associated factors.

In many historical earthquakes, the collapse of retaining structure occurred with disastrous physical and economic consequences. The predominant damage occurs in bridge abutments, quay walls, freeway structures etc. Post earthquake survey of the Hyogo-ken Nanbu earthquake revealed the damage suffered by many retaining structures. Especially near the port facilities, many quay walls were reported to have suffered damages due to unexpected displacements. Most of these reported damages are attributed to the liquefaction of the soil underneath. However, the effect of the increased or decreased lateral earth pressure during the earthquake prior to liquefaction cannot be entirely ruled out.

The excessive deformation or damage by the increased thrust from the backfill can be mitigated by using some lightweight materials such as Expanded Polystyrene (EPS) geofoam as a substitute backfill. EPS geofoam material serves as a key element of a cost-effective design alternative since the earth pressure acting on the structure can be significantly reduced due to its lightweight characteristics (with density one fiftieth to one hundredth of the normal filling materials). A survey of ten sites during the Hyogo-ken Nanbu earthquake revealed that the structures, in the construction of which EPS were used, did not suffer any direct damages from the earthquake (Miki, 1996; Hotta, 1998). The results establish the high earthquake resistant nature of such lightweight geofoam construction method. The earthquake resistant characteristics of such materials have also been experimentally studied (Nomaguchi, 1996; Koga et al, 1991).

In this research, one case of an ideal retaining wall experiencing the earthquake loadings similar to those during the Hyogo-ken Nanbu earthquake is picked up for analysis whose backfill consists mainly of granular materials such as sand or gravel. The purpose is to determine the effect of replacing the backfill partially with lightweight fill, whose function is to reduce the exerted thrust on the structure. Finite element simulations were carried out using modified (considering bi-directional localized strain) constitutive law (Hazarika and Matsuzawa, 1997) in order to simulate of the strain localization phenomenon of the granular backfill. The effect of replacing the backfill on the developed seismic load on the wall is then examined.

WHY LIGHTWEIGHT FILL

There are many situations, in which engineers have to deal with retaining structures that either need to undergo considerable deformation in order to reduce the forces close to the one used for design or have to withstand very high thrust to maintain deformation within the tolerable limit. Both involve extra structural costs. In such situations, it is the responsibility of the engineers to find some cost effective design alternative. One remedy is to use lightweight material behind the structures, which will induce low thrust on the structures. Negussey and Sun (1996) used such lightweight EPS geofoam to reduce the earth pressure against a basement wall successfully. Inglis et al. (1996) reported the use of EPS as compressible buffer in reducing the seismic earth pressure against a non-yielding basement wall. The approach in both this researches are different, however, the function of the geofoam in reducing the lateral earth pressure is proved decisively through case studies and finite element simulations. Nevertheless, Negussy and Sun's approach is the most popular one, which is widely used in most of the construction projects. Various other researches and construction projects have proved that in situations where a cost effective design is to be achieved, the use of EPS as substitute backfill can be a suitable solution.

EARTHQUAKE RESISTANCE OF LIGHTWEIGHT EPS

Earthquake prone Japan was hit by many large earthquakes during the period 1993 to 1995 (Table 1). The assessment of damage caused by these earthquakes to the EPS structures have been studied and published (Kuroda et al., 1994; Hotta et al., 1996). Remarkably, the EPS structures in the vicinity of the epicenters of the earthquakes listed in Table 1 were found to be free from any serious damages.

Table 1: Recent Major Earthquakes in Japan

Occurring Date	Earthquake Name	Magni-tude	Maximum Acc. (gals)
1993.1.15	Kushiro-Oki	7.8	920
1993.2.7	Noto-Hanto-Oki	6.6	130
1993.7.12	Hokkaido-Nansei-Oki	7.8	298
1994.10.4	Hokkaido-Toho-Oki	8.1	353
1995.1.17	Hyogo-ken Nanbu	7.2	1,764

The most remarkable one is the Hyogo-ken Nanbu earthquake, in which, earthquake motions far greater than those of any of the earthquake stated above hit the southern part of Hyogo prefecture. That earthquake devastated heavily many infrastructures of Kobe city. However, the EPS embankment laid in these areas showed that there is little or no serious and direct damage to the structures where EPS were used (Table 2). It was observed that only at the site No. 10, where the sand fill below liquefied during the earthquake, the subsidence (10cm) of EPS occurred.

Table 2: Damages to EPS Embankments during the Hyogo-ken Nanbu Earthquake, 1995

No.	Date of Execution	Place of Execution	EPS Type	Volume of EPS Used	Description of the Work	Damages During Earthquake
1	1991.01	Rokko Island, Kobe	D16	330	Backfilling of an underground parking lot	Hair crack on road surface, but no damage on EPS
2	1991.09	Harbor Island, Kobe	D16	120	Construction of No. 1 parking lot	No Deformation
3	1992.07	JR Amagasaki Station	D16	620	Construction of new No. 2 platform	No Deformation
4	1992.12	Akashi City, Hyogo	D16	2,440	Tarumi Sewerage works	No Deformation
5	1993.03	Hankyu Railway, Kawanishi	D16	331	Construction of new platform	No Deformation
6	1993.03	JR Amagasaki Station	D16	1,052	Improvement work of platform	No Deformation
7	1993.11	Awaji Island	D20	34	Honshu-Shikoku communication bridge	No Deformation
8	1994.01	JR Amagasaki Station	D16	175	Construction of new No. 4 platform	No Deformation
9	1994.06	Yokokawa	D16	1,001	Construction of Yokokawa Golf Club	No Deformation
10	1994.07	Kobe	D16	66	Bridge abutment	EPS subsidence (10 cm) due to liquefaction of the underlying sand

The above research results have proved that the EPS embankments are highly stable during earthquakes. This may be due to the fact that the frictional resistance at the base of the EPS embankment is fully mobilized during the strong earthquake motion. Therefore, it is necessary to take into the account the frictional resistance of the base while checking stability against sliding and overturning of EPS embankment during the earthquake. The new seismic design method in Japan was established taking these factors into the consideration (Miki,1996). In fact, various research institutes in Japan have conducted laboratory experiments as well as field observations to study the earthquake resistant performance of this ultra light construction material. The achievements of these studies have led to the establishment of a seismic design method that is reflected in the current design manual.

EPS geofoam is gaining popularity in recent years as a replacement for backfill against retaining structures due to its lightweight as well as earthquake resistant properties. In the sections that follow, numerical simulations technique and the simulation results are described using such lightweight material as backfill against a rigid retaining structure.

NUMERICAL SIMULATIONS

Many retaining structures fail during earthquakes due to the increased seismic active thrust or the decreased seismic passive resistance. The majority of observed failures of retaining wall during the Hyogo-ken Nanbu earthquake occurred in waterfront areas; many involved liquefaction of the backfill. Especially many quay walls near the port of Kobe were tilted and slid outward (EQE, 1995). Quay wall displacements, which undoubtedly propagated major damages to the port of Kobe, may be attributed to several phenomena one of which is the seismic lateral thrust. There are also instances of the damage of the railway retaining structures during that earthquake. Damages were also occurred in some parts of the subway system of Kobe city. Interestingly, common cause of failures there were due to the lack of passive pressure during the earthquake. Therefore, in order to elucidate behavior of the retaining structure under both the seismic active and seismic passive thrust, a numerical analysis was performed for a retaining wall subjected to the earthquake motion.

Finite Element Modeling

A 10 m high rigid retaining wall supporting a dry cohesion-less backfill was modeled by two dimensional finite element mesh as shown in Fig. 1. Analyses were performed by simulating two conditions (non-yielding and yielding) of the wall-backfill system as shown in Fig. 2. One in which the wall is restrained representing the condition of non-yielding wall (NY) and in others the wall had a rocking motion (rotation about the top and translation) either away (A) or towards (P) the backfill. Figure 2 represents the most general conditions of failure of retaining structures. In the figure, "s" is the mean wall displacement, which is given by the following relationship.

$$s/H = (0.5+\alpha)\sin\theta \qquad (1)$$

Here α represents a factor whose value determines the kind of motion the structure will undergo. In the present study the value of α was taken to be equal to 0.36 representing a rocking motion.

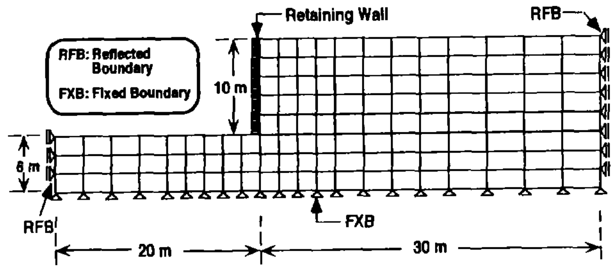

Fig. 1. Finite element model of the wall and the backfill

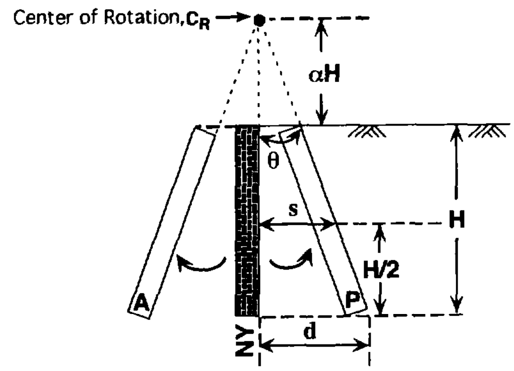

Fig. 2. Wall deformation conditions

The rocking motion represents the field situation of failures of many retaining structures (e.g. bridge abutment, anchored bulkhead etc). This motion is adopted in simulation because the stability of a particular wall is generally reduced by an increase in active thrust and/or a decrease in passive thrust. The lack of passive resistance may be attributed to many failures of retaining walls and seismic motion reduces the available passive resistance.

Two kinds of dynamic motion were used as the input acceleration in the analysis: (1) a pure sinusoidal motion and (2) the recorded earthquake motion of the Hyogo-ken Nanbu earthquake. Figure 3 shows the N-S component of the strong motion records at Port Island Borehole Array Observation Station (Department of Urban Development, Kobe City). Even though at different depth different directional components of accelerations were reported, in this research only the N-S component was adopted for analyses.

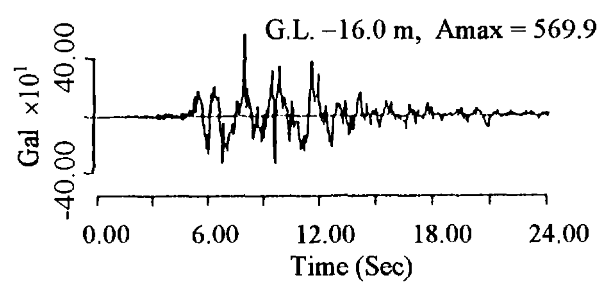

Fig. 3. Acceleration time history

The applied sinusoidal record has a peak acceleration of 200 gals and a frequency of 3.5 Hz. The earthquake motion represented in Fig. 3 was scaled to this value to be used as the input acceleration.

Analysis Procedures and the Materials Parameters

The finite element analyses were performed using the Wilson-θ method (θ = 1.4) using a time step of 0.01 second. Rayleigh damping (α = 0 and β = 0.005) was adopted to ensure stability of the numerical process. The reflected and fixed boundaries of the finite element domain were simulated by viscous dampers to ensure smooth transmission of the seismic wave at the domain boundaries. A localization based material constitutive law (Hazarika and Matsuzawa, 1997) was used for the sandy backfill.

At first analyses were performed using the sandy backfill alone. By determining the failure zone of the finite element model described above, the zone is substituted by EPS geofoam and the analyses were repeated. The interface data for such soil-structure interaction system under seismic loading condition is not widely available. The interface of such a composite wall-backfill system was modeled to the best extent possible by using the available data on the interface. Elasto-plastic constitutive model (Matsuzawa and Hazarika, 1996) based on Drucker-Prager theory was used for simulating the non-linear stress-strain behavior of the EPS geofoam. The constitutive parameters for the EPS geofoam of the specified density were determined from the laboratory tests on unconfined compressive strength and the interface reported in Hazarika (2000). The material parameters values used in the simulation are listed in the Table 3 below.

Table 3: Summary of Materials Parameters

Parameters	**Sand Backfill**	**Geofoam Backfill**
Young's Modulus, E	2.6×10^4 kPa	-
Initial Tangent Modulus, E_t	-	4400 kPa
Poisson Ratio, ν	0.3	0.11
Unit Weight, γ	16 kN/m^3	0.196kN/ m^3
Peak Friction Angle, ϕ_p	40^0	-

SIMULATION RESULTS

The numerical results obtained from the simulations were summarized in the following subsections. At first, the simulations using the sinusoidal motion are described followed by the actual earthquake time history.

Sandy Backfill

Failure Characteristics. Figures 4(a)~(c) show the failure zone predicted by the simulation at the critical state of the backfill. The mean wall displacement, s, required to achieve the respective critical state are also shown in the figures. It can be observed that the failure zone for the dynamic loading is the intermediate between the static passive (with the largest domain) and the static active (with the smallest domain). Now these unstable failure domains can be substituted by lightweight EPS geofoam.

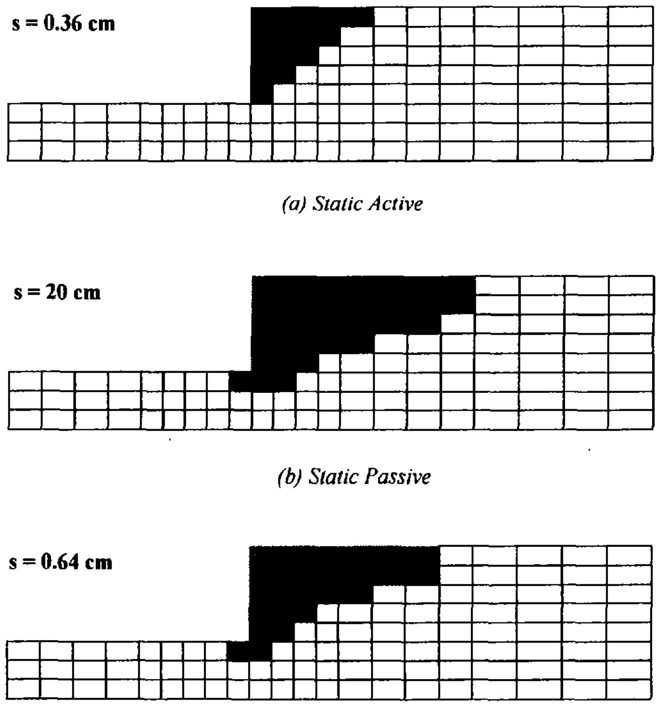

Fig. 4. Failure domains predicted by the analyses

Seismic Pressure. Before observing the resulting pressure using such geofoam, it is important to see how the pressure develops along the wall height for the three cases described. The distribution of the seismic earth pressures acting on the wall at the maximum inertia force is shown in Fig. 5. The figure depicts a picture in which the non-yielding wall experiences loading intermediate between the active and the passive mode, and the distribution pattern depends on the wall deformation pattern during the seismic loading.

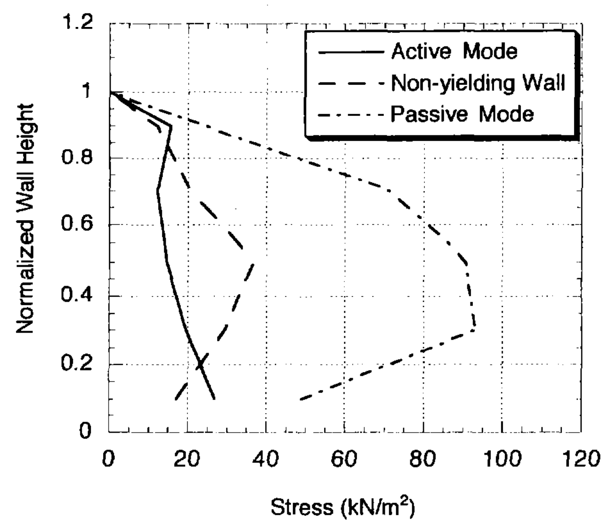

Fig. 5. Seismic thrust from the soil backfill

Composite Backfill with EPS

Similar to those shown in Fig. 4, the failure domain at the maximum inertia force is determined in each case (active, non-yielding and passive) of wall deformations. The sandy backfill is then substituted with EPS geofoam. However, from the economics point of view, only the predicted failure domain needs to be substituted as shown in Fig. 6. Therefore, proper constitutive model to capture the progressive deformation of the backfill need to be adopted for such analyses in order to avoid the underestimation or overestimation of the failure domain. In actual construction, a concrete slab is placed at the top of the EPS structure because EPS blocks are light in weight. In the analyses, this condition was simulated by applying equivalent nodal forces at each node of the free upper boundary.

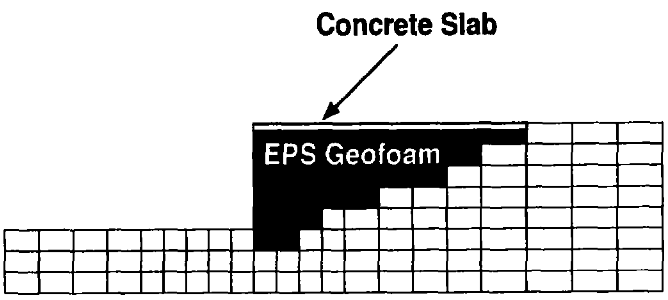

Fig. 6. Geofoam Substituted backfill

Figure 7 shows the resulting earth pressure acting on the wall in the case of the composite backfill condition shown in Fig 6. Comparing with Fig. 5, it is clear that there is a considerable reduction (more than 50%) of the earth pressure by the use of the EPS geofoam. It should also be noted that the seismic pressure on the non-yielding wall is intermediate between the active and passive for both with and without geofoam substituted backfill.

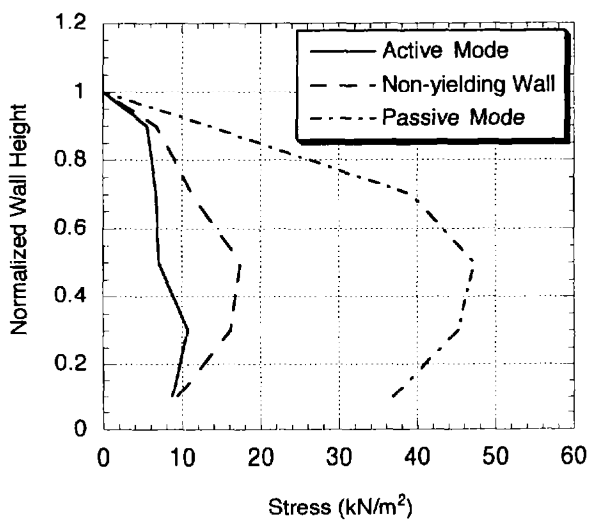

Fig. 7. Seismic thrust resulting from EPS substituted backfill

Calculation for the actual earthquake motion

Figure 8 shows the results of the analysis for the same finite element model (Fig. 1), when instead of the sinusoidal motion, the actual earthquake motion recorded during the Hyogo-ken Nanbu earthquake was applied to the model ground. The time history of the seismic load acting on the wall shows that the use of the geofoam could reduce almost 50% of the load at the peak. There were some irregularities observed in the calculated results. Those could be due to assumed damping properties and the interface data in the analyses.

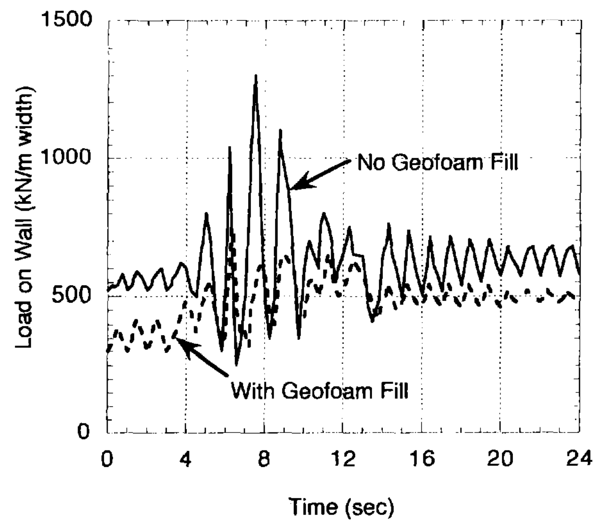

Fig. 8. Lateral seismic load on the wall versus time

SUMMARY AND CONCLUSIONS

The results of the finite element analyses for a rigid retaining wall experiencing earthquake loading demonstrate the need for a proper simulation for determining the backfill behavior of any retaining structure constructed in seismically active areas. When it is required that the excessive deformation of the structure is to be reduced resulting from the seismic thrust, an economic answer can be the substitution of the backfill with low density but high strength EPS geofoam. Such geofoam could reduce the load coming to the structure by almost 50% to 60% then compared to those exerted by the conventional filling materials.

Although the dynamic properties of the EPS geofoam blocks have been firmly established, from the analysis point of view they are not sufficient to simulate the field problems. As in the other soil-structure interaction problems, the interface between the geofoam and the structure as well as between the geofoam and the soil play an important role in the outcome of the final analyses. Research results on the cyclic behavior of these interfaces could greatly enhance the scope of application of this lightweight material in the earth pressure reduction.

ACKNOWLEDGEMENT

The first author gratefully acknowledges the financial support for this research from the Internal Research Grant for Feasibility study of Maizuru National College of Technology, Kyoto, Japan.

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