

NUMERICAL MODELING OF A SOIL-STRUCTURE-EPS SYSTEM

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ABSTRACT

The role of EPS (Expanded Polystyrene) as an innovative construction material in the construction of modern infrastructures is now well recognized due to its low density, but high compressive and rupture strength. Amongst the many Geotechnical Engineering applications the usage of this geofoam product as substitute in the backfill of retaining structures is gaining wide recognition. When EPS is used behind a structure, the structure interacts with the backfill soil via the EPS blocks. This kind of interaction gives birth to a hybrid interactive system, which needs to be modeled properly for the design and analysis of the structure. In this paper, a numerical model is described that can treat such a soil-structure interaction system.

Recognizing the fact that there is always a thin layer of interface that participates in the interaction process, a new hybrid interface model was developed. While the interface was assumed to be in elasto-plastic in behavior, the EPS geofoam constitutive relation was formulated using an elasto-plastic hardening constitutive relationship. The soil backfill was modeled assuming it as the elasto-plastic-hardening-softening material. The model was validated by conducting a numerical experiment on a rigid retaining structure.

KEYWORDS: EPS Geofoam, Hybrid Interactive System, Interface, Numerical Model, Retaining Structure, Seismic Thrust, Soil-Structure Interaction.

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INTRODUCTION

EPS is increasingly used nowadays, in various Civil Engineering construction projects, in many countries around the globe. In countries like Japan, where construction on weak soils is inevitable, use of EPS in the construction of modern infrastructure has been in steady increase over the last decade. Low density (one hundredth of the normal earth filling) EPS has high compressibility and rupture strength to support loads encountered in many applications, including loads from motor vehicles, aircrafts and trains. Compared to the other soil improvement methods, EPS construction method has several merits such as the light weight and self-standing characteristics of the material, ease in handling and shorter construction time during the project execution, etc. Thus, this material can serve as a key element of a cost-effective design alternative in many Geotechnical Engineering applications (embankments, retaining structure, slope stabilization, bridge abutments, etc.).

Geotechnical engineers in many cases need to deal with retaining structures that either have to undergo considerable deformation in order to reduce the forces close to the one used for design or have to withstand enormous pressure to maintain the deformation within the tolerable limit. However, both involve extra structural costs in design. In such situations, to achieve a cost effective design, one alternative can be the use of lightweight EPS geofoam, which when used as substitute backfill (Fig. 1) can significantly reduce the pressures acting on the structures (Negusse and Sun, 1996; Inglis et al, 1996; Hazarika and Nakazawa, 1999). The popularity of such geofoam is also gaining in recent years due to its earthquake resistant properties (Koga et al, 1991) since in earthquake prone areas, beyond the conventional approaches to earthquake disaster mitigation, new strategies need to be developed by utilizing innovative materials that respond intelligently to the external stimuli for the control and protection of civil infrastructure system. In areas where adequate earthquake resistant criteria were not implemented in the design of structures, the excessive deformation or damage to the structures resulting from the increased thrust from the backfill during the earthquake can be mitigated by using EPS geofoam as compressible buffer (Fig. 2). A comprehensive treatment on the compressible inclusion function of EPS can be found in Horvath (1997).

When EPS is used behind a retaining structure, a hybrid type interactive system results involving the backfill soil, the structure and the EPS blocks sandwiching two interfaces as shown in Fig. 3. Numerical analysis of this kind of hybrid interactive system involves modeling of the three different components of the system independently, and implementation by combining them during the simulation. The three required models are: (1) constitutive modeling of EPS geofoam (2) modeling of the two interfaces: (a) between the structure (S) and the geofoam (G), (b) between the geofoam (G) and the backfill (B), and (3) constitutive modeling of the geologic material used as backfill. In this paper, a numerical model is proposed for the simulation of such hybrid interactive system (S-G-B).

Many large-scale projects worldwide where EPS has been used so far resorted to full-scale numerical analyses using rigorous FEM, FDM or DEM technique or such other numerical tools, prior to the execution of the project. However, the project reports lack an adequate description of the constitutive law of EPS geofoam and the interface model used in such analyses. This research attempts to model numerically such hybrid interaction system paying special attention to the interfaces of the dissimilar media (Fig. 3). A new interface model is developed that can realistically simulate the behavior of the system comprising of the structure, the EPS geofoam and the backfill sand. A non-linear constitutive law developed by the authors (Hazarika & Okuzono, 2002) was utilized for simulating the behavior of the EPS blocks during the deformation. The adjacent geologic material (granular in most cases) was modeled utilizing the CSB model proposed by Hazarika and Matsuzawa (1997) based on the shear band bifurcation theory, as the granular backfill is more likely to undergo shear band bifurcation at the large deformation.

A numerical experiment was conducted using the proposed numerical model on a retaining wall of 10 m height and an embedment depth of 3m. The effectiveness of the model is demonstrated by comparing the earth pressure reducing effect of the geofoam.

SYSTEM MODELING

As explained earlier, when EPS is used behind a structure a hybrid interactive system is generated. In such a situation, apart from modeling the stress-strain response of the backfill material and the EPS geofoam, the more important is to how to model the two interfaces that such a hybrid system gives birth to. The modeling of the

interface in such cases plays an important role in the ultimate results of the analyses. Many studies on interface properties are in progress in recent years (Sheeley, 2000; Sheeley and Negussey, 2000). However, development of a numerical tool treating such interfaces is still lagging behind. The interface that results due to sandwiched EPS blocks between the retaining wall and the backfill material exhibits a different picture than those interfaces where the backfill soil is in direct contact with the surface of the retaining structure with which it interacts. Due to non-uniformity of such surfaces and also due to difficulties of fixities between the blocks and the structure, the *Thin Layer Interface Model* (Desai et al, 1984) is more justifiable than the conventional interface element with zero thickness. This research took that factor into the consideration in modeling the interfaces. In the subsections that follow, the theoretical background of the modeling process is discussed in detail.

Interface Model

The two interfaces of the hybrid interactive system can be represented as shown in Fig. 4. The interface I and the Interface II are having the thickness t_1 and t_2 respectively. In general t_1 and t_2 may not be equal, and need to be determined by performing parametric studies for the problem at hand. However, in this research, for simplicity the thickness is assumed to be the same.

The constitutive relationship for such thin layer interface elements can be written in the following form:

$$\{\Delta\sigma\} = [C]\{\Delta\varepsilon\} \quad (1)$$

Here $\{\Delta\sigma\}$ is the vector of increment of the stress component and $\{\Delta\varepsilon\}$ is the vector of increment of the strain component at the thin interface element. Assuming that the normal and the shear components are uncoupled, the constitutive matrix $[C]$ is given by the following equation.

$$[C] = \begin{bmatrix} [C_n] & [0] \\ [0] & [C_s] \end{bmatrix} \quad (2)$$

Here, $[C_n]$ is the portion related to the normal behavior of the interface, and is determined from the appropriate parameters for the thin element. $[C_s]$ is the portion related to the shear behavior of the thin interface zone (thickness = t), which is essentially dependent on the shear modulus given by the following equation based on the direct shear test, where σ_n is the normal stress, τ is the shear stress, and u is the relative displacement.

$$G(\sigma_n, \tau, u) = \frac{d[\tau(\sigma_n, u)]}{du} \times t \quad (3)$$

Fig. 5 shows the conceptual representation of the model, which consists of two interfaces resulting in two interactive systems represented as the system I and system II respectively. The corresponding stiffnesses of the systems are shown in the figure. The stiffnesses of the two interfaces are given by the following equations.

$$[K]_{int I} = [K_n]_{int I} + [K_s]_{int I} \quad (4)$$

$$[K]_{int II} = [K_n]_{int II} + [K_s]_{int II} \quad (5)$$

Here $[K_n]_{int I}$ and $[K_n]_{int II}$ are the stiffness matrices of the normal direction of the Interface I and Interface II respectively, and they can be represented in the form given in Equations (6) and (7). $[K_s]_{int I}$ and $[K_s]_{int II}$ are the shear components of the stiffness of the two interfaces.

$$[\bar{K}_n]_{\text{int I}} = \alpha_1 [K_n]_{\text{int I}} + \alpha_2 [K_n^G] + \alpha_3 [K_n^S] \quad (6)$$

$$[\bar{K}_n]_{\text{int II}} = \beta_1 [K_n]_{\text{int II}} + \beta_2 [K_n^B] + \beta_3 [K_n^G] \quad (7)$$

In the above equations, K_n^S , K_n^G and K_n^B represents the stiffness of the structure, geofoam and the backfill in the normal direction respectively. α_1 , α_2 and α_3 are the participation factors coming from the interface I and β_1 , β_2 and β_3 are the participation factors coming from the interface II, satisfying the following relationship.

$$\alpha_1 + \alpha_2 + \alpha_3 = \beta_1 + \beta_2 + \beta_3 = 1.0 \quad (8)$$

It is to be noted that the interactive systems shown in the Fig. 5 are uncoupled. Hence they have to be solved independent of each other. The influence zones of each media at the interfaces are $t_1/2$ and $t_2/2$. If the geofoam is not present, then the interface thickness becomes equal to t as in that case $t_1 = t_2 = t$. The stiffness of such a single interactive system will be given by:

$$[K]_{\text{Sys}} = [K]_{\text{int}} + [K]_S + [K]_B \quad (9)$$

The constitutive model is assumed to be bi-linear elasto-plastic obeying the Mohr-Coulomb failure criterion.

Constitutive Model of the Composite Backfill

As represented in Fig. 3, the hybrid system constitutes a composite backfill comprising of the EPS and the granular filling material. Numerical solution of such a system also requires the constitutive relationships for these two different materials, which behave differently under the compressive loading they experiences. At the large deformation, the geologic material is more likely to undergo shear band localization. Therefore, that part of the backfill was modeled using the Coupled Shear Band Model (Hazarika and Matsuzawa, 1997), which can capture the progressive deformation of such materials. As for the constitutive relationship of the EPS geofoam, a non-linear plasticity based constitutive model was used. The detail description of the model can be found at Hazarika and Okuzono (2002).

NUMERICAL SIMULATION

The developed hybrid interactive model was applied to analyze a retaining wall-backfill system subjected to seismic motion. Two-dimensional finite element representation of the analysis model with a 10m high retaining wall supporting a dry granular backfill and embedment depth of 3m is shown in Fig. 6. Analyses were performed by simulating two conditions of movement (non-yielding and yielding) of the wall-backfill system. In one case, the wall was restrained representing the condition of non-yielding (NY) wall. In the case of the yielding, the wall had a rocking motion (rotation about its top and horizontal translation) either away or towards the backfill simulating the active mode (YA) and the passive mode (YP) respectively (Fig. 7). The rocking motion represents the common failure condition of many retaining structures (e.g. bridge abutment, anchored bulkhead etc). This motion is adopted in the simulation because the stability of a particular structure is generally reduced by an increase in active thrust and/or a decrease in passive thrust under seismic motion. The parameter α , which determines the modes of movement of the structure, was taken to be 0.36. The input dynamic motion was of pure sinusoidal type with a peak acceleration of 200 gals and a frequency of 3.5 Hz.

The Wilson- θ method ($\theta = 1.4$) was used in the analyses with a time stepping of 0.01 second. Rayleigh damping ($\alpha = 0$ and $\beta = 0.005$) was adopted to ensure stability of the numerical process. The reflected and fixed boundaries of the domain were simulated by viscous dampers in order to ensure that smooth transmission of the seismic wave takes place at the domain boundaries.

Initially analyses were performed with only the sandy backfill behind the structure. By examining the deformation pattern of the ground model, a thin compressible layer of EPS is placed behind the wall, and the analyses were repeated. The values of the various material parameters used in the simulation are listed in the Table 1. The parameters of the interfaces were determined from the data based on the extensive tests performed on various interfaces (Sheeley, 2000). The thickness of the interface element was taken to be 0.05 times the dimension of the adjacent finite element. The following values of the participation factors (appeared in Eq. 8) are adopted: $\alpha_1 = \beta_1 = 0.75$; $\alpha_2 = \beta_2 = 0.25$; $\alpha_3 = \beta_3 = 0.0$.

SIMULATION RESULTS

The state of deformation of the backfill predicted by the simulation at the critical state in the case of the non-yielding wall was first determined. The failure zone resulting from the dynamic loading is the intermediate between the static active (with the smallest domain) and the static passive (with the largest domain), which has been confirmed by previous work (Hazarika et al, 2001) for a model retaining wall.

When the high deformation and the consequent thrust on the non-yielding wall is to be reduced, conventionally, the unstable failure domain is substituted by lightweight EPS geofoam as explained in Fig. 1. However, in this research, the compressible inclusion approach as illustrated in Fig. 2 was adopted along with the interface model represented in Figs. 4 & 5. A thin layer of EPS (thickness 1m) was placed behind the model wall of Fig. 6, and new analyses were performed for this composite backfill (EPS + Sand).

The development of the seismic pressure along the wall height for the three cases of wall deformation modes (i.e. non-yielding, active and passive) is an indicative parameter of the progressive deformation that takes place in the backfill. The distributions of these seismic earth pressures on the wall are shown in Figs. 8-10. The distributions shown in those figures are at the moment when the maximum inertia force acts on the wall.

It is clear that more than 40% reduction of the earth pressure could be achieved by utilizing the EPS as compressible buffer. It should also be noted that the seismic pressure on the NY wall is intermediate between the YA and the YP mode for both the sandy as well as the composite backfill. Also, it can be observed that while the NY and the YP conditions show bulging in the middle of the distribution curve in both cases, the YA mode displays no such distinct bulging. This could be attributed to the role of debonding (Desai et al, 1984) at the interface during the seismic loading. During the active mode of the structure, debonding is more likely to occur, and such debonding can be treated only by the interface model described here. It is also interesting to compare the stress distribution pattern of the NY wall (Fig. 8) for the two cases of the backfilling (sandy and composite). It can be seen from the figure that at the upper one fifth of the wall, there is not much difference of the resulting stress for both the sandy and the composite backfill.

SUMMARY AND CONCLUSIONS

The concept of a modeling of hybrid interactive system is described herein that can simulate the system involving interfaces of three dissimilar media (Geologic material, Geofoam and Structure). An ideal retaining structure was analyzed using the proposed model, and the effectiveness of the model was validated through a numerical experiment.

The idea of including a finite thickness of the interface is more realistic for analyzing system comprising of structure, EPS geofoam and the backfill, since there is always a thin layer element, which participates in the interaction behavior. Apart from the improved performances in the prediction of the deformation of the normal and shear components of the interface, such model can also handle the anticipated modes such as debonding and rebonding during the seismic motion. Therefore, the results offered by the present model can be more reliable than those models where the interface is assumed to have zero thickness. EPS properties are not much affected by the confining pressures. Therefore, there is not much logical ground to conduct complicated triaxial tests for developing its constitutive law. The uniaxial compressive testing is sufficient to characterize the constitutive law of such geofoam as confirmed by the results of the numerical model described here.

The proposed numerical model can very well simulate the interaction behavior of hybrid system subjected to the cyclic loading condition. The interface parameters used in this study were based on the static direct shear tests. When accuracy will be the highest priority, the parameters are to be determined from the dynamic testing of the interfaces.

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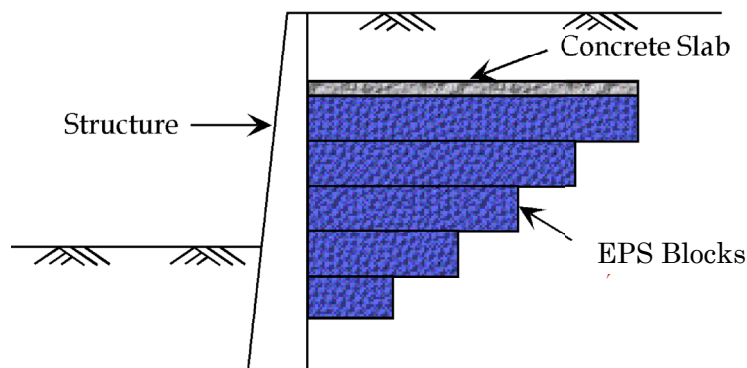


Fig. 1 Conventional usage of EPS as backfill

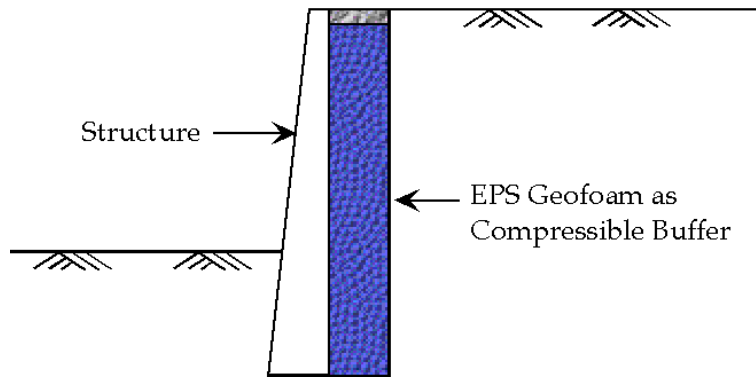


Fig. 2 Compressible buffer approach

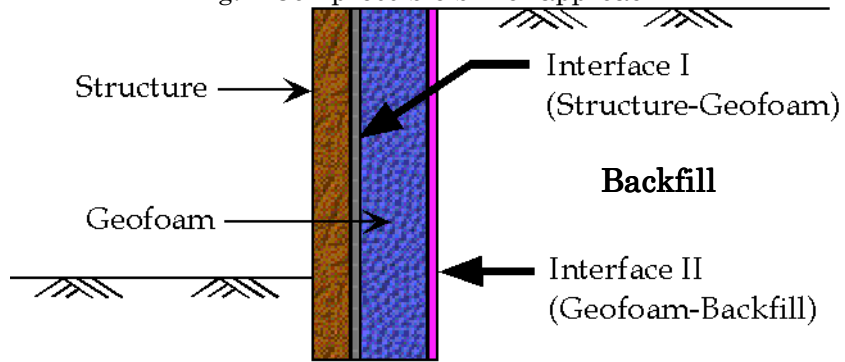


Fig. 3 Interactive system involving the soil, structure and EPS

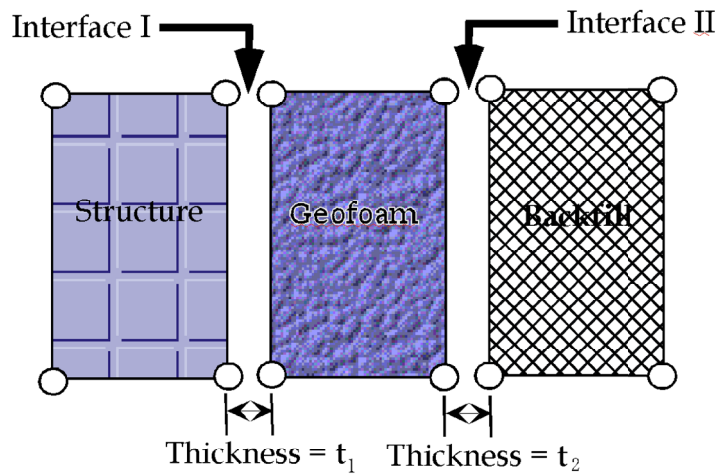


Fig. 4 Interface representation of the hybrid system

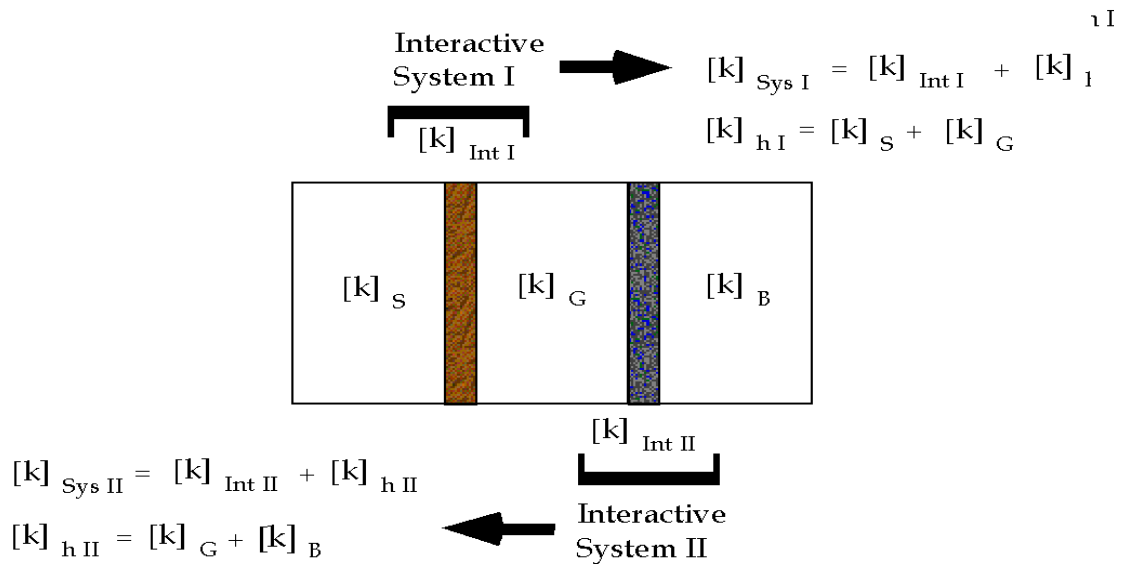


Fig. 5 Interactive model

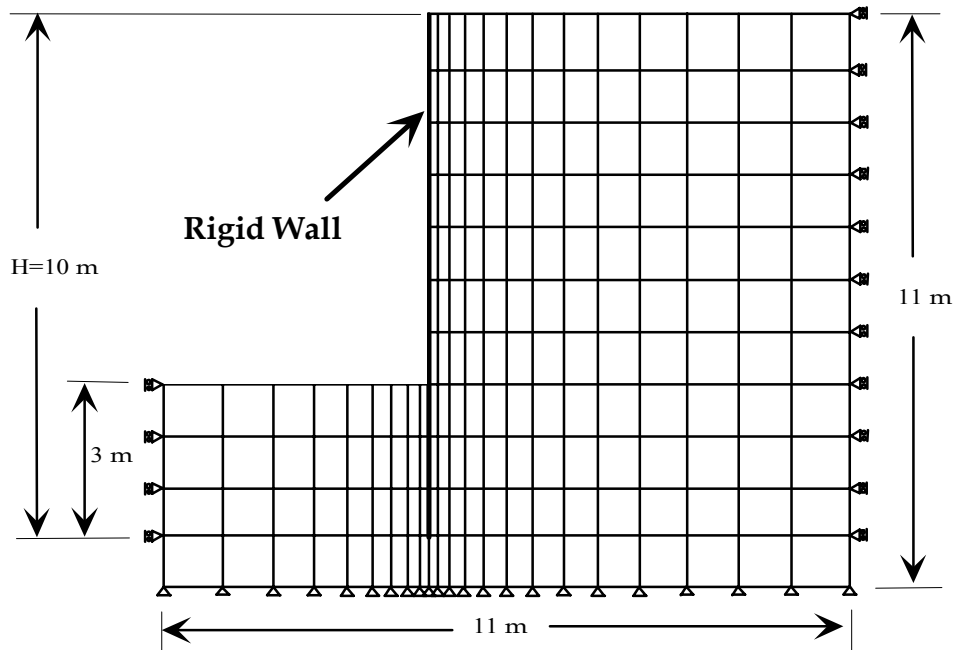


Fig. 6 FEM mesh of the model used in numerical experiment

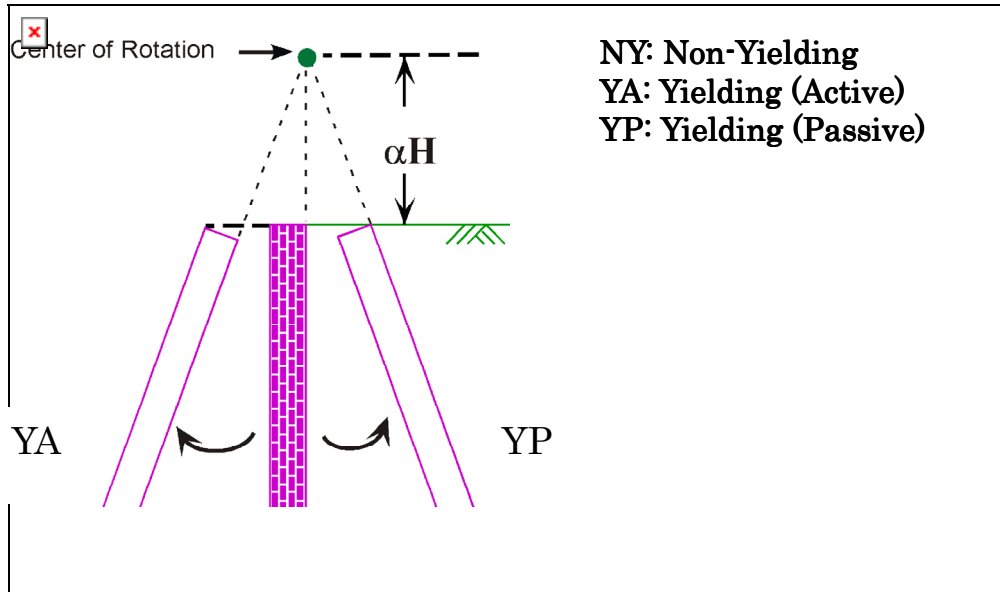


Fig.7 Deformation mode of the structure

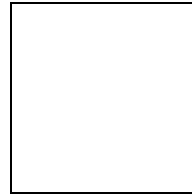


Fig. 8 Stress on the structure (NY mode)

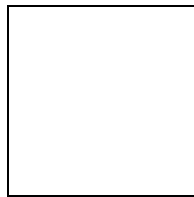


Fig. 9 Stress on the structure (YP mode)

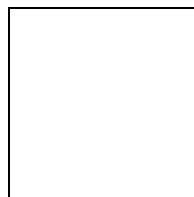


Fig. 10 Stress on the structure (YP mode)

Table 1: Summary of Materials Parameters for the Composite Backfill

Parameters	Sandy fill	EPS Geofom
Young's modulus, E	26 MPa	-
Initial tangent modulus, E_t	-	5.4 MPa
Poisson's ratio, ν	0.3	0.11
Unit weight, γ	16 kN/m ³	0.196 kN/ m ³
Peak friction angle, ϕ_p	40 ⁰	-