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Numerical Investigation on Performance of Expanded Polystyrene Geofoam Block in Protecting Buried Lifeline Structures

M. Abdollahi, S. N. Moghaddas Tafreshi

Abstract**—**Expanded polystyrene (EPS) geofoam is often used in below ground applications in geotechnical engineering. A most recent configuration system implemented in roadways to protect lifelines such as buried pipes, electrical cables and culvert systems could be consisted of two EPS geofoam blocks, "posts" placed on each side of the structure, an EPS block capping, "beam" put atop two posts, and soil cover on the beam. In this configuration, a rectangular void space will be built atop the lifeline. EPS blocks will stand all the imposed vertical forces due to their strength and deformability, thus the lifeline will experience no vertical stress. The present paper describes the results of a numerical study on the post and beam configuration subjected to the static loading. Three-dimensional finite element analysis using ABAQUS software is carried out to investigate the effect of different parameters such as beam thickness, soil thickness over the beam, post height to width ratio, EPS density, and free span between two posts, on the stress distribution and the deflection of the beam. The results show favorable performance of EPS geofoam for protecting sensitive infrastructures.

Keywords**—**Beam, EPS block, numerical analysis, post, stress distribution.

I. Introduction

LIFELINES play vital role in human life. Damage of these infrastructures can result in loss of their performance, thus time and expanses for rebuilding of such structures are considerable. In order to protect these structures, the imposed load on them must be reduced to some consideration.

EPS is a cellular geosynthetic material that can be used in geotechnical engineering applications. The geosynthetic functions of EPS geofoam can be thermal insulation, lightweight fill, compressible inclusion, and small-amplitude wave damping [1]. EPS geofoam was first introduced and used in 1970 in Norway by the Norwegian Public Road Administration (NPRA) to enhance the bearing capacity and to reduce the settlement of soft foundation soil to construct a road atop [2]. Because of its lightweight and compressible inclusion quality [3]-[5], many researchers have investigated the efficiency of EPS materials when used as a soft zone above the pipeline [6]-[8]. This method, known as imperfect trench, reduces the imposed stress on the pipeline due to reverse arching deformation [9]. More recently, another configuration of EPS geofoam block, so called post and beam (e.g. Fig. 1 (a)), was used in a Utah roadway to protect a pipeline from soil severe subsidence and the transferred stresses due to soil settlement [10]. In the post and beam configuration, EPS blocks were placed aside the pipe (posts) and a capping beam was put atop of the posts (beam), therefore the desirable free space above the pipe was achieved. Because of the existing space, the soil could settle without imposing any additional stress to the pipeline. Few researchers have studied this configuration through numerical simulations. Reference [10] simulated the post and beam configuration using a finite difference method and reported the system functionality under traffic load. They used a 2D model to simulate the mentioned configuration and assumed that EPS material would act as elastic material, under imposed strip loading. They found that system would experience stresses which are lower than stresses at 1% strain of blocks. So, they concluded that system would remain in elastic range.

In this paper, a 3D numerical method is utilized through using ABAQUS software to evaluate the system efficiency in protecting lifelines subjected to static load. The effect of various parameters on the soil surface settlement, stress distribution, and deflection of post and beam system is investigated.

II. Numerical Model

The 3D simulation of EPS block of post and beam system and soil cover is performed utilizing the finite element method offered by ABAQUS (6.14.1). It has been assumed that beam thickness, post height to width ratio, free span between two posts, thickness of soil cover, and EPS density play vital role in the system performance. Therefore, the impact of each parameter is investigated through sets of models, each set only one parameter considered variable.

A. Model Geometry

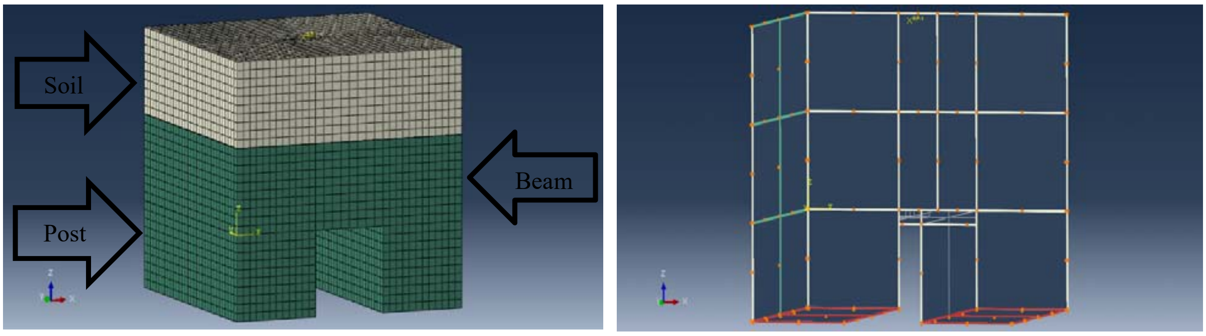
Table I summarizes the model parameters, model geometry, number of elements, and nodes used in the simulations. A mesh type for these models was considered C3D8. The model general display is shown in Fig. 1 (a). The boundary conditions used in the models are shown in Fig. 1 (b). The displacement of outer nodes in X-Z and Y-Z planes was restrained respectively in Y and X directions. The basal nodes were fixed in Z direction.

M. Abdollahi is MSc student at Civil Engineering Department, K. N. Toosi University of Technology, Tehran, Iran (e-mail: masood.abdollahi91@gmail.com).

S. N. Moghaddas Tafreshi is Professor of Geotechnical Eng., Civil Engineering Department, K. N. Toosi University of Technology, Tehran, Iran (e-mail: nas_moghaddas@kntu.ac.ir).

TABLE I
MODEL PROPERTIES

Parameter effect to be studied	model	Key Parameter to be verified	Constant Parameters	Number of elements	Number of nodes
Beam thickness	B40	Beam thickness:40 cm	Soil cover thickness:30 cm Post height to width ratio:1.2 Span length:50 cm Density:20 kg/m^3	32060	37563
	B30	Beam thickness:30 cm		25040	29832
	B25	Beam thickness:25 cm		23048	27714
Soil cover thickness	S30	Soil cover thickness:30 cm	Beam thickness:30 cm Post height to width ratio:1.2 Span length:50cm Density:20 kg/m^3	25040	29832
	S35	Soil cover thickness:35 cm		25624	30366
	S40	Soil cover thickness:40 cm		26556	31359
Post length to width ratio	H/P=1.2	height to width ratio:1.2	Beam thickness:30 cm Soil cover thickness:30 cm Span length:50 cm Density:20 kg/m^3	25040	29832
	H/P=1.4	height to width ratio:1.4		26064	31020
	H/P=1.6	height to width ratio:1.6		26576	31614
Span length	S50	Span length:50 cm	Beam thickness:30 cm Soil cover thickness:30 cm Post height to width ratio:1.2 Density:20 kg/m^3	25040	29832
	S40	Span length:40 cm		26320	31284
	S30	Span length:30 cm		22480	26972
Density	D20	Density:23 kg/m^3	Beam thickness:30 cm Soil cover thickness:30 cm Post height to width ratio:1.2 Span length:50 cm	25040	29832
	D23	Density:23 kg/m^3		25040	29832
	D28	Density:28 kg/m^3		25040	29832



(a) (b)

Fig. 1 3D ABAQUS model: (a) Model mesh, (b) model boundary condition

TABLE II
SOIL PROPERTIES

Description	Values
Cohesion, c	0.5 kPa
Friction angle, ϕ (degree)	38.5°
Elastic modulus	40 MPa
Dilation angle	8.5°
Poisson's Ratio	0.274
Mass Density	17.4 kN/m^3

TABLE III
EPS MATERIAL PROPERTIES

EPS Density (kg/m^3)	Modulus of Elasticity, E (MPa)	Yield stress (kPa)	Plastic Stiffness, E_p (MPa)
20	3.950	98	0.110
23	6.880	129.4	0.286
28	9.200	173.6	0.375

B. Material Properties

In all numerical analyses, the frictional-cohesionless soil as cover soil is considered. The soil properties are summarized in Table II. An elastic-perfectly plastic associative Mohr-Coulomb constitutive model is used to simulate the behavior of the soil. Although other constitutive models like Drucker-Prager exist for elastic-plastic behavior, Mohr-Coulomb model seemed to be reasonable in this case.

The EPS material with density of 20 kg/m^3 is used when geometry of model was the case of study. For investigating the effect of density, EPS23 and EPS28 with respected density of 23 kg/m^3 and 28 kg/m^3 were also modeled. EPS stress-strain behavior assumed to be elastic-plastic hardening [11]. The Poisson's ratio of EPS has very little positive value in small strains, then, as strains enlarge, Poisson's ratio becomes virtually zero and then gains negative values [11]. Thus, in this study, due to small strain values in EPS block, the Poisson's ratio of EPS materials was set to zero. Table III summarizes EPS blocks characteristics for the used three different densities.

Cohesive and tangential behavior is introduced for soil cover and EPS beam block interaction. Friction angle and adhesion values for this interface are considered to be 15° and 13 kPa respectively per proposed values by [12] for the interface of EPS20 (and heavier) and sandy soil. Frictional-cohesional behavior is also used for EPS blocks (beam and post blocks) interaction. Friction angle and adhesion values applied for this interface are 28° and 8 kPa respectively based on proposed values by [13]. These values are affecting residual stress and are more critical than the values for peak

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stress.

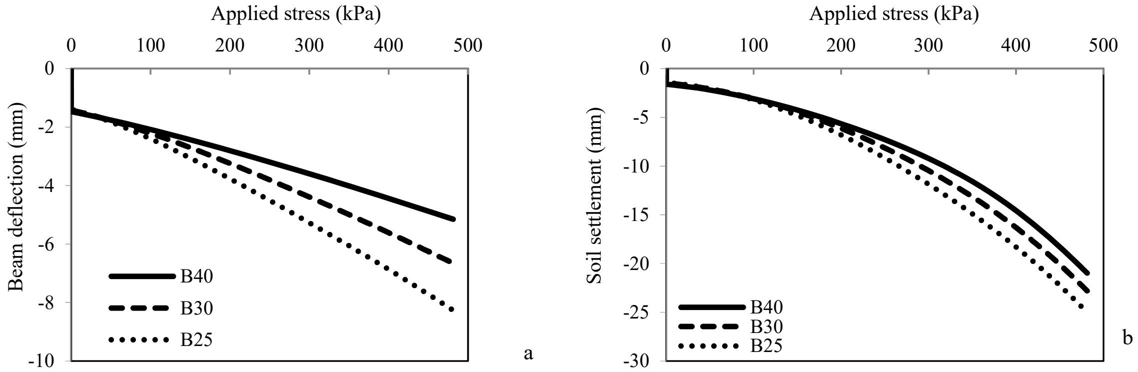


Fig. 2 Effects of beam thickness on deformations in system: (a) beam deflection, (b) soil settlement

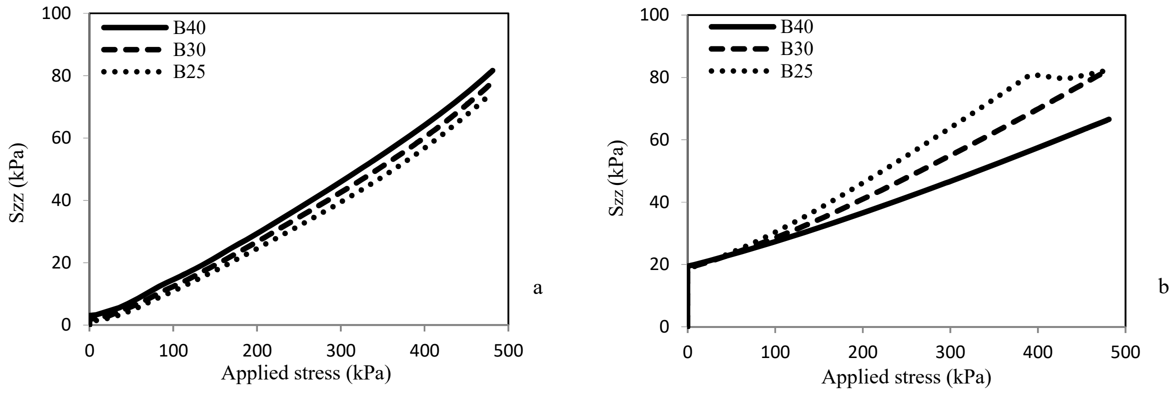


Fig. 3 Effects of beam thickness on stresses in system: (a) beam peak stress, (b) post peak stress

C. Loading

Vertical load with amount of 8500 N is imposed on a circular rigid plate with 15 cm diameter and 2 cm thickness. The load is assumed to be static and is imposed on the model during 5s. It was seen that load durations more than 5s had no effect on the final results.

III. Results and Discussion

In the present numerical study, eight models are analyzed to evaluate the effect of beam thickness, post height to width ratio, free span between posts, soil cover thickness and EPS block density (as detailed in Table I) on the beam deflection, soil settlement and stress distribution of the simulated EPS system. The results of each model are as follow.

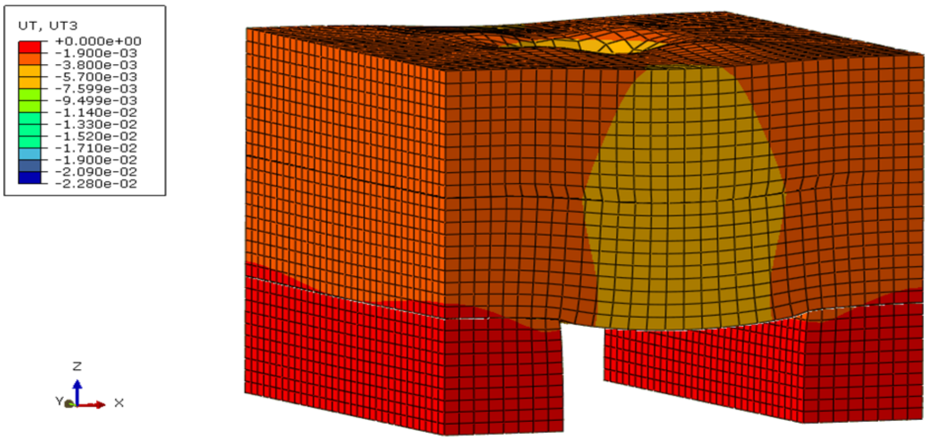
A. Effect of Beam Thickness

Fig. 2 shows the effect of beam thickness on different output parameters. Figs. 2 (a) and (b) indicate that with increase in beam thickness, the soil settlement and beam deflection decrease. Also, the results in Fig. 3 (a) show as the beam thickness increases, the peak stress in beam increases. This behavior could be attributed to the increase in rigidity of EPS beam block as its thickness enlarges. The variation of peak stress in posts with beam thickness in Fig. 3 (b) shows that the use of a greater beam thickness could distribute the load in a greater region, thus the transferred stress to the posts becomes less. It should be noted that the initial values in the diagrams relate to the first phase in which the system reaches the equilibrium under its own weight.

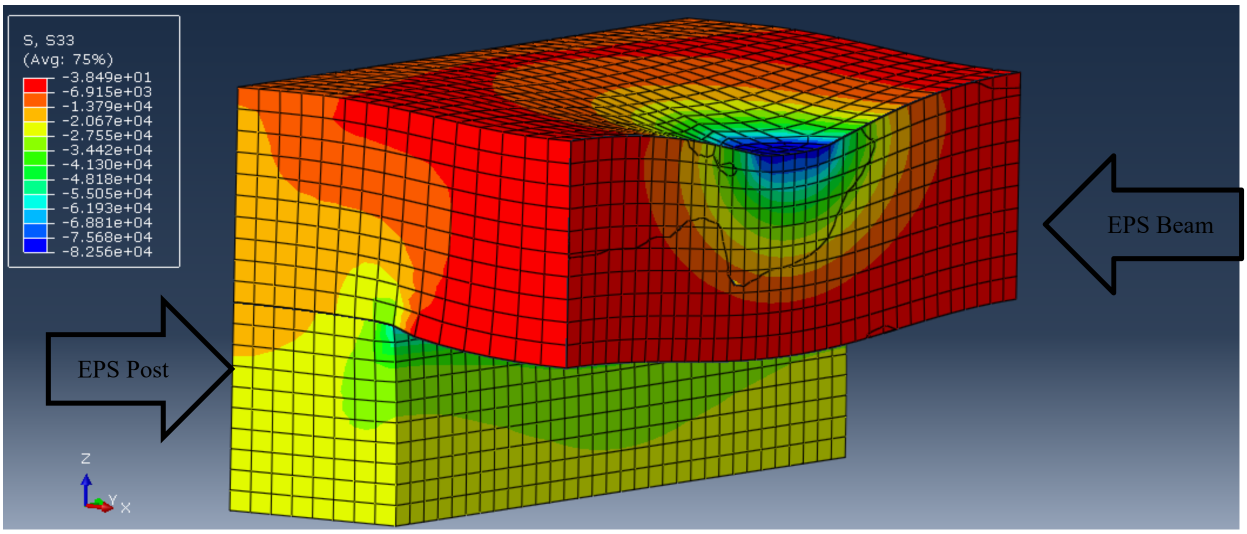
Fig. 4 shows the system deflection and stress distribution in model B30. As seen in Fig. 4 (a), deflections in EPS beam and EPS posts are small (about 6.5 mm deflection in beam) to the system dimensions and thus the EPS material could be considered in its elastic range. Fig. 4 (b) shows the maximum vertical stresses that develop in the EPS beam and EPS posts are about 82.6 and 62.2 kPa, respectively. These values are within the acceptable limits for EPS with density of 20 kg/m3 and are less than the bearing stress at 2% strain obtained of uniaxial tests by [11]. Thus, it implies that no overstressing of the EPS would be appeared under applied load on soil surface. It could be concluded that the EPS posts and beam configuration can prove to function successfully to provide support if used in lifelines protection.

B. Effect of Soil Thickness

Soil cover on the EPS beam plays a major role in distributing the imposed load and thus the transferred stress to EPS beam. As shown in Fig. 5 (b), soil settlement decreases due to increase in the soil cover thickness. As the soil cover thickness increases, the EPS beam moves to be out of the zone where it can most successfully interrupt the applied stress and the soil settlement decreases. It could be anticipated that, with the increase in the soil cover, the EPS system might lie almost entirely outside of the influenced zone of the applied stress on loading plate and the effect of EPS system becomes completely negligible, and the behavior approaches to that of a system with no EPS. As seen in Fig. 5 (a), beam deflection values decrease due to increase in the soil cover thickness. The results in Figs. 6 (a) and (b) show that an increase in soil thickness has noticeable effect in reducing transferred stress to the beam and posts. It could be easily anticipated due to decrease in transferred pressure on the beam surface by applied pressure on plate loading, with the increase in the soil thickness.



(a)



(b)

Fig. 4 Contours for post and beam system: (a) displacement contours in whole system, (b) vertical stress contours in beam and post (cross section)

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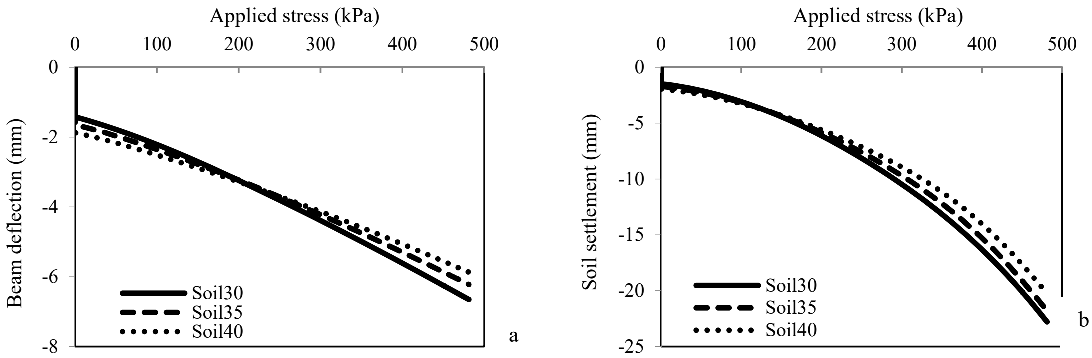

Fig. 5 Effect of soil thickness on deformations in system: (a) beam deflection, b) soil settlement

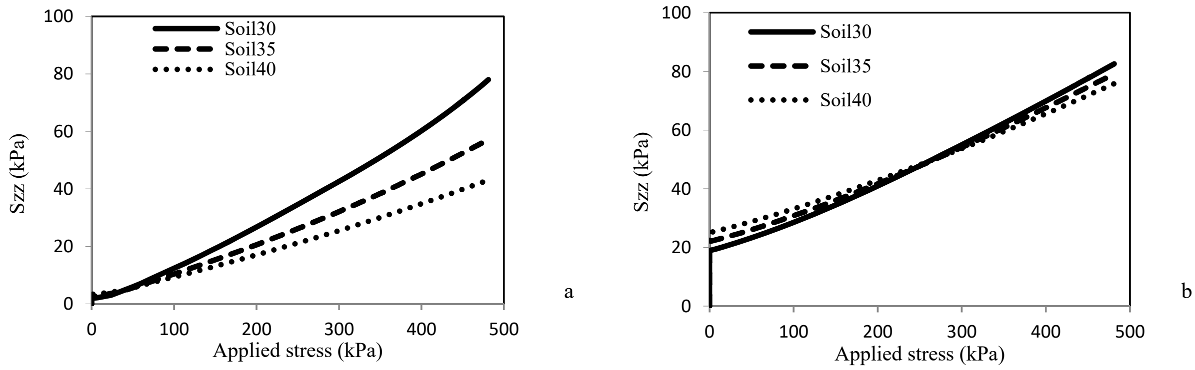

Fig. 6 Effect of soil thickness on stresses in system: a) beam peak stress, (b) post peak stress

C. Effect of Span Length

Figs. 7 (a) and (b) show decreasing soil subsidence and beam deflection, respectively with decrease in the span length (distance between two posts). These can be explained by the fact that the system works as a single frame, thus reducing the span length will create a less critical situation for the beam deflection and as the soil settlement is related to the beam, deformation the subsidence of soil also reduces. Fig. 8 (a) and (b) depict the decrease in span length decreases peak stress in posts but does not cause significant change in beam peak stress.

D. Effect of Post Height to Width Ratio

Fig. 9 (a) shows that, by increasing height to width ratio of the posts, beam deflection increases. But, Fig. 9 (b) and Fig. 10 (a) and (b) illustrates that the post height to width ratio has negligible impact on the soil settlement and peak stresses in either beam or post. This can be explained by the fact that two posts just play a simple support role for the beam, and so, alteration in their dimensions does not make tangible differences in peak stress. Thus, no change in height to width ratio of the posts is recommended.

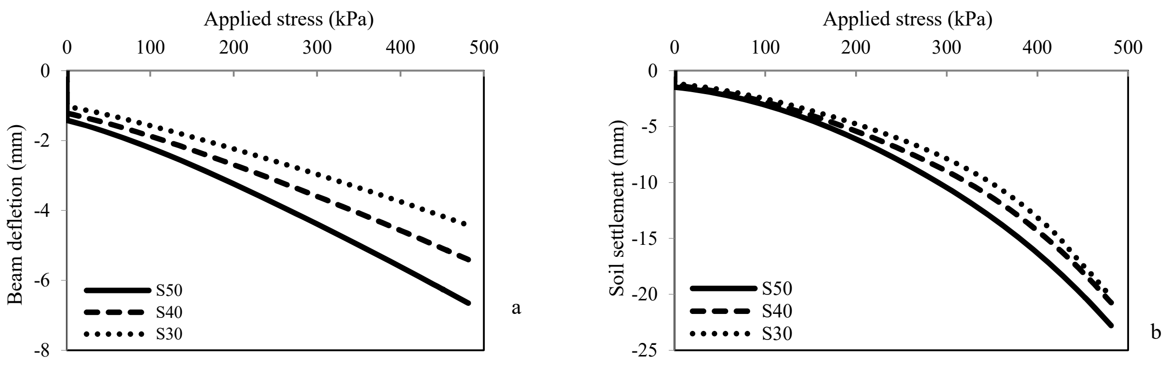

Fig. 7 Effect of span length on deformations in system: (a) beam deflection, (b) soil settlement

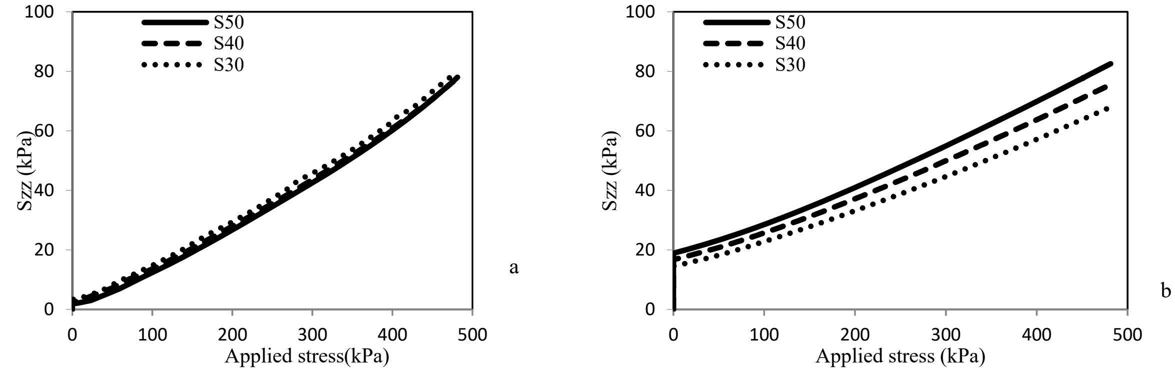

Fig. 8 Effect of span length on stresses in system: (a) beam peak stress, (b) post peak stress

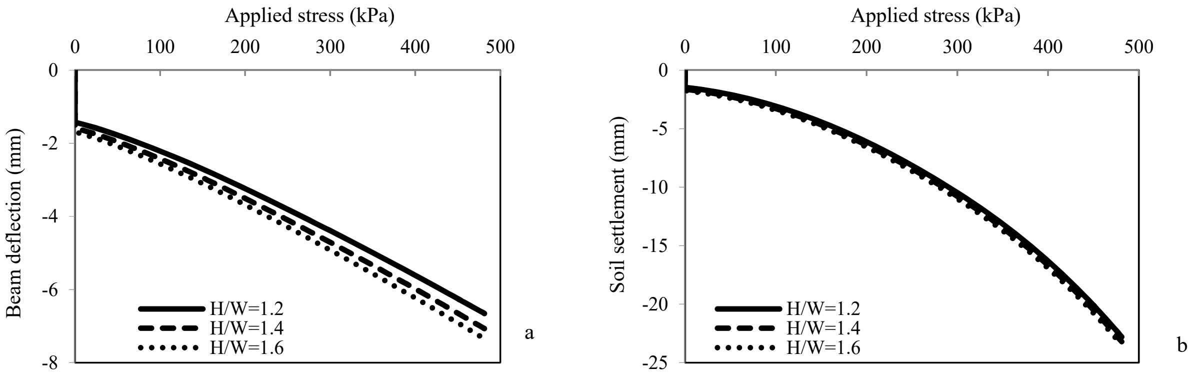

Fig. 9 Effect of post height to width ratio on deformations in system: (a) beam deflection, (b) soil settlement

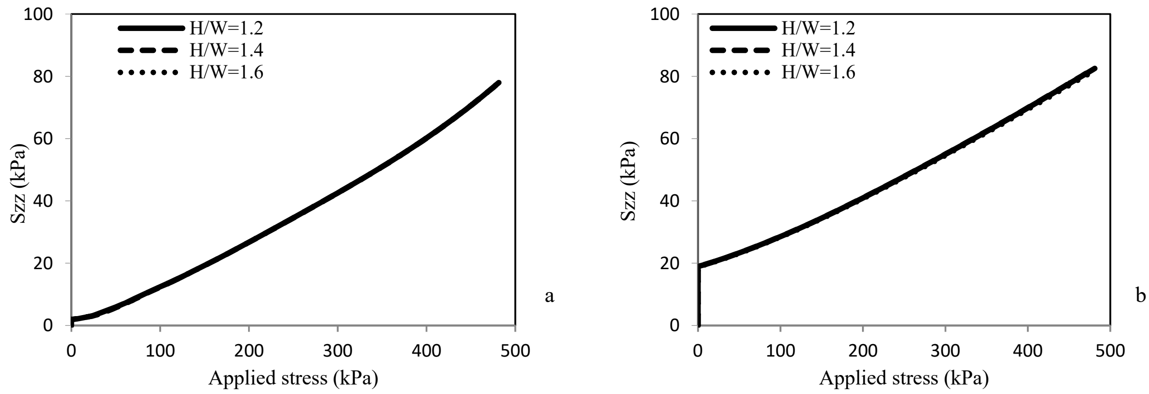

Fig. 10 Effect of post height to width ratio on stresses in system: (a) beam peak stress, (b) post peak stress

E. Effect of Density

Figs. 11 and 12 show the effect of EPS density on the behavior of the system. From Figs. 11 (a) and (b), it is obvious that higher EPS density significantly lowers beam deflection and soil settlement. It can be explained that higher modulus of elasticity of heavier EPS (higher density) causes them to experience less deformation under same stress as compared with lighter blocks. Thus, less deflection in EPS blocks results the lower settlement in soil cover. However, it can be seen in Figs. 12 (a) and (b) that the increase in EPS density has no major effect in peak stresses in posts and beam. It could be attributed to independency of stress with EPS modulus of elasticity.

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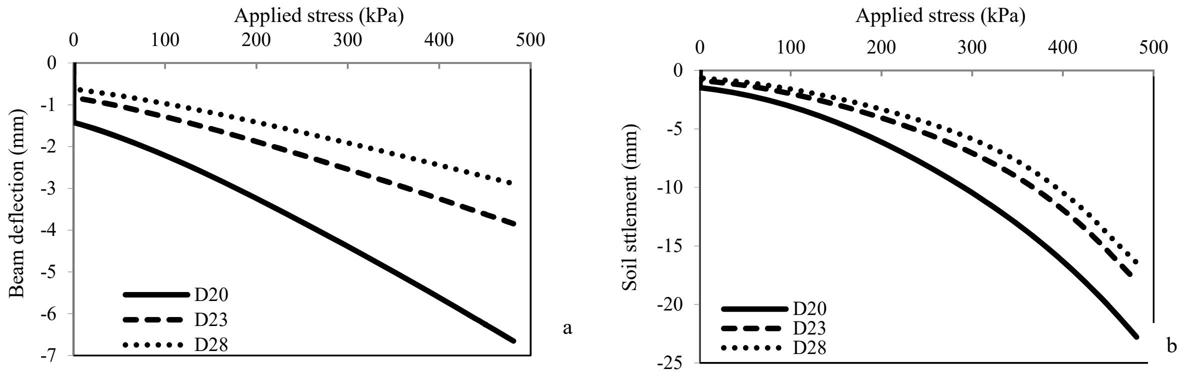

Fig. 11 Effect of EPS density on deformations in system: (a) beam deflection, (b) soil settlement

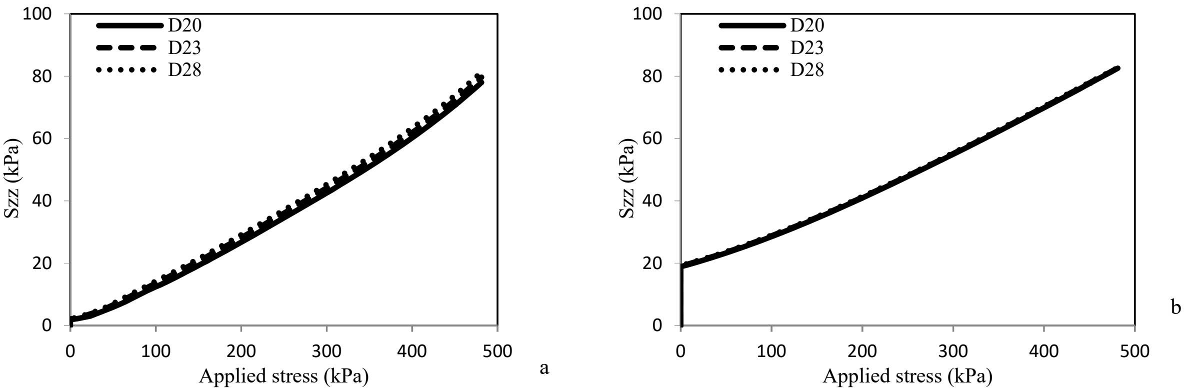

Fig. 12 Effect of EPS density on stresses in system: (a) beam peak stress, (b) post peak stress

IV. Summary and Conclusion

A series of numerical simulations were conducted to evaluate the behavior of EPS post and beam system and its ability in protecting buried lifelines. Through these models, the effect of different parameters on system response such as soil subsidence, beam deflection and stress in post and beam were studied. The summary of results can be drawn as follows:

1. Beam thickness had major impact on stress distribution and deformation of the system. Soil settlement and beam deformation decreased when higher values selected for beam thickness. Also, the peak stress in the beam increases with increase in the beam thickness.
2. Greater soil cover thickness distributed the imposed load in a greater area and thus reduced the peak stress in posts and beam as well as deformations in soil and the beam.
3. As length of span decreased, peak stress in post reduced. However, no sensible difference was seen in beam peak stress. Soil settlement and beam deformation also reduced with lower span.
4. Post height to width ratio had negligible effect on the system performance. As the ratio increased, so did the beam deformation, but no tangible changes were occurred in peak stresses or soil settlement.
5. Higher EPS density gives a lower beam deflection and soil settlement. The EPS density has no major effect in peak stresses in posts and beam.
6. Under the imposed static load and in all simulated conditions, EPS material remained in elastic range. The deformations also were meager in comparison to model dimensions. Thus, it can be inferred that the presented configuration will function efficiently in protecting infrastructures.

Overall, this study provides insight into the basic mechanism that establishes the protecting lifeline system (e.g. pipelines) including EPS beam and post blocks. Therefore, these results could be helpful in designing and simulating model tests and further numerical analysis that could be the subject of future studies.

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