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The Impact of a Thermal Insulation Layer on the Seismic Performance of Energy-Efficient Buildings

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ABSTRACT

Energy-efficient homes are constructed with a continuous and uniform thermal envelope and are commonly built on top of a thermal insulation (TI) layer that encloses the entire building. Lightweight aggregates such as foamed glass aggregate, expanded clay aggregate, and extruded polystyrene (XPS) insulation boards are commonly used as materials for the TI layer to prevent thermal bridging at the ground floor slab. However, the reinforced concrete slab foundation above the TI layer is susceptible to horizontal sliding during seismic loading. To improve the seismic behavior of buildings founded on TI layers, this study discussed the shear stiffness and damping characteristics of lightweight aggregates and three types of XPS boards through laboratory tests available in the literature. A 2-dimensional numerical analysis is performed, and the corresponding validation results of the simulations are presented. The effect of TI layers on the seismic performance of buildings constructed with TI layers made from these materials is assessed. A comparative analysis of various interface conditions of the TI materials under seismic loading is also conducted. Overall, this research aims to enhance the resilience and sustainability of energy-efficient homes by investigating the impact of TI layers on their seismic performance. The findings provide valuable insights for designing more robust structures that can withstand seismic events.

Keywords: energy-efficient buildings, thermal insulation, extruded polystyrene (XPS), finite element analysis, foamed glass aggregate, seismic response

1. INTRODUCTION

The growing need for sustainable construction, green energy transformations, and rapid urbanization led to increased attention towards energy-efficient structures. Thermal insulation systems are proven to be practical solutions. They are used in various civil engineering applications such as tunneling systems (Azinović, Za Gradbeništvo Slovenije, et al., 2014), diaphragm walls(Di Donna et al., 2021), external-wall insulations (Ma et al., 2023), shallow and deep foundations (Kilar & Koren, 2014). Thermal insulation (TI) systems are now often used in modern low-rise buildings for effective energy transformations. These modern buildings, often termed passive houses, are required to maintain constant thermal envelop throughout the buildings. TI should be provided for the installation in this scenario, including the external wall thermal insulations and foundations. These TI layers are considerably soft compared to the conventional foundation systems, and their seismic behaviour is often considered to be different, which can alter the over-building performance during an earthquake (Azinović, Koren, et al., 2014). The foundation systems are provided with TI layers such as thermally insulated aggregates(low-weight aggregates, cellular glass aggregates), TI boards (Cellular glass, Extruded polystyrene (XPS) and Expanded polystyrene (EPS) boards). (Kilar & Koren, 2014) Presented a detailed description of the construction of these foundation systems and their connection with the superstructure (Fig. 1). The low-weight aggregates are seen in recent applications for insulation purposes, settlement reduction, and stability (Lenart & Kaynia, 2019). They presented the dynamic properties under various conditions. These material properties indicate their performance under extreme conditions. In addition, these aggregates are water and frost-resistant. Most of the studies on the TI boards concentrate on material behaviour related to energy efficiency. Some studies are available for EPS boards, such as dynamic test investigations of the compressive creep of the EPS (Gnip et al., 2011; Horvath, 1997). These studies indicate that the EPS boards are not water resistant and have lesser compressive and shear strength properties. The manufacturing changes in EPS with the same base material yield XPS water-resistant material with higher structural strength. Some investigations have been presented for XPS boards with unique applications, such as a vibration isolating screen installed in the soil near a test public transport track. Lenart & Likar, 2019 studied the cyclic behaviour of XPS boards placed on gravel foundations by performing large-scale cyclic direct shear tests. In addition, there are studies related to XPS microstructure, its compression mechanism, and long-term mechanical properties. Past studies (Kilar & Koren, 2014)indicate that the installation of insulation layers under the foundation of a building increases its period of vibration. In addition, the major problem is the rocking phenomena, which might significantly increase the building's horizontal sway and top displacements. In this regard, these TI foundation systems should be extensively studied, and due attention should be given to the horizontal displacement and axial Stress-strain behaviour. These displacements eventually control the transfer of earthquake-induced forces and displacements. The present study focuses on the seismic response of TI foundation systems installed with XPS and low-weight aggregates.

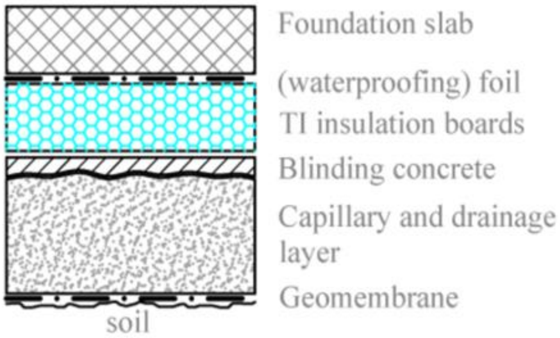


Figure 1 Schematic representation of TI foundation layers obtained from (Kilar & Koren, 2014)

2. Finite Element (FE) Modelling

In the present study, the seismic behaviour of thermal insulated foundation systems for multi-storeyed structures is analyzed. Fig. 2 shows the two-dimensional (2D) plane-strain FE numerical model with the simplified boundary conditions for the TI foundation system considered in this study. For validation and parametric study, the geometry and the material properties of the FE model are adopted from Kilar & Koren, 2014. They carried out the static and dynamic analysis of various multi-storeyed RC framed structures developed in SAP2000. The height of the two-framed RC structure considered in the present study was 12m, constructed on a foundation system with XPS insulation and another with a rigid foundation slab, as shown in Fig.2. The current FE model is developed in ABAQUS version 6.14. The components, such as soil, foundation slab, XPS insulation, and gravel, are modelled using 4-node iso-parametric quadrilateral elements. The RC framed superstructure is modelled using 2-node beam elements. The XPS insulation layer and the concrete foundation are modelled in the present study with a thickness of 0.24m and 0.30m, respectively. The domain and other geometries are consistent with Koren & Kilar, 2014. The underlying soil below the foundation system is modelled using an elasto-plastic model with mohr-colomb behaviour. The soil is assigned unit weight γ = 17.2 kN/m3, Young's modulus E = 50 MPa, peak friction angle ϕ = 38°, dilation angle ψ = 8°, and Poisson's ratio ν = 0.3.

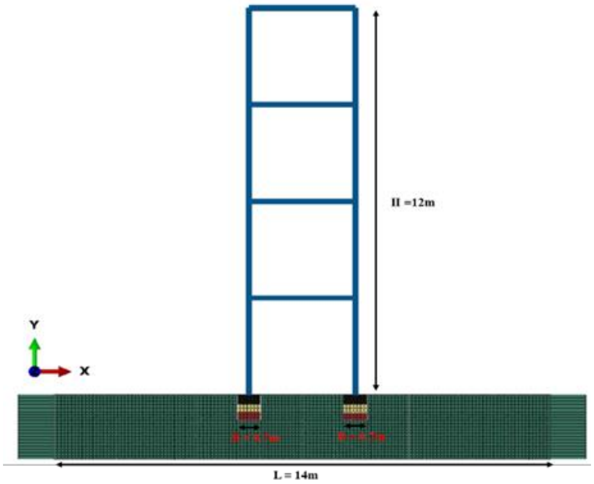


Figure 2 Schematic representation of finite element model

The rigid reinforced foundation slab and XPS insulation are modelled using a linear elastic material model. The material properties of all the materials are summarised in Table 1. Bearing pads are not modelled in this study to keep the FE model simple. The interfaces between soil-foundation slab, XPS-foundation slab, and XPS-soil, using surface-to-surface contacts in Abaqus. These interfaces simulate the relative movements between two bodies in connection. The normal behaviour of the contacts is defined using "Hard contact," while the tangential behaviour is determined using the "Coulomb-friction model."

Table 1 Parameters of the materials used in the present study

Material	Thickness /Height	Density	Friction angle	Dilation angle
Foundation Slab	0.3m	30kN/m3		
Foundation Soil	5m	17kN/m3	38 kPa	8
TI Layer	0.24m	0.5kN/m3		
Gravel	0.26m	20kN/m3	44 kPa	10
RC Frame	12m	30kN/m3		

Material	Type	Youngs Modulus	Poisson ratio
Foundation Slab	RCC	30GPa	0.15
Foundation Soil	Sandy Soil	50MPa	0.3
TI Layer	XPS400	30MPa	0.3
Gravel	-	75MPa	0.3
RC Frame	RCC	30GPa	0.15

3. Boundary Conditions and stage-wise construction

Fig. 2 shows the numerical model used in this study. The base of the domain is fixed in both the x and y directions.

At the same time, the lateral end of the domain is restrained in the horizontal direction while free in the vertical direction in static analysis. The connection between the foundation and column is assigned the "Tie" boundary condition, which implies a rigid relationship. Nonlinear static analysis followed by nonlinear dynamic analysis is performed. The geostatic stress condition is simulated initially to perform an analysis close to the actual state. In this stage, the elements of the foundation system are deactivated. In the second stage, the soil is excavated by deactivating the elements in the foundation region; simultaneously, the elements of the foundation system are activated. In the third stage, the earthquake dynamic load is applied at the base of the model. Time discretization for incremental calculation is small enough to achieve a stable and accurate solution; it is considered 0.002 for the present analysis. The input motion for the present study is adopted from Koren & Kilar, 2014, with two different PGA levels (ag = 0.25g and ag = 0.35g) considered. The selected ground motions were Eurocode 8 (Raoul et al., 2012) spectrum-compatible. The EC8 elastic spectrum for selected soil type (A), scaled to a peak ground acceleration of ag = 0.25g for a 5% damping ratio, was used as a target spectrum. For parametric studies, the input ground motion is scaled from 0.25g to 0.8g with an increment of 0.1g. The ground motion records are corrected by applying the baseline correction.

To reduce the effect of boundaries in the region of interest, left and right vertical boundaries are more than nine (9) times the width of the foundation. In dynamic analysis, the vertical boundaries are modelled as absorbing boundaries (Lysmer and Kuhlemeyer 1969), whereas earthquake excitation is applied horizontally at the base. Frequency extraction analysis is performed to get the predominant frequency and Rayleigh damping coefficients α and β, which are calculated from Eq. (1) and Eq. (2) (Chen et al 2012).

$$\alpha = \frac{2\left(\frac{\zeta_1}{\omega_1} - \frac{\zeta_2}{\omega_2}\right)}{\frac{1}{\omega_1^2} - \frac{1}{\omega_2^2}} \quad (1)$$

$$\beta = \frac{2(\zeta_2\omega_2 - \zeta_1\omega_1)}{\omega_2^2 - \omega_1^2} \quad (2)$$

Where ω1 and ω2 are natural frequencies and ζ1, and ζ2 are damping ratios of the first two modes of vibration. In the present analysis, element size was kept at 0.1 m with an aspect ratio of one.

4. Model Validation

(Koren & Kilar, 2014 had done ample research to identify failure mechanisms of building founded on TI foundation systems. The seismic response of the original structure (4-storey YZ and XZ frames, ag = 0.25g, foundation slab 30 cm, XPS400 of thickness d = 24 cm). The observations from their study indicated that the obtained displacements in most cases do not exceed the limit values chosen equal to 0.33 % of the total building's height (H) and 2.1 % of the thickness of the TI (XPS) layer (d) for lateral roof displacement and XPS compressive deformation, respectively. In Fig. 3 (a) & (b), the obtained typical damage patterns of the conventional and XPS foundation systems are presented with the absolute maximum accelerations measured at different building storey levels. The damage patterns indicate the performance levels of the superstructure.

Further, they ascertained that the obtained damages for the considered ground motions are more prominent in the case of buildings with XPS foundation systems. Moreover, no damage was recorded in the analyzed conventional framed structure in the columns. At the same time, there were some plastic deformations in the column(s) of the first storey of the buildings with XPS foundation systems. The results of the present FE model panels are compared with those discussed above. Fig. 4(a) & (b) shows the lateral damage pattern obtained from the present study and the corresponding peak accelerations at each floor level. In addition, the comparisons of displacements obtained from the earthquake load are summarised in Table 2. The compressive deformations (Negative values) are presented for vertical displacements of the foundation slab. As shown in Table 2, higher seismic intensity induces lateral roof displacements up to two times larger. In contrast, the increase in vertical displacements at the edge of the foundation slab is much smaller. The standard deviations of the calculated roof were up to 35% in the case of ag = 0.25g and up to 50% in the case of ag = 0.35g. The present FE model underestimated lateral displacements at the top floor. However, the ground floor displacements in the present study are higher for the XPS foundation system. This is due to the interface effect of the foundation slab and XPS layer, which was not considered in the previous studies. Further, the differences can be attributed to the soil constitutive model obtained in the present study. However, the differences can be considered insignificant from a practical point of view (Koren & Kilar, 2014).

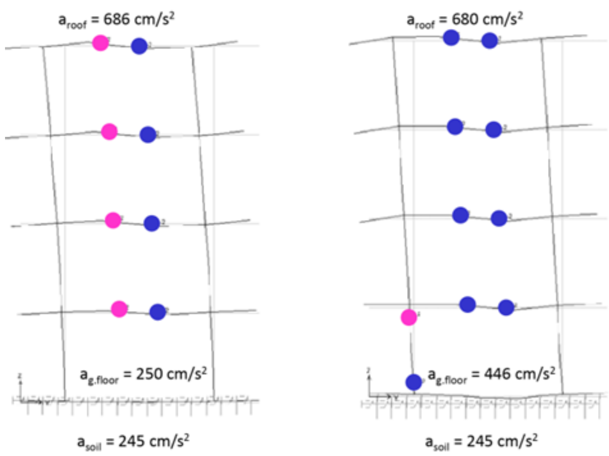


Figure 3 The typical damage pattern and average absolute acceleration values of an RC framed structure at different locations for (a) Conventional foundation system (Fixed base) and (b) TI foundation system with XPS layer obtained from Koren & Kilar, 2014

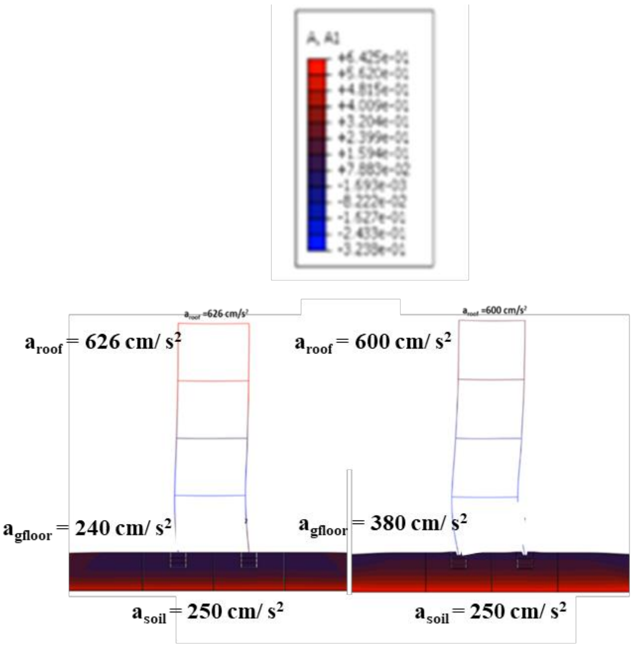


Figure 4 The typical damage pattern and average absolute acceleration values of an RC framed structure at different locations for (a) Conventional foundation system (Fixed base) and (b) TI foundation system with XPS layer from the present study

Table 2 Displacement Response of the structure with two different earthquake intensities

Seismic Intensity			ag =0.25g	ag =0.35g
Top floor Lateral Displacement (mm)	Fixed Base	Koren & Kilar, 2014	1.13	1.86
		Present Study	1.09	1.53
	XPS	Koren & Kilar, 2014	2.09	4.22
		Present Study	1.62	3.98
Ground floor Vertical Displacement (mm)	Fixed Base	Koren & Kilar, 2014	0.017	0.019
		Present Study	0.017	0.018
	XPS	Koren & Kilar, 2014	-0.357	-0.449
		Present Study	-0.85	-1.095

5. Parametric Study

The present validated model is further investigated to study the seismic response of TI-insulated foundation systems. In recent years, TI foundation systems for energy-efficient homes have been extensively constructed on the lightweight gravel support layer in Europe. In the current study, a 0.7m wide and 0.3m thick footing is modelled to represent the foundation slab and seismic loads of different PGA's (0.3g-0.8g) are applied at the base of the domain. These peak ground accelerations are to represent the minimum and maximum earthquake intensities. Fig. 5 depicts the detailed schematic illustration of the foundation system considered in the present study. To illustrate the superstructure load, a uniform surface weight of 1000kN is applied at the top of the foundation slab. This parametric analysis aims to study the impact of seismic loads on the lateral Displacement and shear stress behaviour of insulated foundation systems. As explained earlier, XPS foundation systems generated higher lateral and vertical displacements than conventional foundation systems. This can be attributed to the interface lateral displacements and shear stresses. Hence, in this analysis, Three interface conditions are considered for the study: (1) coefficient of friction is zero (FS interface), (2) coefficient of friction is 0.4 (PS interface), and (3) coefficient of friction is infinity (NS interface). The three interface conditions are chosen because the closed-form solutions exist for FS and NS; however, the actual interface condition PS is between FS and NS, taken as 0.75 for the present analysis, corresponding to a friction angle 38°.

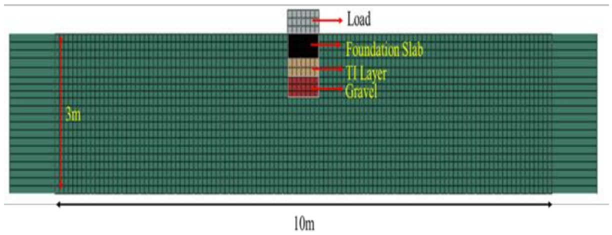


Figure 5 Schematic representation of finite element model used for the parametric study

PGA of ground motion is varied from 0.3 g to 0.8 g with an increment of 0.1 g. The effect of pore water pressure is neglected since the groundwater table is assumed to be 3-5 m below foundation systems. Figure 6(a), (b), (c) presents the contours of vertical stresses, horizontal stresses, and vertical displacement for PGA OF 0.8g at a critical time of 4.5 s for PS interface with an overburden load of 1000kN. Higher displacements are observed at 0.8g due to its intensity. Figure 7(a), (b), and (c) depicts the variation of accelerations, lateral displacements, and shear stresses with time at the interface of the foundation slab and TI layer. The peak shear Stress and Displacement at the critical time are 7.5kPa and 0.004m, respectively. The dynamic response of the foundation system was evaluated based on the shear stresses generated between the foundation slab and soil. The TI-concrete slab interaction condition was assumed to have an NS interface, PS interface, and FS interface. All the stresses are taken corresponding to critical time 4.5 s. Critical time is almost identical for different overburden loads and interface conditions. Displacement transfer from the foundation slab to the TI layer is controlled by the relative stiffness of the TI layer and foundation slab and the interface slip condition. Free field deformation of soil depends on its stiffness; as the soil stiffness increases, the free field deformation reduces. For the NS interface, soil transfers maximum shear Stress to the concrete slab, and thus, the deformation increases. However, the NS interface holds the soil, and slight shear modulus degradation occurs during seismic loading.

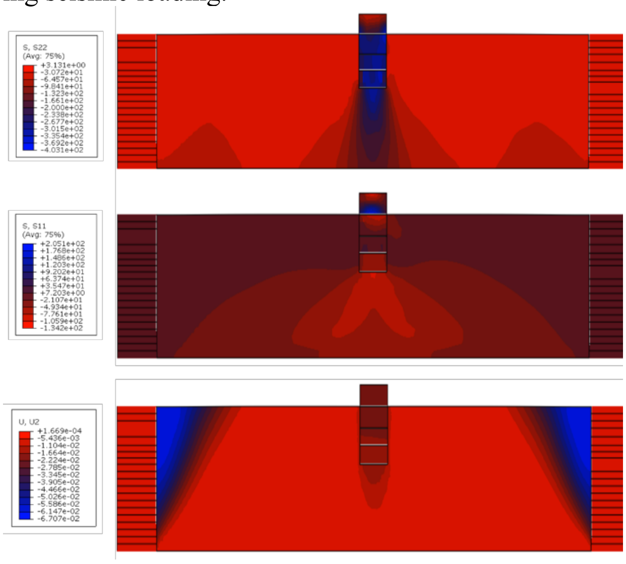
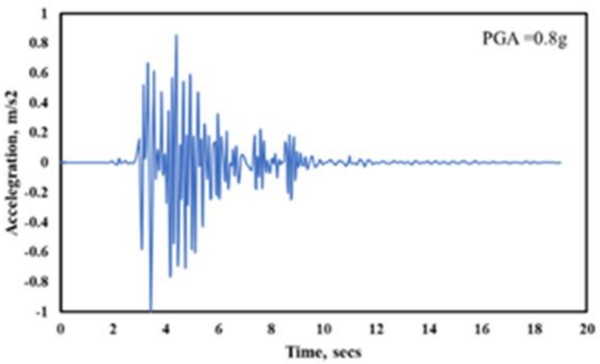
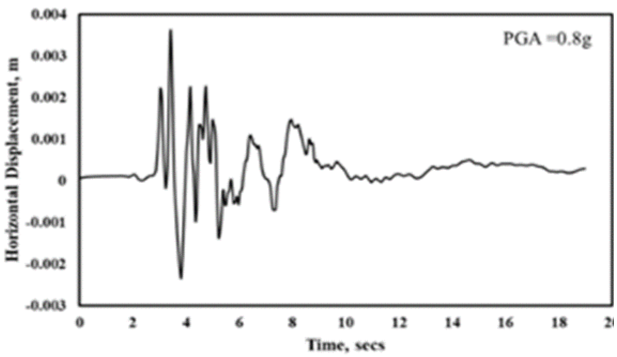


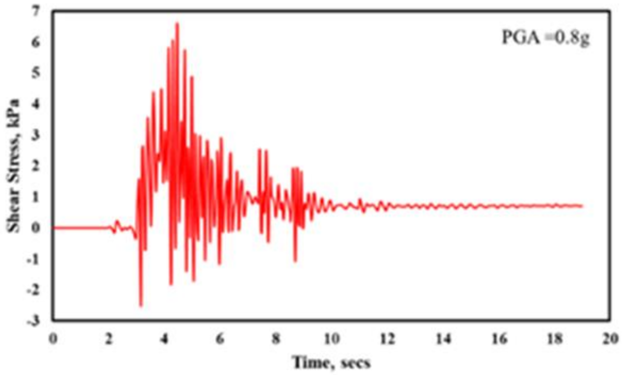
Figure 6 Contour diagram of (a) vertical stresses (kPa), (b) horizontal stresses (kPa), and (c) vertical displacement (m) in the soil at a critical time of 4.5 s for PS interface with overburden load and 0.8g PGA



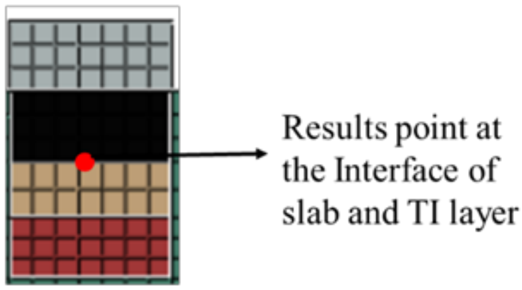
(a)



(b)



(c)



(d)

Figure 7 Variation of (a) Acceleration, (b) Horizontal Displacement, and (c) Shear Stress with time at interface of foundation slab and TI layer

In the case of the FS interface, the small shear Stress is transferred to the foundation slab, and the deformation is small. In contrast, here, the TI displacement along the foundation slab is more because the slab does not hold the TI layer and leads to more considerable shear modulus degradation of the TI layer. So, the FS interface generates significant shear stresses in the TI layer compared to NS and PS interfaces. The shear stresses in soil having contact with the foundation slab bottom for a PGA range of 0.3-0.8g are summarised in Table 3.

Table 3 Summary of results for various interface conditions

Peak Value	Shear Stress at interface, kPa		
PGA m/s2	FS	NS	PS
0.3	4.2	2.24	2.8
0.4	6.3	3.36	4.2
0.5	8.1	4.32	5.4
0.6	9.15	4.88	6.1
0.7	10.05	5.36	6.7
0.8	11.25	6	7.5

Peak Value	Horizontal Displacement at interface, m			Vertical Displacement at Top of concrete slab, m		
PGA m/s2	FS	NS	PS	FS	NS	PS
0.3	0.0034	0.0015	0.002	1.8615	0.82125	1.095
0.4	0.00374	0.0017	0.0022	2.091	0.9225	1.23
0.5	0.00425	0.0019	0.0025	2.584	1.14	1.52
0.6	0.00493	0.0022	0.0029	3.145	1.3875	1.85
0.7	0.00646	0.0029	0.0038	3.604	1.59	2.12
0.8	0.0068	0.003	0.004	4.25	1.875	2.5

6. CONCLUSIONS

Currently, the foundations of energy-efficient houses are typically insulated using l materials such as EPS, XPS, and cellular glasses due to their reliability, ease of installation, and low cost. The main drawback of these materials is their lesser stiffness, and the interface conditions of these materials with concrete and soil still need to be explored. Hence, in the present study, attempts were made to study the impact of interface conditions on the shear stresses and displacement behaviour of the XPS-insulated foundation systems when subjected to seismic loading. The present study is initially validated from the available data and results from the previous literature. The following conclusions can be drawn from the obtained results:

(a) The consideration of the elasto-plastic behaviour of the soil to assess the superstructure response gives an appropriate response.

(b) The displacement behaviour of the superstructure mainly depends on the load transfer mechanism of the foundation slab to the TI layer.

(c) The interface conditions control This load transfer mechanism, which is a prime parameter in assessing the foundation stability.

(d) The FS interface generates significant shear stresses in the TI layer compared to the NS and PS interfaces. Hence, appropriate partial slip conditions should be adopted by estimating the frictional constant between the TI layer-concrete slab and the TI layer-gravel/soil.

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