International Journal of Research in Interdisciplinary Studies
Volume 3, Issue 3, March 2025
https://www.ijris.com | ISSN (Online): 2584-1017

Effect of Using Compressible Inclusion Around Footing on the Behavior of Short-Period Structures Under Seismic Loading

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Abstract— This paper presents a study to investigate the seismic performance of short-period structures using compressible materials around foundations. Short-period structures are exposed to high seismic loads as a result of being located in the sensitive region of the acceleration response spectrum. A potential solution to this problem is to enclose the foundations of these structures with compressible materials such as expanded polystyrene foam in order to shift the periods of such structures from the sensitive region in the acceleration response spectrum to longer periods. A parametric study was carried out to examine the effect of using expanded polystyrene foam on the fundamental natural period of structures with isolated footings by analyzing single-degree-of-freedom systems. Results indicate that the use of expanded polystyrene foam has a significant effect on shifting the fundamental natural period of structures depending on the soil type. An increase in the period was up to 55%, compared to SDOF systems with a fixed-base.

Index Terms— **EPS foam, Isolated footing, Single Degree of Freedom, Seismic performance.**

1. Introduction

Over the past decades, humanity has been exposed to many hazards resulting from natural phenomena, which threaten human life and community stability. To cope with these hazards, researchers have tried to devise ways and means to control and mitigate the effects of these hazards and try to adapt to them. Among these natural disasters are earthquakes, hurricanes, volcanoes, floods and droughts [1]. Although the annual damage caused by earthquakes is less than that of floods and tsunamis, the immediate and unexpected damage from earthquakes has negative effects on those who are affected. Many typical structures, particularly those of short natural periods, are exposed to extensive damages caused by earthquakes and ground shaking that destroy many of these structures [2]. Since most of the public and private residential buildings in Saudi Arabia can be considered short-period structures [3]. The proposed study is of significant importance to the construction industry in the Kingdom.

The seismic performance of structures is a crucial factor in earthquake-prone areas, as earthquakes can severely damage infrastructure, resulting in loss of life and significant economic impacts. Short-period structures are particularly weak, as they experience amplified seismic forces due to their resonance with the critical region of the acceleration response spectrum, often associated with high ground accelerations during earthquakes. Addressing these loads is vital to improve the safety and resilience of such structures.

Seismic isolation systems, which incorporate elements such as elastomeric bearings, sliding bearings, and damping devices, are designed to decouple a building's foundation from the ground motion during an earthquake. By introducing a layer of flexibility and energy dissipation, these isolation systems can significantly reduce the transmission of seismic forces into the structure, effectively minimizing the risk of damage and collapse.

Conventional strategies to mitigate seismic exposure typically involve strengthening structural components, adjusting their stiffness, or implementing seismic isolation systems. However, these methods can be expensive, complex, or impractical for certain structures. A potential and cost-effective solution involves altering the dynamic properties of structures by surrounding their foundations with compressible materials, such as expanded polystyrene foam. Fig. 1 shows SDOF system with isolated footing with a corresponding fundamental period (T_{FS}), Fig. 2 considers an SDOF system with EPS foam around the foundation with a corresponding fundamental period (T_{SF}). By enclosing the foundation with EPS, the overall stiffness of the system is altered, which can shift the natural period of the structure away from the period range of significant ground motion. This shift minimizes resonance effects, leading to reduced seismic demands. Fig. 3 shows acceleration response spectrum with period shifting.

The use of EPS foam as compressible material around isolated footings of typical structures can effectively improve the seismic structural performance of short-period structures by (1) reducing the risk of structural failure, (2) enhance the overall stability and safety of the building by effectively reducing the transmission of seismic forces, (3) provide a cost-effective and practical solution for improving the seismic performance of buildings in earthquake-prone regions.

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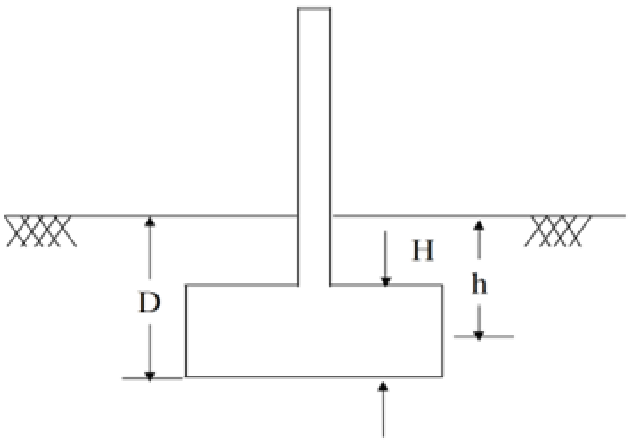

Fig. 1. SDOF system

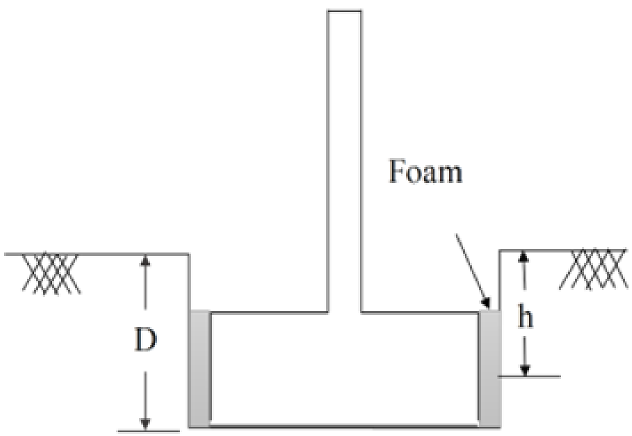

Fig. 2. SDOF system with EPS around the foundation

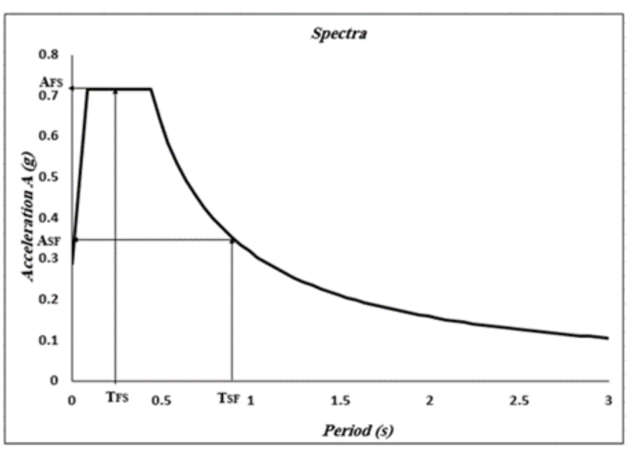

Fig. 3. Shifted period in the response spectrum

The main objective of this research is to investigate the seismic performance of structures utilizing EPS foam around their foundation by (1) examining the effect of the foam on the fundamental natural period of structures with isolated footings via analyzing single degree of freedom systems, (2) conducting time-history analyses on these systems to evaluate their seismic performance in terms of inelastic deformations.

In this research, the effect of expanded polystyrene foam around the foundation of typical structures is investigated as a seismic protection technique to reduce the seismic loads. The use of such a compressible material on a structure alters the dynamic characteristics of the structure, allowing a significant change to its seismic behavior.

2. Literature Review

The literature review of this study is divided into three sections. The first section addresses geotechnical seismic isolation (GSI) systems in general; the second part discusses the usage of EPS foam in construction; and the third section reviews the physical and mechanical properties of expanded polystyrene (EPS) foam.

A. *Geotechnical Seismic Isolation (GSI) Systems*

Geotechnical seismic isolation systems are used to reduce damage caused by earthquake loads. It involves the use of various geotechnical techniques to isolate a structure or a building from the ground motion of an earthquake. These systems typically consist of single or multiple layers of special materials that are placed between the foundation of the structure and the soil. These layers are designed to absorb seismic energy and minimize the transmission of ground vibrations to the building [4]. The primary function of the geotechnical seismic isolation system is to provide a stable base for the building during an earthquake. By isolating the structure from the ground motion, the system reduces the risk of damage to the building's foundation and other structural components. This helps to ensure the safety of occupants and the longevity of the structure. There are two typical example techniques of GSI systems, one of which is where the isolation material is placed directly under the foundation, while in the other, the isolation material is placed at some depth in the soil [5].

B. *Usage of EPS Foam in Construction*

Over the past few years, a great number of research studies have been conducted to investigate the use of compressible materials to reduce the impact of seismic hazards on structures [6]–[14]. Many of these studies used experimental and numerical analyses to investigate the effectiveness of using EPS to improve the seismic performance of structures [15]–[20]. EPS foam is a promising material for seismic protection of structures since it is readily available, easy to install without any specialized equipment [21].

There are numerous applications of EPS foam in the construction industry, such as utilizing EPS foam as a fill material for earth slope stabilization and road embankments [22], [23]. Furthermore, EPS foam has been used since the 1970s in constructing bridge abutments [24]. EPS foam abutment blocks have also been used to support a concrete bridge in Norway [25], and to reduce vertical and horizontal stresses on culverts systems and pipelines in transportation infrastructure [26].

C. *Physical and Mechanical Properties of EPS Foam*

Expanded polystyrene foam has made rapid advancements in numerous new applications since it was recognized as a

Table 1
ASTM standards related to EPS and its applications

ASTM Standard	Description
ASTM C578 [28]	Standard specification for rigid, cellular polystyrene thermal insulation
ASTM D1621 [32]	Standard test method for compressive properties of rigid cellular plastic
ASTM D1622 [31]	Standard test method for apparent density of rigid cellular plastics
ASTM D6817 [29]	Standard specification for rigid cellular polystyrene geofoam
ASTM D7180 [6]	Standard guide for use of expanded polystyrene (EPS) geofoam in geotechnical projects

traditional insulating material in the 1950s [24]. EPS is lightweight and stiff closed-cell foam made from styrene and pentane. EPS also has many useful characteristics such as light weight, ability to retain its shape, shock absorbance, water resistance, durability, and relatively high compressive strength. In addition, EPS is chemically inert in both water and soil, and consists of approximately 98% air and 2% polystyrene [27]. EPS has great cushioning qualities, low thermal conductivity, moisture resistance, durability, sound absorption, low moisture absorption rate, and it has well-known mechanical properties [28]–[31]. The structural integrity of various constructions can be improved by using EPS as a building material. Nevertheless, the use of foam has some drawbacks, such as a very low maximum working temperature of 80°C.

The American Society for Testing and Materials (ASTM) has various standard specifications related to rigid cellular polystyrene. Table 1 presents some of the ASTM standards that are related to EPS and its applications. Mechanical properties and testing of EPS foam should be as per ASTM D6817. According to this specification, EPS foams shall adhere to physical property requirements such as dimensions and density, compressive resistance, and flexural strength [29].

Table 2
Commonly manufactured dimensions of foam according to ASTM D6817 [29]

Dimension (mm)	All EPS Types
Width	305-1219
Length	1219-4877
Thickness	25-1219

Among the physical properties of EPS foam, the key dimensions are length, width, and height. These measurements are relatively straightforward and have little ambiguity associated with them. Table 2 provides the typical dimensions of the commonly available EPS foam products in the North American market according to ASTM D6817 [29].

Classification of EPS foam is better to be according to its density (ρ) since its mechanical properties are directly related to it [21]. Table 3 presents standard types of EPS and their minimum densities according to ASTM D 6817 [29].

Table 3
Standard types of EPS and their minimum densities [29]

ASTM D 6817	Density (kg/m³)
EPS12	11.2
EPS15	14.4
EPS19	18.4
EPS22	21.6
EPS29	28.8
EPS39	38.4
EPS46	45.7

Using the proper EPS foam density is important, for example, some researchers found that the best range of EPS densities for highway embankment is between 16 kg/m^3 and 32 kg/m^3, and EPS foam can reach up to 100 kg/m^3, where high strength and low compressibility are needed [13]. For geotechnical applications, EPS types EPS19, EPS22, and EPS29 have been used for several functions [33].

Poisson's ratio (υ) can be considered as an indication of the lateral pressure of the EPS foam, and its value ranges from 0.05 to 0.5, depending on the density and loading stage [22]. Generally, EPS Poisson's ratio is approximately equal to 0.12 within the elastic range of response [27]. The following equation can be used to determine Poisson's ratio for EPS foam as follows [34]:

$$\nu = 0.0056\,\rho + 0.0024 \qquad (1)$$

where ρ is in kg/m^3

Table 4
Minimum elastic modulus of EPS according to ASTM D 6817 [29]

ASTM D 6817	Elastic Modulus (MPa)
EPS12	1.5
EPS15	2.5
EPS19	4.0
EPS22	5.0
EPS29	7.5
EPS39	10.3
EPS46	12.8

The elastic modulus (E_f) of EPS foam is the slope of the elastic portion of the stress-strain curves, and it is related to its density [25]. Table 4 presents minimum values for elastic modulus for various types of EPS according to ASTM D 6817 [29].

Table 5
Elastic modulus for various EPS types [25]

EPS type	Elastic Modulus (MPa)
EPS 15	3.242
EPS 19	4.747
EPS 25	7.223
EPS 29	10.778
EPS 39	13.779

Depending on the density of the foam, higher-density EPS foam generally has a higher elastic modulus [35]. Table 5 shows some of the elastic modulus for different EPS densities as defined by Bartlett and Neupane [25].

Elastic modulus at low compressive strains can also be calculated using the following empirical linear equation [34], where ρ is in kg/m^3:

$$E_f = 450\,\rho_f - 3000 \qquad (2)$$

Table 6
Minimum compressive strength according to ASTM D 6817 [29]

Physical property	**ASTM D6817**					
	EPS12	**EPS15**	**EPS19**	**EPS22**	**EPS29**	**EPS39**
Compressive Resistance at 1% Strain (kPa)	15	25	40	50	75	103
Compressive Resistance at 5% Strain (kPa)	35	55	90	115	170	241
Compressive Resistance at 10% Strain (kPa)	40	70	110	135	200	276

The compressive strength of EPS foam is an important factor in determining its suitability for use in construction and geotechnical application [35]. The compressive behavior of EPS foam is typically evaluated according to standard test methods such as ASTM D1621 [32]. Table 6 shows that the compressive strength of EPS given by the compressive stress at a strain of 1%, 5%, and 10%, as specified by the ASTM D 6817 standards [29].

The behavior of EPS foam under application of a gradually increasing force, without any reversal of the applied force, is an important consideration in its use as a lightweight fill material in construction applications [25]. The stress-strain relationship of EPS foam during monotonic loading is generally nonlinear, and can be affected by factors such as the density and size of the material, the rate of loading [25]. The densification strain decreases with the increasing density of the EPS specimen [36].

Based on laboratory testing conducted by various researchers, it has been found that the cyclic load behavior of block molded EPS foam is predominantly linear elastic, with strains of approximately 1% or less. When subjected to three loading cycles with a 10% strain, the initial tangent modulus in the second and third cycles is lower than that of the first cycle [7]. Moreover, cyclic load tests have demonstrated that EPS foam can withstand an unlimited number of load cycles, provided that the repetitive loads are not greater than 80% of its compressive strength [22]. When the applied load exceeds the elastic limit, the EPS foam will experience residual deformation and a reduction in its modulus. This reduction can be observed through the progressive flattening of the loading-unloading curves [7].

3. Methodology

The research methods employed to achieve the objectives of this proposed study include a parametric analysis to examine the effect of expanded polystyrene (EPS) foam on the fundamental natural period of structures with isolated footings. This is accomplished by analyzing single-degree-of-freedom (SDOF) systems.

A. *Stiffness Relations for Isolated Footing*

The stiffness expressions for the isolated footing spring model are represented first for the foundation at the surface of the ground ($D_f = 0$) as given in Eq. 3 to Eq. 6. These expressions are proposed by Gazetas [37], and they are then corrected for embedment as given in Eq. 7 to Eq. 10. Fig. 4 presents isolated footing dimensions. Fig. 5. (a) shows an idealized fixed-base SDOF system, and Fig. 5. (b) present the idealized SDOF system as uncoupled springs.

Footing translation stiffness along the x-axis:

$$k_x = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 1.2\right] \tag{3}$$

Footing translation stiffness along the y-axis:

$$k_y = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 0.4\frac{L}{B} + 0.8\right] \tag{4}$$

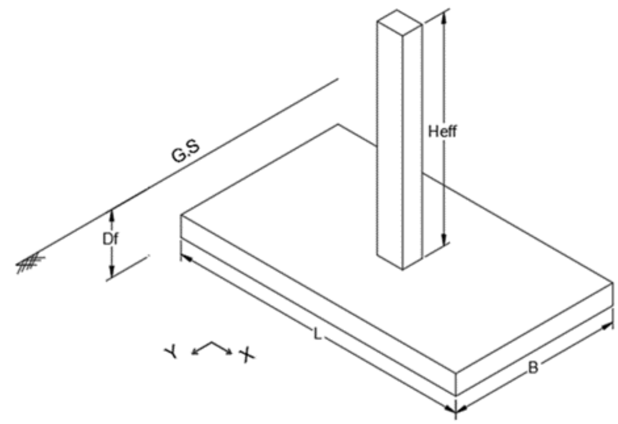

Fig. 4. Rectangular isolated footing dimensions

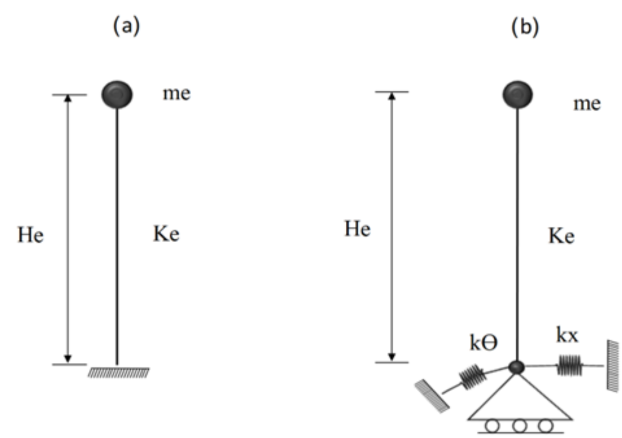

Fig. 5. (a) Idealized fixed base SDOF system, (b) Idealized system as uncoupled springs

Footing rocking stiffness about the x-axis:

$$k_{\theta x} = \frac{GB^3}{1-\nu}\left[0.4\left(\frac{L}{B}\right) + 0.1\right] \tag{5}$$

Footing rocking stiffness about the y-axis:

$$k_{\theta y} = \frac{GB^3}{1-\nu}\left[0.47\left(\frac{L}{B}\right)^{2.4} + 0.034\right] \tag{6}$$

Embedment correction factor for footing translation stiffness along the x-axis:

$$\beta_x = \left(1 + 0.21\sqrt{\frac{D}{B}}\right)\left[1 + 1.6\left(\frac{hd(B+L)}{BL^2}\right)^{0.4}\right] \quad (7)$$

Embedment correction factor for footing translation stiffness along the y-axis:

$$\beta_x = \beta_y \quad (8)$$

Embedment correction factor for footing rocking stiffness about the x-axis:

$$\beta_{\theta x} = 1 + 2.5\frac{d}{B}\left[1 + \frac{2d}{B}\left(\frac{d}{D}\right)^{-0.2}\sqrt{\frac{B}{L}}\right] \quad (9)$$

Embedment correction factor for footing rocking stiffness about the y-axis:

$$\beta_{\theta y} = 1 + 1.4\left(\frac{d}{L}\right)^{0.6}\left[1.5 + 3.7\left(\frac{d}{L}\right)^{1.9}\left(\frac{d}{D}\right)^{-0.6}\right] \quad (10)$$

B. Stiffness Relations for EPS Foam Contribution

To formulate the stiffness expressions of the EPS foam around the isolated footing in the horizontal plan, it is assumed that the contribution of foam stiffness in the translation direction is equivalent to the axial stiffness of a compression member. It should be noted that the foam layer can only resist compressive forces, and hence, tension stiffness is neglected. These expressions are presented below.

EPS foam translation stiffness along the x-axis:

$$k_{xf} = \frac{E_f\, B\, H}{t_f} \quad (11)$$

EPS foam translation stiffness along the y-axis:

$$k_{yf} = \frac{E_f\, L\, H}{t_f} \quad (12)$$

To formulate the rotation stiffness of the EPS foam around isolated footing, it is assumed that under lateral loading of the column, the foam is subjected to bending action, causing compressive stresses on its upper or lower half-height on one side and the opposite on the other side, while tension is ignored on both sides, as shown in Fig. 6. The equations shown below can be used to find the rotational stiffness of this isolation system. Fig. 7 present SDOF system after adding EPS foam to the system.

EPS foam rotational stiffness about the x-axis:

$$k_{\theta xf} = \frac{E_f\, L\, H^3}{24\, t_f} \quad (13)$$

EPS foam rotational stiffness about the y-axis:

$$k_{\theta yf} = \frac{E_f\, B\, H^3}{24\, t_f} \quad (14)$$

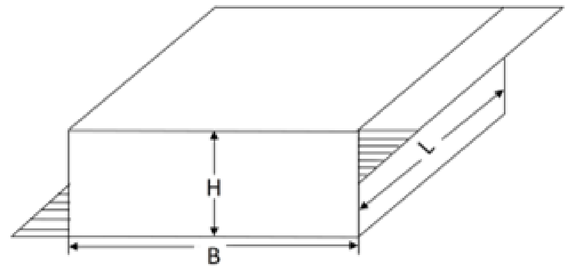

Fig. 6. EPS bending under lateral loading of the column

C. Effect of Using EPS Foam on Fundamental Periods of SDOF Systems

The change in the fundamental period of the system due to adding EPS foam around the footing is quantified by calculating the ratio of TSF to TFB as given below [38]:

$$\frac{T_{SF}}{T_{FB}} = \sqrt{1 + \frac{k_e}{k_{xt}} + \frac{k_e\,(H_e)^2}{k_{\theta t}}} \quad (15)$$

where k_{xt} and $k_{\theta t}$ are the total translation and rotational stiffnesses of the system, respectively.

D. Soil Properties

A viscous boundary was applied to the lateral sides of the soil stratum, while the bottom side was rolled to restrict only perpendicular movements. Three different types of soil were used in this study: stiff soil, medium soil, and soft soil, designated as (C), (D), and (E), respectively, as shown in Table 7.

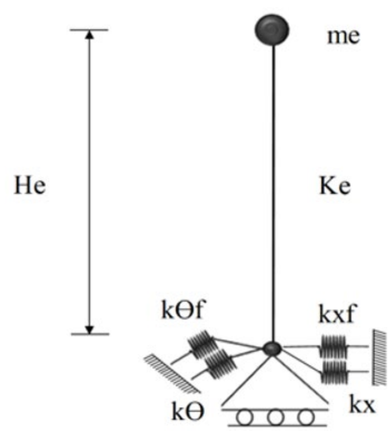

Fig. 7. Uncoupled springs after adding EPS foam to the system

Table 7
Soil properties used for the analysis

Soil type	v_{so} (m/s)	Poisson's ratio (v_s)	G_s/G_{so}
C	762	0.3	0.6
D	365	0.35	0.2
E	182	0.4	0.03

4. Results and Discussion

The results of the research investigation reveal the findings regarding the efficiency of using EPS foam as an isolating material on the seismic behavior of short-period structures. The following sections present these results with a brief discussion. Using EPS Foam has a significant effect on the Fundamental Periods of SDOF Systems. The stiffness of SDOF systems is influenced by the properties of the foam enclosing the footings. EPS foam has a relatively low stiffness compared to soil, and hence, when used as a fill material, it can reduce the stiffness of the system. The stiffness of the structure affects the fundamental period, where a decrease in stiffness generally leads to an increase in the fundamental period. The results indicate that the use of EPS foam of varying thicknesses and densities around isolated footings of SDOF systems of different soil types can increase the period up to 55%, compared to SDOF systems with fixed-base.

A. Effect of EPS foam on RC Structure in Soft Soil Conditions

When dealing with soft soil types and utilizing EPS foam with different densities, thicknesses, and elastic moduli, an increase in the fundamental period of SDOF systems is observed. This increase reaches up to 55%. Fig. 8 illustrates the relationship between the ratio T_{SF}/T_{FB} and EPS foam thickness and elastic modulus for soft soil conditions. It is noted that when the thickness increases, the ratio T_{SF}/T_{FB} also increases. Conversely, an increase in the elastic modulus results in a reduction in the ratio T_{SF}/T_{FB}.

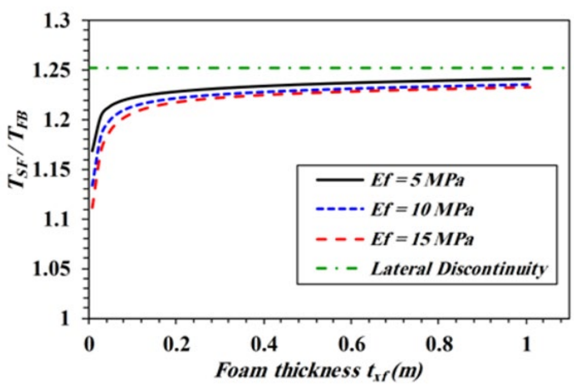

Fig. 8. Relation between T_{SF} and T_{FS} for a structure with an isolated footing on soft soil

B. Effect of EPS Foam on RC Structure in Medium Soil Condition

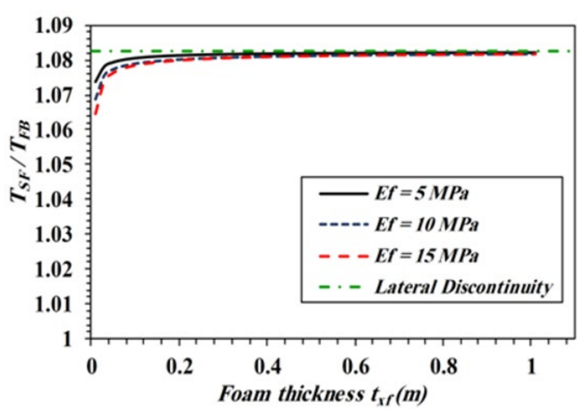

Fig. 9. Relation between T_{SF} and T_{FS} for a structure with an isolated footing on medium soil

When the soil type is medium and the EPS foam has different densities, thicknesses, and elastic moduli, there is a percentage increase in the period of the RC structure, ranging from nearly 20% to 30%. Fig. 9 illustrates the relationship between the period and thickness of foam, under medium soil conditions, for various foam elastic moduli.

C. Effect of EPS Foam on RC Structure in Stiff Soil Conditions

In the case of stiff soil and varying densities, thicknesses, and elastic moduli of the EPS, the period of the RC structure is observed to have a percentage increase ranging from 10% to 20%. Fig. 10 shows that using different thicknesses of foam for different moduli of elasticity of foam on stiff soil will produce an increase in SDOF period.

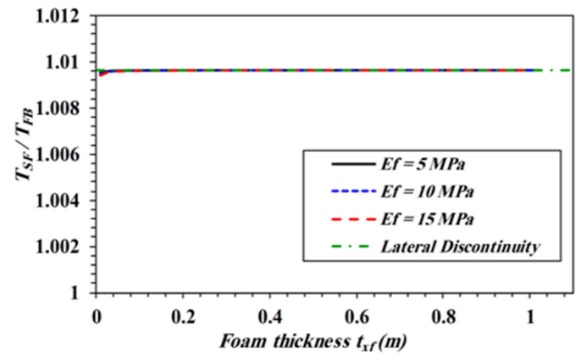

Fig. 10. T_{SF} and T_{FS} relation for a structure with an isolated footing on stiff

5. Conclusion

In conclusion, the use of expanded polystyrene (EPS) foam as an isolation system for single-degree-of-freedom (SDOF) structures presents a promising solution for enhancing seismic performance. EPS foam's lightweight nature, excellent energy absorption characteristics, and cost-effectiveness make it an ideal material for improving structural resilience against seismic forces.

Through this parametric study, it has been demonstrated that EPS foam effectively increases the natural period of SDOF systems, leading to decreased response acceleration and improved stability during seismic events. Usage of EPS foam with different thicknesses and densities around isolated footing of SDOF systems on different soil types can increase the period up to 55%, compared to SDOF systems with fixed-base.

Overall, incorporating EPS foam into isolation systems not only improves safety and performance but also supports sustainable construction practices, making it an important option for future engineering applications in seismic-prone regions.

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