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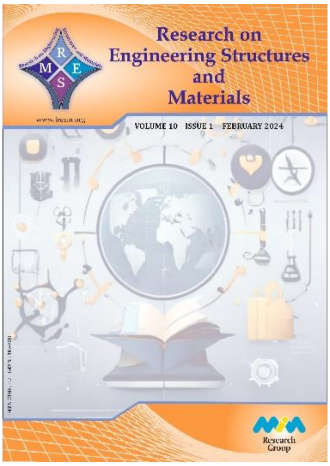

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Research Article

Thin layer interface: An alternative modeling consideration in soil-structure interaction system

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Abstract

The numerical modeling of a soil-structure interaction (SSI) system subjected to lateral loads depends mainly upon the interface behavior. The soil stiffness in relation to the structure is quite low, and the structure generally has a rough surface in contact with the soil. As a result of the slipping and rolling of soil grains caused by friction, a thin layer of shear zone forms in soil with the application of lateral loads. A thin layer interface is represented by the shear zone. As a result, the decision on the thickness requirement is critical for appropriate modeling of the thin layer interface, which is rarely documented by researchers. Furthermore, it has been reviewed in the literature that modeling the SSI system with a thin layer interface more accurately replicates the physical system than modeling it with a zero-thickness interface. The methodology for effective usage (in terms of proper interface thickness) of the thin-layer interface in SSI system using finite element (FE) modeling is proposed in this work. The thickness of the interface has also been determined via numerical modeling of a large direct shear test (DST).

1. Introduction

The modeling of the SSI system with a thin layer interface has many advantages [1-3]. The performance and execution of numerical modeling considering thin layer interface mainly depends on the interface thickness [4]. This paper effectively deals with thin layer interface element as well as evaluation and execution of interface thickness for various normal stresses.

According to the reviewed literature, it has been reported that the thin layer interface is appropriately representing the physical state of the SSI problem than that of the zero-thickness interface [5-10]. Also, it has been noted that due to the bottom roughness of the footing, the soil particles slip as well as roll because of lateral loads as a result the thin layer interface has formed [11-13]. The interface acts differently than the rest of the soil [3, 14-16]. If both footing and underlying material act as solid such as footing-rock interaction, then the representation of interface has considered as zero thickness [17]. Such interface has been modeled with appropriate constant normal stiffness values and meshing aspect ratio, to avoid the numerical ill-conditioning [18-19]. It is worth to mention that many researchers showcased the computational difficulties that occur in zero thickness interfaces [2, 4, 18, 20-23]. In contrast, the recent software is using zero thickness interfaces for SSI problems by adopting only interface reduction factor with a high value of normal stiffness [24-29]. Such analysis is based on certain assumptions or approximations which have considered the interface performance by selecting only interface reduction factor, which may not be suitable for every soil and footing/structure condition. So,

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consideration of zero thickness interfaces in SSI problem is disadvantageous, whereas there are many advantages of using a thin layer interface.

The implementation of a thin layer interface necessitates the use of an appropriate evaluation interface thickness. According to Desai et al. [1], Dalili et al. [7] and Dhadse G.D. et al. [23], the interface thickness should be 0.1 to 0.01 of the adjacent element size. If the adjacent mesh size fluctuates, the thickness value is inconsistent and altering regardless of soil type or structure surface roughness. According to the literature, the interface thickness should be five times the average soil grain size [6, 11, 13, 30-33]. Whereas Fang H. and Wang W. [34], Saberi et al. [35] and Gennaro et al. [36] proposed the interface thickness should be 5 to 10 times the average particle size. The criteria given with respect to average particle size is realistic and varies according to grain size. But the formation of a thin layer interface is due to roughness of footing surface [11] in contact with soil and depends upon soil type, particle size, normal stress etc. [13, 30, 37-39]. As a result, the criterion based solely on particle size appears insufficient for determining optimal interface thickness for every SSI analysis situation.

The methodology for thickness evaluation and thin layer interface execution in FE modeling of the SSI system has been proposed in this study. The proposed methodology is inclusive of normal stress only, but the same methodology can be adopted by taking into consideration all interface thickness influencing parameters.

2. Proposed Problem Statement

Many scholars have claimed that employing a thin layer over zero thickness interfaces has advantages. The research into the decision on interface thickness requirement is insufficient and requires further analysis. Few researchers had proposed the criteria based on grain size for the determination of interface thickness. This criterion may not be effective for every SSI system as the thickness predominantly relates to contact roughness and indirectly relates to soil type, grain size, normal stress etc.

The methodology for effective evaluation of interface thickness and execution of thin layer interface is proposed in the present study. The FE model of a large DST with a thin layer interface has been developed to validate the experimental results for various proposed thicknesses. The relation between normal stress and interface thickness has been established. The footing-soil interaction (FSI) problem considering zero thickness interfaces by Viladkar et al. [40] has been solved using the proposed thin layer thickness for the execution of the interface thickness. Non-linearity at the soil and interface has also been incorporated into FE formulations.

3. Finite Element Modeling

The footing and soil mass is modeled with 8 noded isoparametric plane strain element. Each node in the element has two degrees of freedom (DoF) i.e. translations in ξ and η directions in a local coordinate system. The elements geometry is shown in Fig. 1. The mathematical formulation of the element is referred from J. N. Reddy [41], Chandrupatla and Belegundu [42], S.S. Rao [43] and O.C. Zienkiewicz et al. [44]. This element is very well compatible with 6 noded thin layer interface element as well as the various constitutive models of soil. Also, the element is useful in the proper evaluation of stresses near junction points [45].

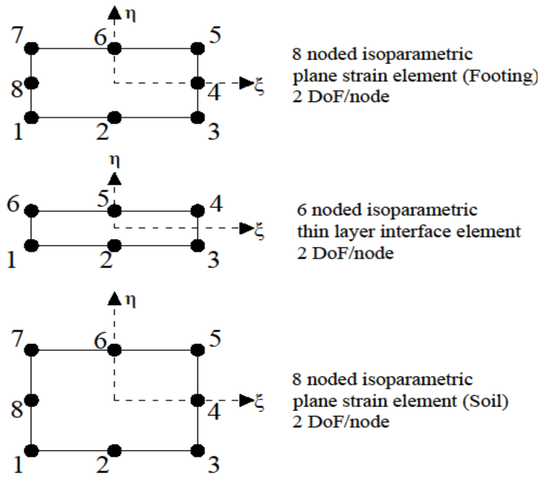


Fig. 1. Geometrical details of elements used for footing, interface and soil

3.1. Thin Layer Interface Element Formulation

The 6 noded thin layer isoparametric interface element depicted in Fig. 2 serves as a continuum interface between soil and footing. The element's constitutive performance is thought to differ from that of adjacent solid elements, and it is mostly determined by the interface's normal and shear stiffness (as determined by the shear test). The element is compatible with adjacent soil and footing element. Earlier, this element has been used by Sharma and Desai [3], Zaman et al. [14] and Noorzaei et al. [9] to analyze various soil-structure interaction systems. In the present study, the same element is executed for analyzing the SSI problem with proper thickness. The detailed element stiffness matrix formulation is given below.

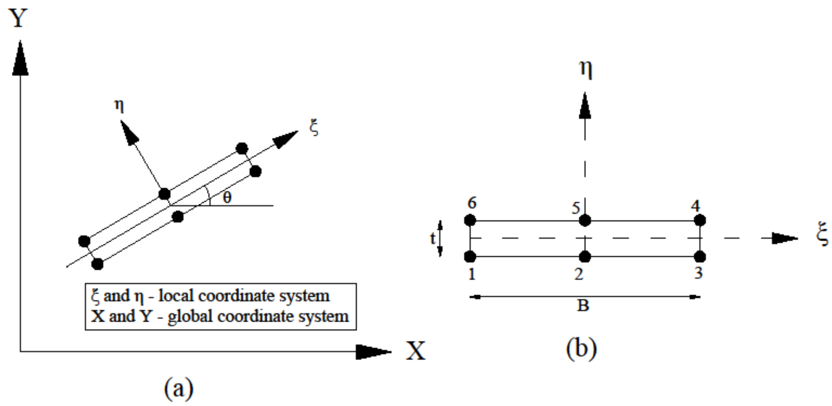


Fig. 2. Thin layer interface element representation in the global and local coordinate systems

The six-noded thin layer interface element is depicted in Fig. 2 in both global and local coordinate systems. In general, the interface details are evaluated in a local coordinate system, therefore the orientation of the interface is an important criterion. As a result, the formulation I generated in a local coordinate system and then transformed to the global system using the transformation matrix. It is also worth noting that as the interface thickness approaches zero the in-plane stress and strain become minimal in compared to normal and shear stress and strain [3]. As a result, the contact response is approximate idealized by simply normal and shear stiffness.

In the global X and Y systems, U and V represent nodal displacement. In the local coordinate and system, u and v are the nodal displacements. Equation 1 gives the shape functions 'N' in the local coordinates system at each node,

$$\begin{aligned} N_1 &= \frac{1}{4}(-\xi)(1-\xi)(1-\eta) \\ N_2 &= \frac{1}{2}\left(1-\xi^2\right)(1-\eta) \\ N_3 &= \frac{1}{4}(\xi)(1+\xi)(1-\eta) \\ N_4 &= \frac{1}{4}(\xi)(1+\xi)(1+\eta) \\ N_5 &= \frac{1}{2}\left(1-\xi^2\right)(1+\eta) \\ N_6 &= \frac{1}{4}(-\xi)(1-\xi)(1+\eta) \end{aligned} \tag{1}$$

The element displacement matrix in the global system is (Equation 2),

$$\delta_e = \{U_1 \quad V_1 \quad U_2 \quad V_2 \quad U_3 \quad V_3 \quad U_4 \quad V_4 \quad U_5 \quad V_5 \quad U_6 \quad V_6\}^T_{1X12} \tag{2}$$

Therefore, the displacement at any point within an element is given by Equation 3;

$$\begin{Bmatrix} U \\ V \end{Bmatrix} = \begin{bmatrix} N_1 & 0 & N_2 & 0 & N_3 & 0 & N_4 & 0 & N_5 & 0 & N_6 & 0 \\ 0 & N_1 & 0 & N_2 & 0 & N_3 & 0 & N_4 & 0 & N_5 & 0 & N_6 \end{bmatrix} \{\delta_e\} \tag{3}$$

$$U = N_i U_i$$

$$V = N_i V_i$$

The strain at any point within an element is given by strain displacement relationship as given in Equation 4,

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial U}{\partial x} \\ \dfrac{\partial V}{\partial y} \\ \dfrac{\partial U}{\partial y} + \dfrac{\partial V}{\partial x} \end{Bmatrix} \qquad \underset{3x1}{\{\varepsilon\}} = \underset{3x12}{[B]} \underset{12x1}{\{\delta_e\}} \tag{4}$$

where, $\varepsilon_x, \varepsilon_y$ and γ_{xy} are axial strain, normal strain and shear strain respectively in the global system. Whereas 'B' is the strain displacement relation matrix and 'δ_e' is the global element displacement matrix.

It is discussed earlier that, interface properties are in a local coordinate system, hence stress-strain relation is written as shown in Equation 5,

$$\begin{Bmatrix} \sigma_n \\ \tau \end{Bmatrix} = \begin{bmatrix} k_{nn} & k_{ns} \\ k_{sn} & k_{ss} \end{bmatrix} \begin{Bmatrix} v_r \\ u_r \end{Bmatrix} \quad (5)$$

where, σ_n and τ are normal and shear stress (Local coordinate system). k_{nn} and k_{ss} are normal and shear stiffness whereas k_{sn} and k_{ns} are in-plane stiffness. v_r and u_r are relative displacements. As thickness is very small for the interface, the in-plane stresses are negligible, hence Equation 5 can be written as (Equation 6),

$$\begin{Bmatrix} \sigma_n \\ \tau \end{Bmatrix} = \begin{bmatrix} k_{nn} & 0 \\ 0 & k_{ss} \end{bmatrix} \begin{Bmatrix} v_r \\ u_r \end{Bmatrix} \quad (6)$$

As in-planes stresses are negligible, hence (Equation 7)

$$\begin{aligned} &\varepsilon_x = 0 \\ &\sigma_x = 0 \\ &\varepsilon_y = \varepsilon_n = \frac{v_r}{t} \because t = thickness \\ &\sigma_y = \sigma_n \\ &\gamma_{xy} = \gamma = \frac{u_r}{t} \end{aligned} \quad (7)$$

Thus equation 6 can be written as, (Equation 8)

$$\begin{aligned} &\begin{Bmatrix} \sigma_n \\ \tau \end{Bmatrix} = \begin{bmatrix} tk_{nn} & 0 \\ 0 & tk_{ss} \end{bmatrix} \begin{Bmatrix} \varepsilon_n \\ \gamma \end{Bmatrix} \\ &\{\partial\sigma\} = [D_e]\{\partial\varepsilon\} \end{aligned} \quad (8)$$

Where, [De] is material matrix or relation matrix in the local coordinate system

To transform the local coordinate system into the global coordinate system, use the transformation matrix [T] in Equation 9,

$$[T] = \begin{bmatrix} s^2 & c^2 & -cs \\ -2cs & 2cs & (c^2 - s^2) \end{bmatrix} \quad (9)$$

where, s = sinθ, c = cosθ and θ is the angle made by interface with X-axis. Therefore, the global stress-strain relation matrix is expressed as (Equation 10)

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_{3x1} = \begin{bmatrix} s^2 & -2cs \\ c^2 & 2cs \\ -cs & \left(c^2 - s^2\right) \end{bmatrix}_{3x2} \begin{bmatrix} tk_{nn} & 0 \\ 0 & tk_{ss} \end{bmatrix}_{2x2} \begin{bmatrix} s^2 & c^2 & -cs \\ -2cs & 2cs & \left(c^2 - s^2\right) \end{bmatrix}_{2x3} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}_{3x1} \tag{10}$$

$$\{\partial\sigma\} = [T]^T [D_e][T]\{\partial\varepsilon\}$$

Thus, the element stiffness matrix [K] in global form can be written as, (Equation 11)

$$[K] = \int [B]^T [T]^T [D_e][T][B] dv_e$$

$$[K] = \sum_{gp=1}^{n} [B]^T [T]^T [D_e][T][B] J| W_{gp} \tag{11}$$

$$gp = gauss\,pt.$$

$$W_{gp} = weights$$

where, v_e is the volume of the element. The MATLAB FE model for analyzing the SSI system with soil and interface non-linearity has been developed using the formulation of all the elements.

3.2. Soil and Interface Constitutive Modeling

Soil is a highly non-linear material. Many researchers have proposed various constitutive relations to predict the appropriate complex behavior of soil [46-47]. The choice of constitutive models amongst the available model depends on the type of soil as well as purpose and type of analysis [46]. Almost all the constitutive relations are compatible with FE formulation. Soil nonlinearity is typically integrated into FE formulation using an incremental iterative method. [48]. In the present analysis, the Hyperbolic Model proposed by Duncan-Chang [49-51] (based on associated flow rule [52]) is used to represent the response of the soil. In this model, the stiffness non-linearity and hardening are appropriately included whereas softening and dilatancy are not included [6]. It is amongst the commonly used model for SSI analysis due to its versatility. The tangent modulus 'ET' [45, 53] at every load step is evaluated using equation 12,

$$E_T = \left[1 - \frac{R_f (1 - \sin\phi)(\sigma_1 - \sigma_3)}{2(C\cos\phi + \sigma_3 \sin\phi)}\right]^2 K.P_a \left(\frac{\sigma_3}{P_a}\right)^n \tag{12}$$

where, 'R_f' is failure ratio, 'φ' is the angle of friction, 'σ_1' and 'σ_3' are major and minor principal stresses, 'C' is cohesion, 'K' is Modulus number, 'P_a' is atmospheric pressure and 'n' is the exponent.

In addition to soil non-linearity, interface non-linearity has also been considered in the present research. The interface hyperbolic model developed by Clough and Duncan 1971 [54] has been used in present investigation. The model is versatile as well as it solves the purpose of present study. The model is capable of dealing with cohesive soil-structure interface as well, because it is inclusive of interface adhesion. The hyperbolic relation is used to approximate the interface's stress-strain response [7, 40, 45] as given in equation 13. During lateral loading, the shear zone has been formed due to slipping and rolling of soil particles over the rough foundation surface. As the analysis has been performed with the Finite Element Method, the slipping and rolling of the particles have been idealized by tangential stiffness value as express in equation 13 and the shear zone has been idealized with thin layer interface element (with appropriate thickness) as discussed in Section 3.1. The tangential stiffness 'K_{ss}' from equation 13 is evaluated at every load step whereas normal stiffness 'K_{nn}' is approximately evaluated as 'E_T/t' [3] ('t' is interface thickness). It is also reviewed from the literature that, due to a very thin interface, few problems may face computational difficulties as a result; arbitrary high value for normal stiffness is also considered [40, 45, 55].

$$K_{ss} = (1-\lambda_2)^2 Ki$$
$$K_i = k_j \gamma_w \left[\frac{\sigma_n}{P_a}\right]^n \tag{13}$$
$$\lambda_2 = \frac{R_f \tau}{(C_a + \sigma_n \tan\phi)}$$

From equation 13, 'k_j' is modulus number, 'γ_w' is the unit weight of water, 'σ_n' is normal stress, 'P_a' is atmospheric pressure, 'R_f' is failure ratio, 'τ' is shear stress, 'C_a' is adhesion at the interface, 'φ' angle of friction, 'n' is the exponent and 'K_i' is initial stiffness.

4. Methodology

The non-linear plane strain SSI-FE model consisting of footing, soil and interface element has been developed in MATLAB. The mixed incremental iterative algorithm [48, 56] is used to apply non-linearity in soil mass and interface. The model is versatile and realistic with the availability of various elements and the inclusion of interface thickness. It is also able to solve variable degree of freedom system with ease.

In the current investigation, a 6 noded thin layer element has been selected for modeling the interface, together with an 8 noded plane strain isoparametric element for soil and footing. The developed FE model is validated using experimental findings from the large box shear test performed by Viladkar et al. [40] and also the same model has been checked for various interface thickness values. Further, the FSI problems with thin layer interface have been analyzed using the validated FE model.

4.1. Proposed Procedure for Prediction and Execution of Interface Thickness

According to reviewed literature as per section 1, it is reported that the interface thickness for any SSI problem should lie between 5-10 times the average particle size. The said criterion is purely dependent on particle size without considering parameters such as surface roughness, soil type, normal stress etc. But for physical cases, the site conditions are completely different and interface thickness mostly depends on every parameter as mentioned. Hence thickness criteria may vary according to these parameters. As a result, the current study proposes a systematic technique for predicting interface thickness based on normal stresses.

In this study, for the large box shear test (details are given in section 5), only one type of sand and a single mild steel rough surface as a footing has been used. Thus particle size, sand type and surface roughness are kept constant whereas only normal stress keeps varying. It is decided to use four different interface thicknesses such as $3D_{50}$, $5D_{50}$, $10D_{50}$ and $12D_{50}$ (D_{50} is the mean diameter of sand particle) for every normal stress. These proposed thicknesses cover the criteria given in the literature as well as some values are beyond literatures.

The large box shear FE model has been analyzed for maximum shear stress for given normal stress. The result for tangential displacements (for every thickness) has been compared to get a value that approximately matches with experimental data. Thus for every normal stress, the interface thickness has found out. The plot between interface thickness and normal stress gives the best fit prediction about interface thickness based on a variation of normal stress. The predicted equation further used for the execution of thin layer interface in soil-structure interaction problem.

5. Validation of Large DST with Thin Layer Interface

The plane strain idealization with boundary conditions of large DST in FE modeling [57-58] is shown in Fig. 3. Each box is of dimension 300 x 300 x 75 mm. Shear stress acts on the side of the structure portion, whereas normal stress acts on the top of the upper box. The thin layer interface is located between two boxes as shown in Fig. 3. By maintaining normal stress constant, shear stress is applied with each load step, and tangential displacement is determined. Both boxes and interface has been discretized into 8 noded isoparametric and 6 noded thin layer isoparametric plane strain elements respectively. For the structure part, concrete or mild steel material is used (analyzed as linear elastic) with a rough bottom in contact with the soil whereas sand is used in the upper box.

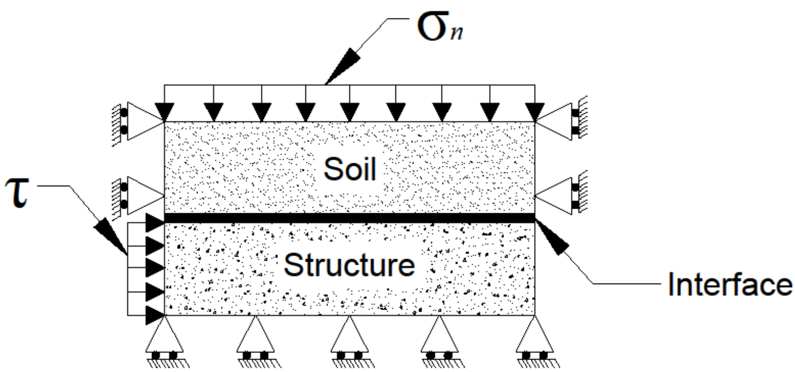
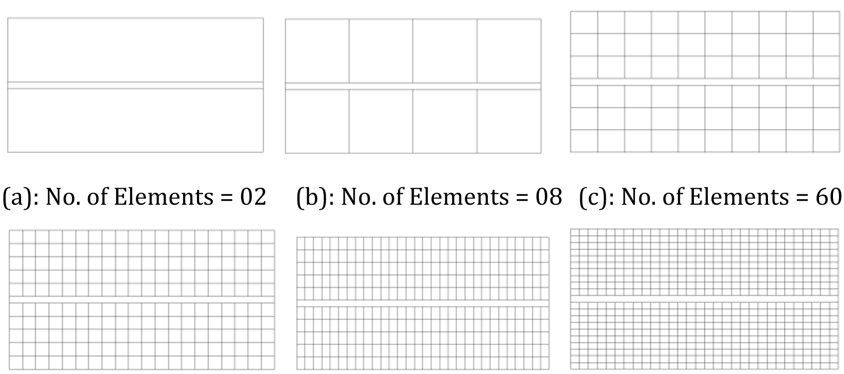


Fig. 3. Idealization of the large DST [57]



(a): No. of Elements = 02 (b): No. of Elements = 08 (c): No. of Elements = 60

(d): No. of Elements = 200 (e): No. of Elements = 300 (f): No. of Elements = 600

Fig. 4. Mesh configurations for large DST

Desai et al.'s example was used to conduct the mesh convergence study [1]. The linear elastic analysis is checked with various meshes as shown in Fig. 4 for the materials used by Desai et al. [1]. The result for tangential displacement (Table 1) is compared with the literature result.

The tangential displacement of large DST subjected to the normal stress of 0.955 N/mm^2 and shear stress of 0.5 N/mm^2 for all meshes is plotted in Fig. 5. The interface thickness is considered as 3mm for all mesh configurations. From Fig. 5, it is observed that the mesh configuration with 200 elements has been found optimum. Thus in further analysis, the same configuration of elements has been used. Also, the result for tangential displacement (mesh = 200 elements) from Table 1 is appropriately matching with literature results.

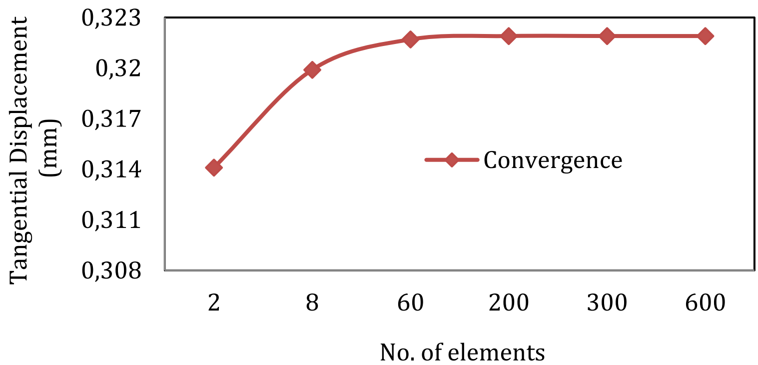


Fig. 5. Large box shear test mesh convergence analysis

Table 1. Validation with Desai et al. 1984[1]

Author	Tangential displacement (mm)
Desai et al.	0.34
Present Study	0.3219
% Variation	5.32 %

5.1. Prediction of interface thickness

The large box shear test performed on the soil-mild steel interface by Viladkar et al. [40] has been numerically modeled (section 5.0) in the present study to find out the interface thickness. The optimum mesh size as per Fig. 4(d) is used to discretize the soil, mild steel and interface. The experimental plot of tangential displacement against shear stresses for soil-mild steel interface shows non-linear nature. Thus, in addition to soil non-linearity; interface non-linearity has also been incorporated in the developed FE model. As the hyperbolic constitutive relation is used to represent soil and interface behavior as per section 3.2, the hardening and stiffness non-linearity can appropriately be included in the FE model. Hence, it is decided to analyze the system for maximum shear stress for given normal stress and the corresponding displacement is found out.

Table 2. Material properties for structure (Mild steel)

Sr. No.	Component	Elastic Modulus (N/mm^2)	Poisson's Ratio
1	Structure (Mild steel)	2.1 x 10^5	0.3

The structure part is modeled as mild steel (considered as linear elastic) with a rough side in contact with sand. The test had been carried by Viladkar et al. [40] for four normal stress conditions such as 40.8 kPa, 61.24 kPa, 81.65 kPa and 102.07 kPa as shown in Fig. 6. The mild steel, sand, and interface material properties are provided in Table 2, Table 3 and Table 4 respectively.

Table 3. Material properties for sand

Sr. No.	Description	Value
1	Soil Type	SP
2	Unit weight	16.3 kN/m^3
3	Relative Density	84%
4	Modulus Number ‘K’	700
5	Exponent ‘n’	0.50
6	Failure Ratio ‘Rf’	0.90
7	Cohesion ‘C’	0
8	The angle of Internal Friction ‘ϕ’	41^0
9	Poisson’s Ratio of sand	0.3
10	Mean diameter of sand particle ‘D_{50}’	0.25 mm

Table 4. Material properties for interface

Sr. No.	Description	Value
1	Modulus Number ‘k_j’	8625
2	Exponent ‘n’	0.662
3	Failure Ratio ‘Rf’	0.82
4	Adhesion ‘C_a’	0
5	The angle of Internal Friction 'ϕ'	29.3^0
6	Unit weight of water ‘γ_w’	0.00001 N/mm^3
7	Atmospheric pressure ‘P_a’	0.10132 N/mm^2

5.1.1 Result and Discussion

The graph of shear stress v_s shear displacement by Viladkar et al. [40] is shown in Fig. 6 for the various normal stress conditions. To determine the thickness of the interface, the FE model for large DST has been subjected to normal stress and maximum shear stress. Normal stress is kept constant throughout loading, while shear stress is applied in stages.

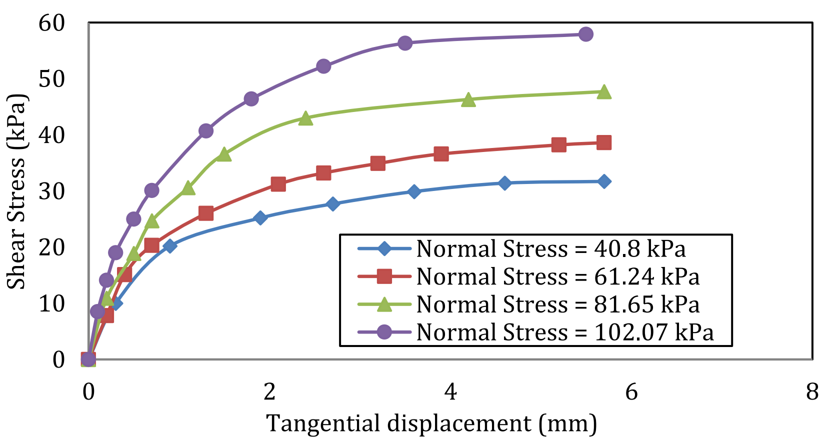


Fig. 6. Large box shear test result for sand-footing interface [40]

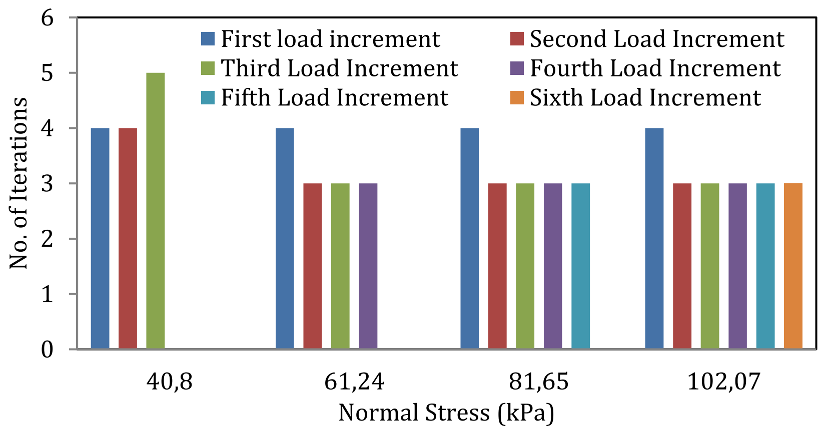


Fig. 7. No. of iterations performed for each normal stress during interface shear test

Fig. 8, Fig. 9, Fig. 10 and Fig. 11 show the results for tangential displacement (Experimental and FE model result) in interface shear test for each normal stress and maximum shear stress condition. (IT – Interface Thickness, σ_n – Normal stress and τ – Shear stress)

The no. of iterations performed by the FE model for each load increment till convergence is shown in Fig. 7. For every normal stress, four different interface thicknesses (such as $3D_{50}$, $5D_{50}$, $10D_{50}$ and $12D_{50}$) have been considered. The tangential displacement for maximum shear stress of every interface thickness has been compared and a value having good agreement with the experimental result is considered in further analysis. Hence interface thickness is found out for every normal stress.

Results observed from Fig. 8, Fig. 9, Fig. 10 and Fig. 11 show consistent in nature i.e. as the interface thickness is increased, the corresponding tangential displacement is also increased. Because in the formulation of thin layer interface, the element stiffness is indirectly proportional to interface thickness, hence if the thickness is increased the corresponding tangential displacement also increased. For Fig. 8 and Fig. 9, interface thickness equal to $5D_{50}$ show good results with 9 % and 1.53% difference with experimental results. Whereas, Fig. 10 with interface thickness of $10D_{50}$ demonstrates good agreement with experimental results with a difference of 1.63%. In case of σ_n = 102.07 kPa (Fig. 11), $12D_{50}$ interface thickness gives appropriate result (difference = 0.9 %). Thus it can be said that considering common interface thickness for every normal stress is not suitable. The available criteria for interface thickness from literature seem insufficient, as for every normal stress the interface thickness is changing.

The maximum average change in tangential displacement from $3D_{50}$ to $12D_{50}$ is about 13% to 15% from Fig. 8 to Fig. 11. In the present study only variation of normal stress has been considered for determination of interface thickness (to achieve the objective of the paper) whereas there are various parameters such as particle size, moisture content, density, interface adhesion, etc. are responsible for change in interface thickness as per the literatures. Hence due to change in interface thickness, the system's response is very robust.

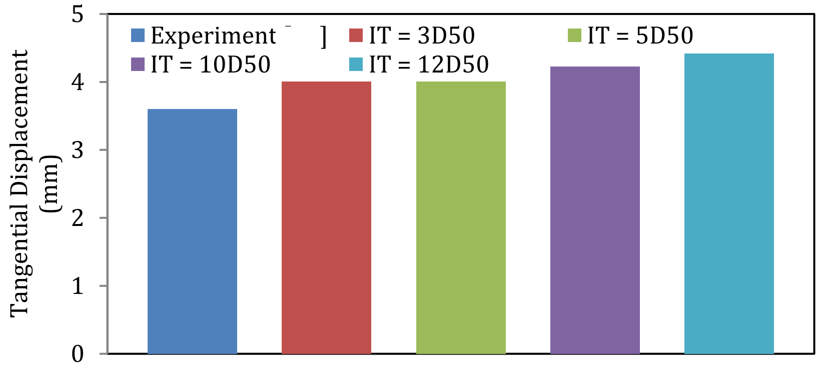


Fig. 8. Interface shear test - tangential displacement plot for σn = 40.8 kPa and τ = 30 kPa

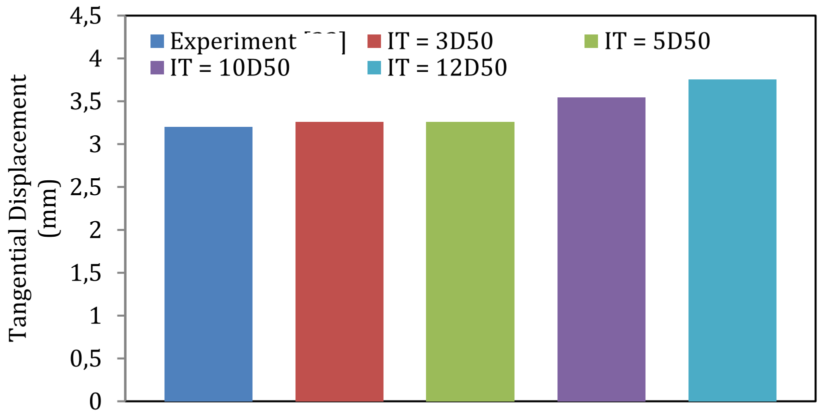


Fig. 9. Interface shear test - tangential displacement plot for σn = 61.24 kPa and τ = 35 kPa

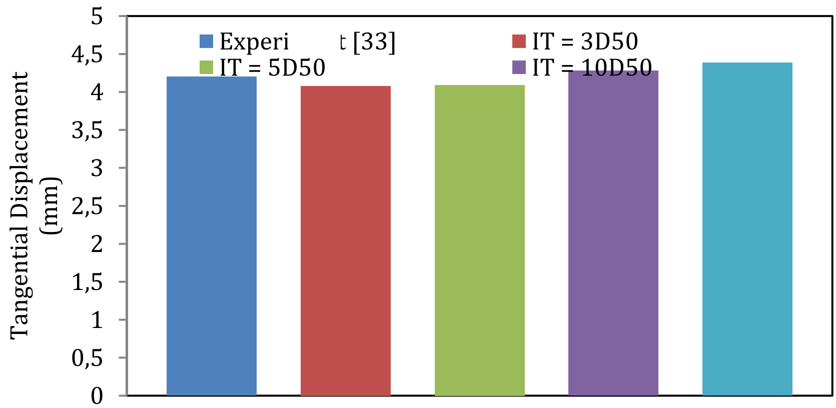


Fig. 10. Interface shear test - tangential displacement plot for σn = 81.65 kPa and τ = 46.3 kPa

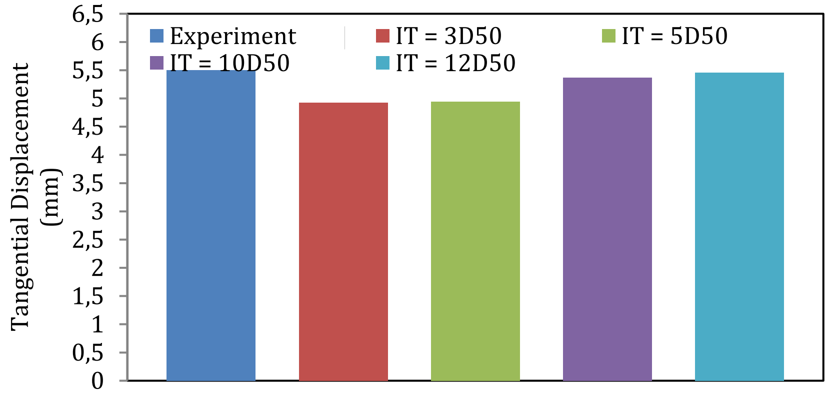


Fig. 11. Interface shear test - tangential displacement plot for σn = 102.07 kPa and τ = 57.9 kPa

The interface thickness (thickness which validates with experimental values) observed from Fig. 8, Fig. 9, Fig. 10 and Fig. 11 have been plotted against corresponding normal stress values shown in Fig. 12. The graph is useful in predicting interface thickness for various normal stresses.

It is observed from Fig. 12 that, the interface thickness is increasing as normal stress goes on increasing. The formation of a thin layer interface is because of rolling and slipping of the sand particle due to contact roughness. In the present investigation, normal stress is increasing in addition to contact roughness, thus additional sand particles may take part in the shearing action. Therefore, such condition leads to increase in the interface thickness with respect to increase in normal stress.

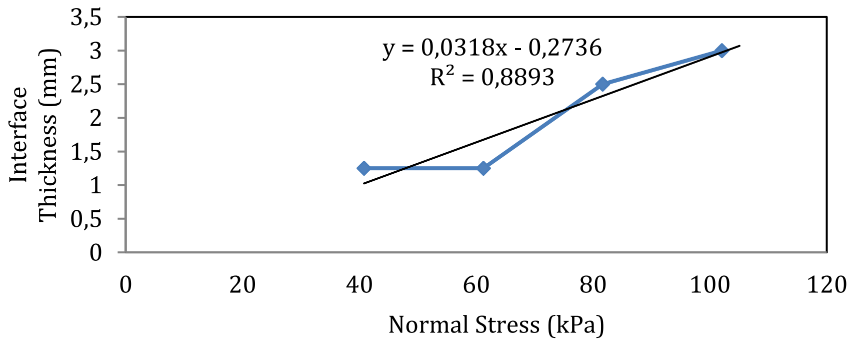


Fig. 12. Variation of interface thickness against normal stress

The graph shown in Fig. 12 has been fitted with a linear equation. The equation shows the prediction of interface thickness for various normal stress values. Present investigation is a proposed methodology for effective evaluation and execution of interface thickness hence the equation in Fig. 12 is limited for this particular study only. If the interface thickness (according to equation in Fig. 12) is less than $5D_{50}$ then the minimum thickness of $5D_{50}$ can be consider for analysis. To execute the predicted equation from Fig. 12, the FSI problem subjected to inclined-eccentric load has been solved with the developed FE model.

6. Implementation of Interface Thickness for SSI Analysis

The FSI problem experimented by Agrawal [59] and numerically modeled by Viladkar et al. [40] and Zedan [60] for zero thickness interface element has been considered in the present investigation for the execution of thin layer interface. The FE model has been developed as shown in Fig. 13. The settlement and horizontal displacement of the footing with a thin layer interface are compared and validated with an experimental and zero thickness FSI system. The thickness evaluation for the FSI problem has been carried out from the equation given in Fig. 12.

FSI system has consisted of strip footing resting on sand and subjected to eccentric inclined loads. The FE model is developed as a plane strain problem. Considering the thin layer interface, 3 different cases are analyzed (Fig. 14), such as,

Case I: $D_f/B = 0$; $e/B = 0.2$ and angle of inclination for inclined load with vertical = 15^0

Case II: $D_f/B = 0$; $e/B = 0.2$ and angle of inclination for inclined load with vertical = 10^0

Case III: $D_f/B = 0$; $e/B = 0.2$ and angle of inclination for inclined load with vertical = 5^0

where, 'D_f' is depth of the footing, 'B' is width of the footing and 'e' is eccentricity of load.

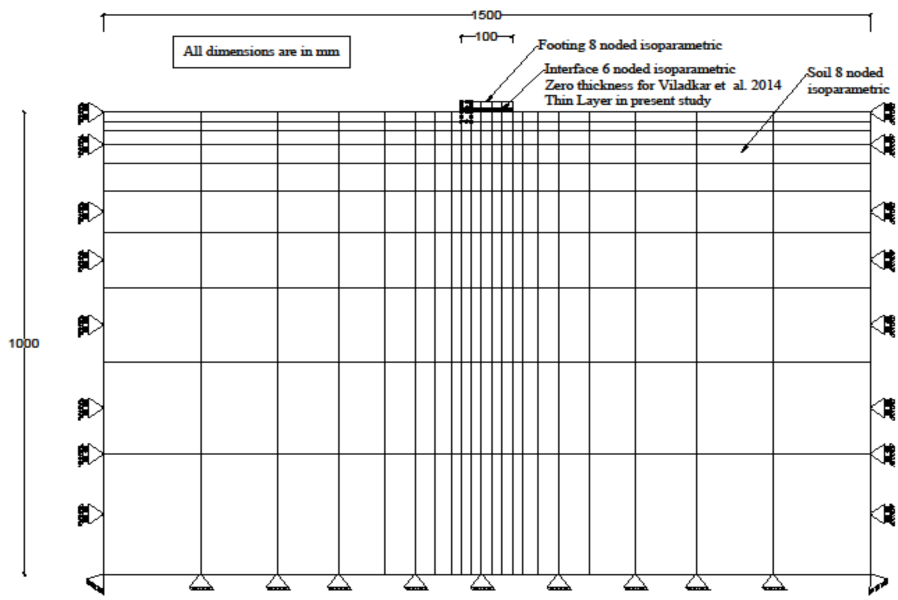
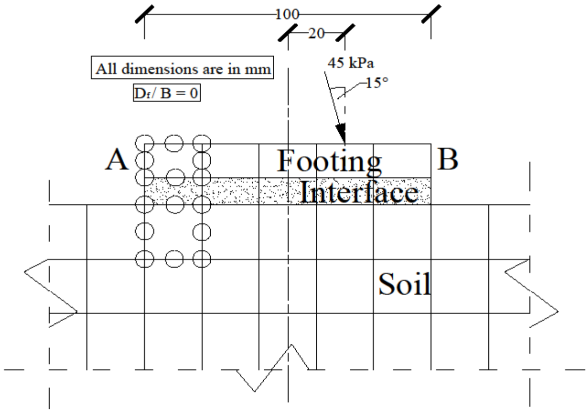
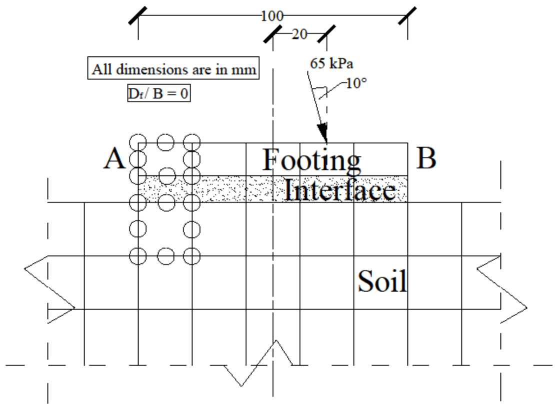


Fig. 13. FE model for FSI system

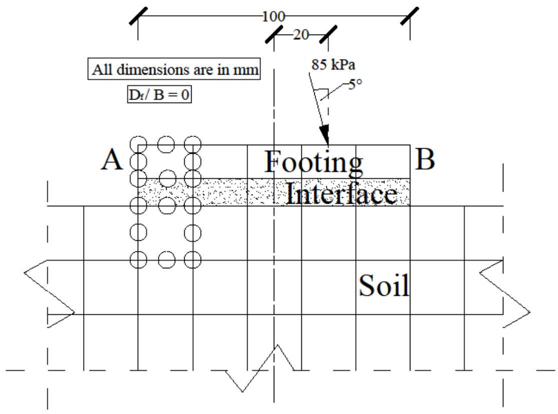
The soil and footing are discretized with 8 noded isoparametric elements whereas the interface is discretized as 6 noded thin layer interface element. The constitutive relations as discussed in section 3.2 are used for soil and interface. The footing is considered to be made up of mild steel (thickness = 12mm) with the same roughness in contact with soil as that of large DST mild steel specimen. The materials used for carrying out FSI analysis are same as that of large DST as discuss in section 5.1. Table 2, Table 3 and Table 4 show the properties for footing, soil and interface.



(a) Case I



(b) Case II



(c) Case III

Fig. 14. Various cases considered for eccentric inclined loading in FSI problem

The interface thickness for the case I, case II and case III are 1.25 mm, 1.71 mm and 2.35 mm respectively. The thickness has been calculated based on the maximum normal stress acting on the footing from equation in Fig.12.

6.1. Result and Discussion

The FSI system with a thin layer interface's non-linear analysis (Fig. 13) for various cases (Fig. 14) has been carried out with a mixed incremental iterative procedure. The plot between pressure-settlement and pressure-horizontal displacement at end B (Fig. 14) of the footing for various cases are shown in Fig. 15 (a), Fig. 15 (b), Fig. 16 (a), Fig. 16 (b), Fig. 17 (a) and Fig. 17 (b).

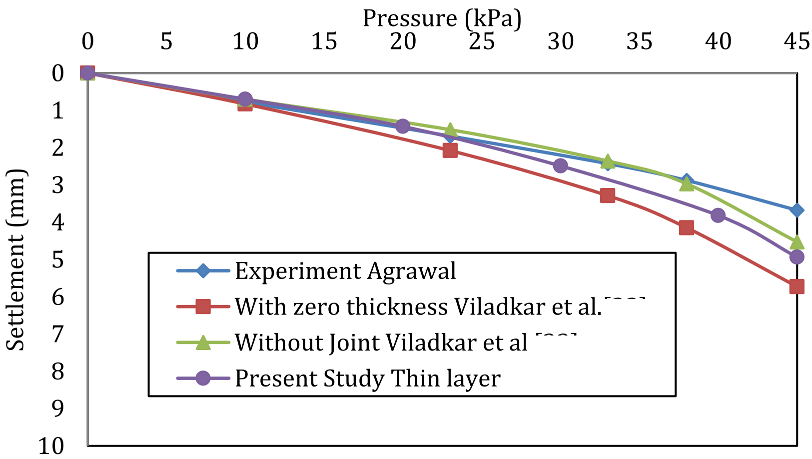


Fig. 15 (a). Pressure-Settlement plot for Case I

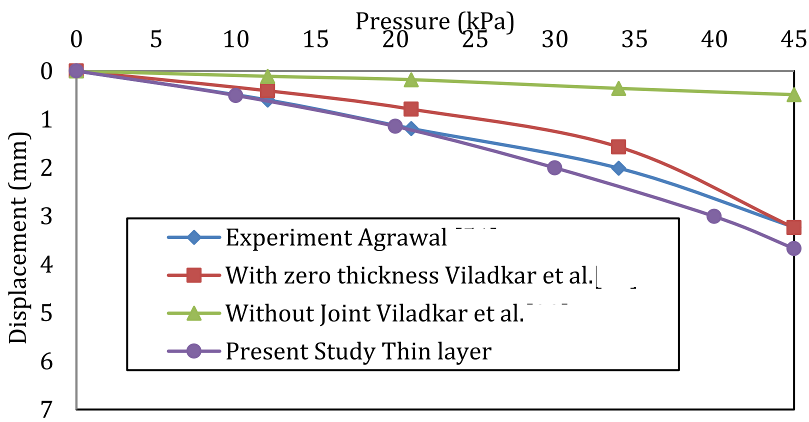


Fig. 15 (b). Pressure-Horizontal displacement plot for Case I

Fig. 15 (a) and Fig. 15 (b) shows the results for experimental analysis by Agrawal [59], numerical analysis (without interface and with zero thickness interface) by Viladkar et al. [40] and analysis considering thin layer interface as present investigation. For pressure-settlement, the effect of the interface is negligible because of the full bond between soil and footing. Wherein, pressure-horizontal displacement plot shows the necessity of interface. It is also reported that the results for settlement and horizontal displacement considering thin layer interface shows very good agreement with the experimental result.

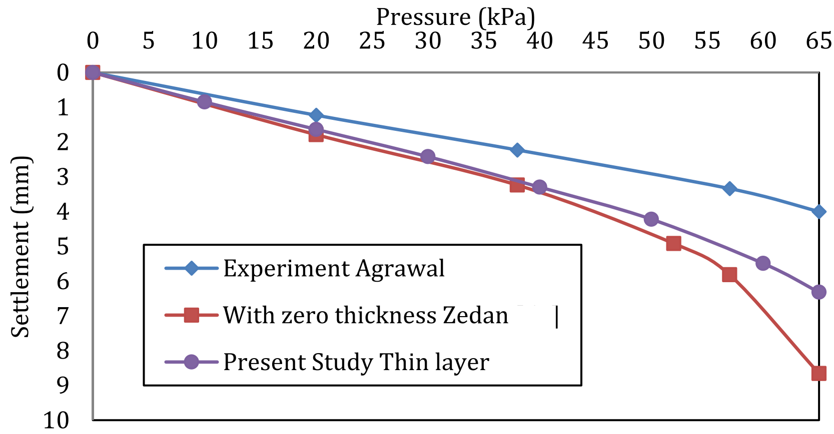


Fig. 16 (a). Pressure-Settlement plot for Case II

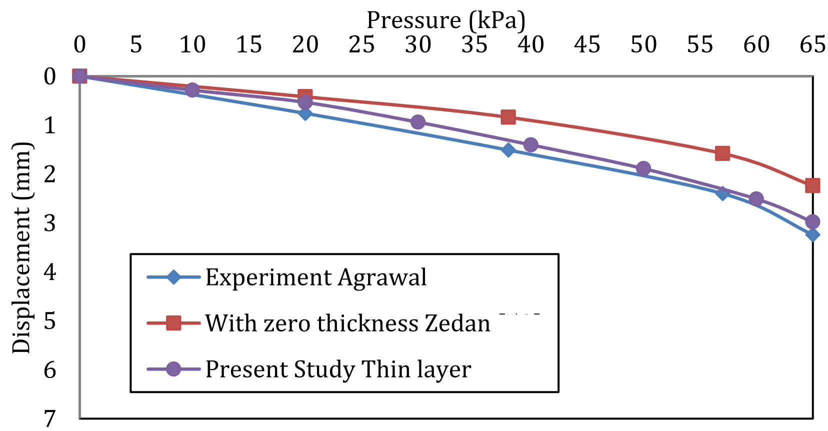


Fig. 16 (b). Pressure-Horizontal displacement plot for Case II

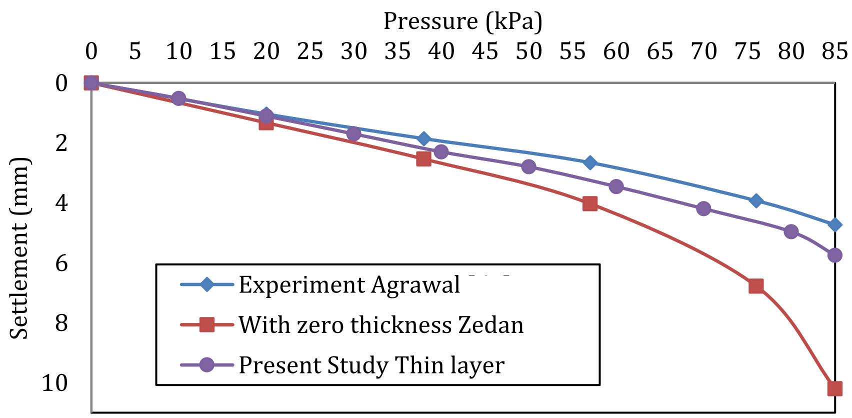


Fig. 17 (a). Pressure-Settlement plot for Case III

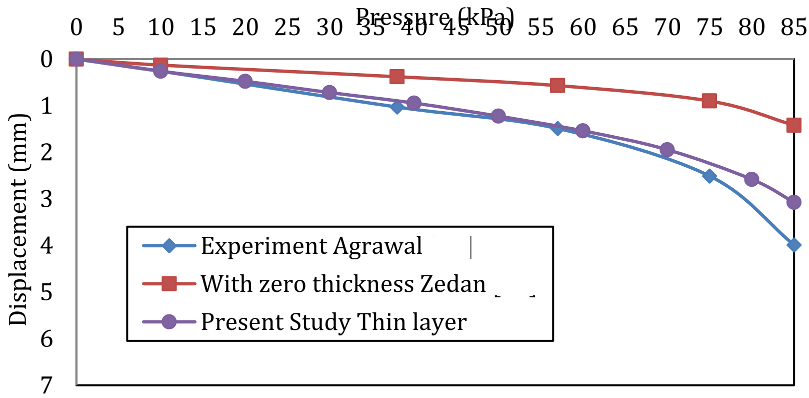


Fig. 17 (b). Pressure-Horizontal displacement plot for Case III

It is observed from Fig. 16 (a) to Fig. 17 (b) that the settlement and horizontal displacement considering thin layer interface shows appropriately matching results with experimental analysis. It is also noted that the results considering thin layer interface are superior to zero thickness interface. It may be because of consideration of normal stiffness for thin layer interface as 'E_T/t' and not a constant value. Thus, such value is giving more appropriate results than the constant value. Also by considering this normal stiffness, the interface nodes are not penetrating thus it satisfies the contact stiffness criteria.

In addition to the above, due the roughness of footing in contact with the soil; the soil particles are rotate and slip during the application of lateral loads thus it is obvious to form the thin shear zone just beneath the footing which is called as thin layer interface. Hence the SSI model with thin layer interface is giving realistic results as compared to the zero thickness interfaces.

There are some results such as Fig. 16 (a) and Fig. 17 (a), where the settlement by thin layer interface showing more than 10% difference with respect to experimental values. Such difference may due to consideration of only normal stress for deciding the interface thickness. Whereas there may be a few other parameters responsible for interface thickness, such as surface roughness, particle size, and soil type, which need to be investigated further.

7. Conclusions

There are numerous advantages of using a thin layer interface over a zero-thickness interface. The selection of interface thickness is important and must be deal with caution. The methodology for effective usage (in terms of interface thickness) of the thin-layer interface in FE modeling of the SSI system has been investigated in this work. The following findings are reached from the evaluation and execution of interface thickness,

- The parameters which are responsible for interface thickness such as, surface roughness, particle size, normal stress and soil type are varying for every soil condition. Thus, the criterion for interface thickness based only on D_{50} looks insufficient. Hence there is a need to propose a methodology consisting of these parameters for predicting appropriate interface thickness.
- The proposed methodology, which was used to evaluate interface thickness while taking normal stress into account, is also applicable to other contributing parameters.

- The non-linear hyperbolic model is suitable for modeling large DST. Thus it is useful in the evaluation of interface thickness.
- The relation between interface thickness and normal stress (derived from numerical validation of large DST) is useful in predicting interface thickness based on normal stress value. In general, such methodology can be adopted for various SSI systems for interface thickness prediction.
- The pressure-settlement response in the FSI system is independent of interface effect whereas under lateral and eccentric-inclined loading condition for appropriate horizontal displacement, interface consideration is necessary.
- The results for settlement and horizontal displacement in the FSI system considering thin layer interface have been improved in comparison to the zero-thickness interface.
- The proposed methodology for effectively utilizing thin layer interfaces in FE modeling of SSI problems has been successfully applied.

In order to obtain the more realistic results of SSI system, the consideration of proper thickness of thin layer interface (considering all variations in soil and structure) and advanced constitutive model is necessary.

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