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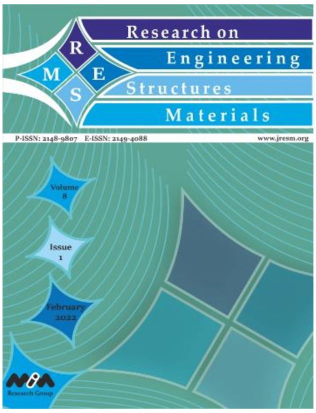

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Online Publication Date: 13 Oct 2021

URL: http://www.jresm.org/archive/resm2021.322st0702.html

DOI: http://dx.doi.org/10.17515/resm2021.322st0702

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article

Dhadse GD, Ramtekkar G, Bhatt G. Influence due to interface in finite element modeling of soil-structure interaction system: a study considering modified interface element. *Res. Eng. Struct. Mater.*, 2022; 8(1): 127-154.

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Research Article

Influence due to interface in finite element modeling of soil-structure interaction system: a study considering modified interface element

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Article Info

Article history:
Received 02 July 2021
Revised 31 Aug 2021
Accepted 6 Oct 2021

Keywords:

Soil-Structure Interaction; Interface Modeling; Interface Non-Linearity; De-bonding; Finite Element Analysis; Solid to Skeletal Contact

Abstract

The finite element (FE) modeling of interface in Soil-Structure Interaction (SSI) problem is most important aspect from early days of modeling i.e. during 1960. The overall performance of the structure is completely influenced due to behavior of interface. Such as realistic interface modeling of SSI system subjected to lateral loads leads to appropriate evaluation of lateral sway and base shear stress. During recent times, many modifications have been done in interface modeling such as incorporation of slip and bonding effects. Also the interface joining variable degrees of freedom system (interface for solid to skeletal contact) has come into existence. Still the de-bonding behavior, interface non-linearity as well as modification in solid to skeletal contact has been unexplored in literatures. Hence there is necessity to develop a FE-SSI model and to study the influence of interface in SSI system considering unexplored features. In this paper, an attempt has been made to show the influence due to interface (including de-bonding and non-linearity) in FE modeling of SSI system using modified 5 noded zero thickness interface element. The performance of modified interface element is a novel contribution in present paper. The present study is limited to static loading conditions only. The effect of interface has been studied by determining bending moment, lateral sway, base shear stress and footing settlement in structure. The inclusion of modified interface has improved the performance of structure by reducing the base shear stress and allowing the sway. Also, the true redistribution of bending moment has been observed after considering the modified interface.

1. Introduction

The modeling of soil-structure interface model considering slip, bonding and de-bonding at soil-structure junction including interface non-linearity is an active topic of research. During 1960's, the researchers started working on interfaces with finite element method. The performance of the structure is highly influenced by interface between soil and structure [1-2]. Hence modeling the interface considering realistic physical condition is an important task [3]. In early days of research, the interface between solid-solid contacts has been studied considering slip and bonding. Later stages the need of soil non-linearity has been investigated for interface performance. The solid-solid contacts don't suitable for representation of all physical cases. Hence the need of solid-skeletal interface has been arisen. As a results zero thickness solid-skeletal interface came into existences during 1990's. Later years, the thin layer interfaces have been invented as an alternative modeling consideration to zero thickness interface. The modification in solid-skeletal interface has been reported by few authors stating the suitability as per physical condition [4-5]. Thus by modeling the interface as per physical conditions, the realistic SSI modeling can be executed [5-7]. The appropriate modeling of interface is applicable to many SSI problems for evaluation of true settlement, lateral displacement, etc. [8-11].

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DOI: http://dx.doi.org/10.17515/resm2021.322st0702

The inclusion of interface in SSI modeling alters the performance of structure. The interfaces allow the structure to slip, bond and de-bond with soil mass [12-15]. Frequently the researchers have been focused on slip and bonding analysis in interface [16-18]. De-bonding has been unexplored due to occurrence of numerical ill-conditioning [19-20]. Interfaces were also used as a geometric attachment to various dissimilar materials where relative motion is not of great importance [21-22].

As per Aivazzadeh and Verchery [23], the discontinuous deformations and stresses at the junction of two dissimilar materials are taken care by the interfaces. The presence of interface permits the slip, bonding and de-bonding between soil-structure contacts and redistributes the member forces in structure [15, 19, 24]. The consideration of bonding and de-bonding in addition to slip at interface has improved the performance of SSI analysis in this paper.

According to the literature available on interface modeling for two dissimilar materials, there are two types of zero thickness interfaces. The first type consists of solid-to-solid contact whereas the second type consists of solid to skeletal contact. As of now, various interface elements have been presented by researchers. The solid-to-solid contact element includes modified Goodman's element by Viladkar et al. [25], axisymmetric element by Rafael et al. [12] and Sharma et al. [26]. Whereas solid to skeletal contact element includes 3 noded isoparametric zero thickness interface element proposed by Viladkar et al. [19], Noorzaei et al. [27] and 5 noded thin layer isoparametric interface element by Dalili et al. [24]. These solid to skeletal elements are of special importance as they used to combine variable degree of freedom (DoF) system at interface. Few researchers commented on computational difficulties observed in zero thickness interface elements, such as meshing and ill-conditioning due to aspect ratio [26, 28-30]. Mayer and Gaul [31] suggested the zero thickness elements have been most compatible for Solid-to-Solid contact due to independency of contact stiffness on interface thickness. One more special interface for solid to beam element is suggested by Jang-Keun Lim et al. [21]. This element is used as a geometric arrangement for joining variable DoF system. The execution of zero thickness interfaces in many SSI problems has proved its feasibility. In this paper, the thin layer interface element proposed by Dalili et al. [24] has been modified to zero thickness interface with non-linearity for studying the influence of interface in SSI system.

In present scenario, the interfaces are used in almost all SSI problems. But the modeling of interface considering realistic physical condition is unexplored and needs to be address precisely. As a result, the de-bonding at soil-structure junction in addition to slip and bonding as well as interface non-linearity has been considered in this paper to get acquainted with field conditions. Also, the SSI analysis has been carried with modified interface element. Hence the obtained results are more appropriate because of the realistic modeling than that of earlier research. Presently the scope of study has been restricted to static loading only. The methodology presented in this study will definitely put foundation of future research such as dynamic SSI analysis with realistic interface modeling.

The primary objective of this study is to investigate the influence due to interface in FE modeling of SSI system. The study is essential to understand the bonding and de-bonding in addition to slip at interface. The investigation has been completed with modified 5 noded zero thickness interface element with non-linearity, which is a novel contribution.

2. Problem Definition

From the reviewed literatures, it has been observed that, the modeling of soil-structure interface needs to be explored in more details such as; realistic physical condition must be taken into considerations. As a result, the appropriate performance of structure and soil can be evaluated. Hence the realistic modeling of interface has been carried out by modified 5 noded zero thickness interface elements, considering de-bonding in addition to slip and bonding as well including non-linearity. Therefore, considering all such modifications, the appropriate influence due to interface on SSI system has been studied.

In order to study the influence due to interface on SSI system, a frame structure with combined footing resting on soil subjected to vertical and lateral loads has been considered. In this problem, the interface is used to study slip, bonding and de-bonding at soil-structure junction. The FE model of SSI system with interface has been developed on MATLAB platform. The superstructure and footing have been modeled as 2 noded beam bending elements having 3 DoF per node and soil is modeled as 8 noded plane strain isoparametric elements with 2 DoF per node. The interface is modeled as 5 noded zero thickness isoparametric element. The soil and interface non-linearity have also been included in FE model. The elements used in FE model are shown in Fig. 1.

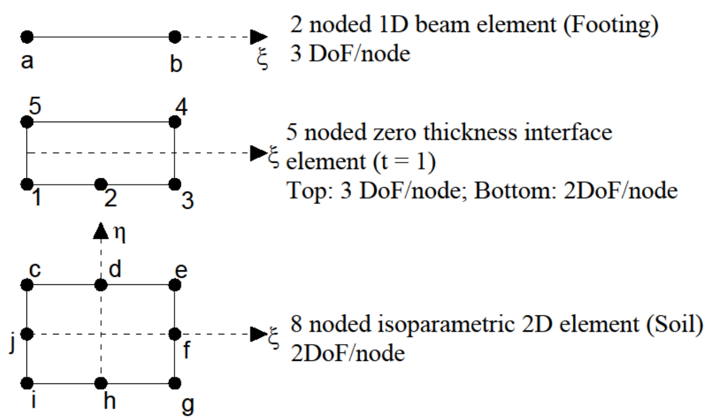


Fig. 1 Elements used in the FE Model of frame footing Soil Interaction System (t – thickness of interface)

3. Mathematical Formulation

3.1. Frame, Footing and Soil Element

For modeling the frame and combine footing, 2 noded isoparametric beam bending element has been used. The detailed formulation with the stiffness matrix is referred from Chandrupatla and Belegundu [32]. The geometry of the element is shown in Fig. 2.

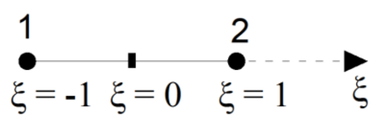


Fig. 2 Two noded isoparametric beam bending element

The idealization of the soil has been done by using quadrilateral 8 noded isoparametric plane strain element (Fig. 3). The selection of element is helpful in getting high-stress concentration near footing [19, 33]. Also, it is reported that the element is compatible with various soil constitutive models. The detailed mathematical formulation for this element is referred from Chandrupatla and Belegundu [32].

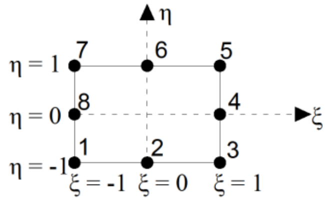


Fig. 3 8 noded isoparametric plane strain element

3.2. Interface Element

The soil-structure interface is an important component for modeling of SSI system. Interface connects soil and structure as well as allows structure to slip, bond and de-bond at soil-structure junction. In present study, the interface has been used to connect soil and beam element with consideration of slip, bond and de-bond as well as inclusion of non-linearity.

The thin layer interface element proposed by Dalili et al. [24] has been modified for zero thickness as given below. The element is compatible with 2 noded isoparametric beam bending element and 8 noded isoparametric plane strain soil element. The geometrical details of the element are shown in Fig. 4.

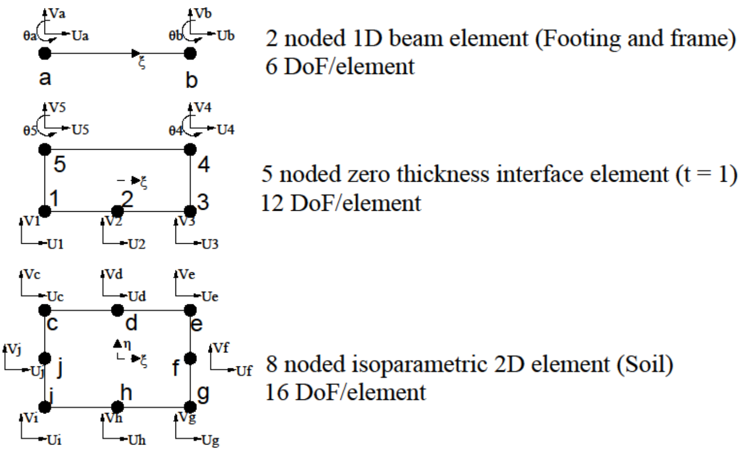


Fig. 4 Geometrical details of 5 noded zero thickness interface element with adjacent element

As per the geometrical details, the interface element is having 12 DoF. The upper part is having 3 DoF per node wherein the lower part is having 2 DoF per node. The element thickness is considered to be unit, though it is called zero thickness interface [19].

The formulation of 5 noded zero thickness interface element has been initialized with combining two one dimensional 3 noded isoparametric element separated by unit thickness as shown in Fig. 5. But the top layer of the interface element is attached to 2 noded beam elements hence incompatibility has been raised due to middle top node as shown in Fig.5. As a result, the middle node has been eliminated in Fig. 4. The corresponding displacement of the node is reported as an average displacement of adjacent upper nodes as given in equation 1. Thus, using equation 1, the transformation matrix has been developed (equation 2).

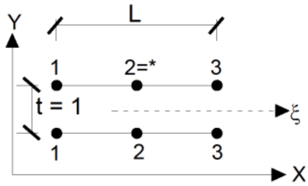


Fig. 5 Formation of 5 noded zero thickness element with two-three noded 1D element

According to Fig. 4, the displacement compatibilities are shown in Table 1.

Table 1. Displacements Compatibility with Soil and Beam element [24]

Node 1	U1 = Uc	V1 = Vc	
Node 2	U2 = Ud	V2 = Vd	
Node 3	U3 = Ue	V3 = Ve	
Node 4	U4 = Ub	V4 = Vb	θ4 = θb
Node 5	U5 = Ua	V5 = Va	θ5 = θa

$$U^{*}=\frac{U_a+U_b}{2} \qquad V^{*}=\frac{V_a+V_b}{2} \qquad \theta^{*}=\frac{\theta_a+\theta_b}{2} \tag{1}$$

where,

U = horizontal displacement, V = vertical displacement and θ = rotation

Therefore, considering Δ as a vector of interface element displacement and δ as a vector of adjacent element displacement, the relation between Δ and δ has been formed using transformation matrix [T] (equation 2 and 3) .

$$\begin{Bmatrix} U1\\ V1\\ U2\\ V2\\ U3\\ V3\\ U4\\ V4\\ \theta 4\\ U*\\ V*\\ \theta *\\ U5\\ V5\\ \theta 5 \end{Bmatrix}_{15x1} = \begin{bmatrix} 1&0&0&0&0&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0&0&0&0&0\\ 0&0&1&0&0&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0&0&0&0\\ 0&0&0&0&1&0&0&0&0&0&0&0\\ 0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&0&0\\ 0&0&0&0&0&0&0&1&0&0&0&0\\ 0&0&0&0&0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0.5&0&0&0.5&0&0\\ 0&0&0&0&0&0&0&0.5&0&0&0.5&0\\ 0&0&0&0&0&0&0&0&0.5&0&0&0.5\\ 0&0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&1&0\\ 0&0&0&0&0&0&0&0&0&0&0&1 \end{bmatrix}_{15x12} . \begin{Bmatrix} U_c\\ V_c\\ U_d\\ V_d\\ U_e\\ V_e\\ U_b\\ V_b\\ \theta_b\\ U_a\\ V_a\\ \theta_a \end{Bmatrix}_{12x1} \tag{2}$$

$$\Delta_{15x1}=[T]_{15x12}.\delta_{12x1} \tag{3}$$

As the interface element is of isoparametric type, the displacements and rotations at any point in an element are expressed in terms of shape functions (equation 4).

$$\Delta U = \sum_{i=1}^{n} N_i U_i$$
$$\Delta V = \sum_{i=1}^{n} N_i V_i \qquad (4)$$
$$\Delta \theta = \sum_{i=1}^{n} N_i \theta_i$$

Therefore from Fig. 5, the shape functions at node 1, 2 and 3 is written as, (equation 5)

$$N_1 = -\frac{1}{2}\xi(1-\xi),$$
$$N_2 = (1-\xi^2), \qquad (5)$$
$$N_3 = \frac{1}{2}\xi(1+\xi),$$

The element is having a unit thickness; thus, the strain displacement relation has been written in terms of relative displacement of upper and lower nodes as shown in equation 6 [19, 24]. Also, it has been reported that the coordinates of upper beam nodes and lower soil top nodes along with interface element nodes are same; hence the element is called a zero-thickness interface element.

$$\varepsilon = \begin{Bmatrix} \varepsilon_{s1} \\ \varepsilon_n \\ \varepsilon_{s2} \end{Bmatrix} = \frac{1}{t}\begin{Bmatrix} \overline{\Delta U} \\ \overline{\Delta V} \\ \overline{\Delta \theta} \end{Bmatrix} = \frac{1}{t}\begin{Bmatrix} U_{top} - U_{bottom} \\ V_{top} - V_{bottom} \\ \theta \end{Bmatrix}$$

$$\because t = 1$$

$$\begin{Bmatrix} \varepsilon_{s1} \\ \varepsilon_n \\ \varepsilon_{s2} \end{Bmatrix} = [B]\{\Delta\} = [B][T]\{\delta\} = [B_J]\{\delta\} \qquad (6)$$

ε_{s1}, ε_n and ε_{s2} are tangential, normal and rotational strain respectively corresponding to $\Delta U, \Delta V$, and $\Delta\theta$. Therefore, strain displacement matrix [B_J] as per Viladkar et al. [19] is given in equation 7.

$$[B_J] = \begin{bmatrix} -N_1 & 0 & -N_2 & 0 & -N_3 & 0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 & 0 \\ 0 & -N_1 & 0 & -N_2 & 0 & -N_3 & 0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & N_1 & 0 & 0 & N_2 & 0 & 0 & N_3 \end{bmatrix} . [T] \qquad (7)$$

The stresses at any point in interface element are related to corresponding strain by constitutive relation in equation 8 in local coordinates. It has been also noted that the parameters in stress-strain relation are in non-linear form, the details are elaborated in a further section.

$$\begin{Bmatrix} \tau_s \\ \sigma_n \\ M \end{Bmatrix} = \begin{bmatrix} K_{ss1} & 0 & 0 \\ 0 & K_{nn} & 0 \\ 0 & 0 & K_{ss2} \end{bmatrix} \begin{Bmatrix} \varepsilon_{s1} \\ \varepsilon_n \\ \varepsilon_{s2} \end{Bmatrix}$$

$$\{\sigma\} = [D]\{\varepsilon\} \tag{8}$$

Here τ_s, σ_n and M are known as tangential stress, normal stress and moment corresponding to $\varepsilon_{s1}, \varepsilon_n$, and ε_{s2}. Also K_{ss1}, K_{nn} and K_{ss2} are tangential, normal and rotational stiffness respectively.

The relation matrix [D] is written in a global form as,

$$[D_{global}] = [D_g] = [R]^T \begin{bmatrix} K_{ss1} & 0 & 0 \\ 0 & K_{nn} & 0 \\ 0 & 0 & K_{ss2} \end{bmatrix} [R]$$

where,

$$[R] = \begin{bmatrix} \frac{1}{J}\frac{dx}{d\xi} & \frac{1}{J}\frac{dy}{d\xi} & 0 \\ -\frac{1}{J}\frac{dy}{d\xi} & \frac{1}{J}\frac{dx}{d\xi} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

and

$$J = Jacobian = \left[\left(\frac{dx}{d\xi} \right)^2 + \left(\frac{dy}{d\xi} \right)^2 \right]^{\frac{1}{2}}$$

Therefore, the element stiffness matrix in global form for the interface is written as,

$$[K] = \int [B]_J^T [D_g] [B]_J \, dv$$

$$[K] = \sum_{gp=1}^{n} [B]_J^T [D_g] [B]_J |J| W_{gp} \tag{10}$$

$gp = gauss\ pt.$

$W_{gp} = weights$

The above formulation for structure, soil and interface has been used to develop a FE model using MATLAB for the analysis of frame-footing and soil interaction system.

4. Soil and Interface Non-Linearity

Soil is a non-linear material; as a result, many constitutive relations have been established to model its appropriate behavior. In present study, sand is used, hence amongst the well-established constitutive models, Duncan-Chang hyperbolic model has been used to represent the non-linear nature of soil [34-35]. This model is mainly based on the stress-strain curves of drained triaxial compression tests of sands and clays. Its failure criterion is based on the Mohr-Coulomb model. Also, the model has been worked on associated flow rule and non-linearity of stiffness parameters has also been included [36]. The model has some limitations such as neglecting volume change and unloading stiffness hence it is called a non-linear elastic model. Due to the versatile nature of the model, it is amongst the commonly used model for SSI analysis [19]. This model calculates the tangent modulus (E_T) at any stress level using equation 11. The parameters 'K' and 'n' in equation 11 have been used to predict the in-situ condition from stress-strain relation. The parameters predominately depend on the stress-strain response of material as a result there is no specific range for 'K' and 'n'.

$$E_T = \left[1 - \frac{R_f(1-\sin\varphi)(\sigma_1-\sigma_3)}{2(C\cos\varphi+\sigma_3\sin\varphi)}\right]^2 K.P_a\left(\frac{\sigma_3}{P_a}\right)^n \tag{11}$$

where, 'K' is Modulus number, 'P_a' is atmospheric pressure, 'σ_1' and 'σ_3' are major and minor principal stresses, 'φ' is the angle of friction, 'R_f' is failure ratio, 'n' is an exponent. The incremental loading is used to calculate 'E_T' at any stress level. As 'E_T' is a stress-dependent parameter, its value is updated based on earlier stress level.

The variation of stress-strain at the interface has been considered as hyperbolic. In the present study, the hyperbolic relation given in equation 12 has been used for calculation of tangential stiffness and assumed an arbitrary high value for normal stiffness [19]. The reason of choosing high value of normal stiffness is that, the interface node should not intersect at soil-footing junction. These arbitrary normal stiffness values are chosen from the permissible range (i.e. 10^5–10^{10} kN/m^3) through trial and error basis [19]. In this research the normal stiffness of 10^8 kN/m^3 has been chosen by taking reference from Viladkar et al. [25]. The hyperbolic behavior of interface (tangential stiffness) is given as,

$$K_{ss1} = (1-\lambda_2)^2 K_i$$

$$K_i = k_j\gamma_w\left[\frac{\sigma_n}{P_a}\right]^n \tag{12}$$

$$\lambda_2 = \frac{R_f\tau}{(C_a+\sigma_n\tan\varphi)}$$

where, 'K_i' is initial stiffness, 'γ_w' is the unit weight of water, 'C_a' is adhesion at the interface, 'τ' is shear stress, 'φ' angle of friction, 'P_a' is atmospheric pressure, 'R_f' is failure ratio, 'σ_n' is normal stress, 'n' is the exponent and 'k_j' is modulus number. The value of tangential stiffness is obtained in incremental loading at every load step. Also, K_{ss1} is evaluated as a function of 'σ_n' and 'τ' at any stress level of non-linear analysis.

Few literatures have suggested the values for 'K_s' and 'K_n' at soil-structure interface. Thus, for full bond case it is in between 10^5–10^{10} kN/m^3, whereas for no bond case 'Ks' is zero and 'Kn' is in between 10^5–10^{10} kN/m^3 [25].

5. Methodology

In order to model the realistic SSI system with modified interface, it is necessary to write a FE program consisting of soil and interface non-linearity. Hence it is decided to develop the FE model in MATLAB. The developed model has been validated with literature and then it has been used for studying the influence due to interface on SSI system. Hence such methodology is useful in tackling present problem.

The FE model of SSI system was developed using MATLAB. This model is formed of the soil, footing and frame. It also considers the interface between the different modeled elements and it is capable of handling multiple DoF systems. The developed FE model includes soil and interface non-linearity with the incremental iterative process which is helpful in carrying out realistic SSI analysis.

The convergence in non-linear analysis has been achieved by residual forces. The tolerance of 1 % for residual forces has been chosen. The residual forces are checked against tolerance limit. If the solution does not converge, the residual forces are again calculated and applied on the structure so that the corresponding displacement is calculated and sum up to the total displacement. The process is continued till convergence is achieved. If convergence has not achieved till 15th iteration, then solution will stop. After convergence, the next load increment is applied and the same process is repeated.

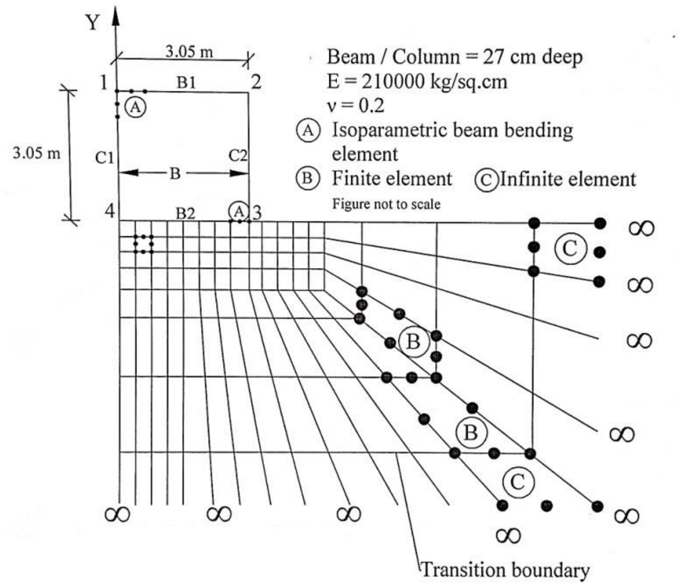
In order to validate the FE model, the SSI example from Viladkar et al. [37] has been solved with the developed FE model. After validating the results, further analysis has been carried out for understanding the influence of interface in frame-footing-soil interaction system with modified interface element.

The methodology is versatile and it can be used to analyze realistic SSI system with interface.

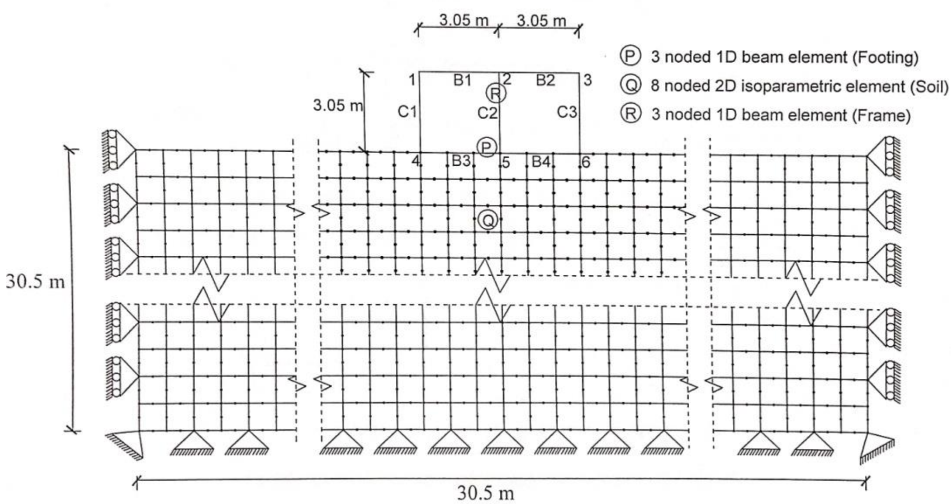
6. Validation of the FE model

The developed FE model has validated with Viladkar et al. [37] model for Bending Moment and Settlement of the Footing. Viladkar et al. [37] has used finite-infinite elements for modeling soil as linear elastic and non-linear elastic. The frame structure with combined footing has modeled as 3 noded isoparametric beam bending element. In the present study, a similar model has been prepared in MATLAB with soil as finite element (8 noded isoparametric plain strain element) and other components are same as that of Viladkar et al [37]. The finite extent of soil mass has been modeled in such a way that, the deformations in x and y directions up to 0.5 m from the boundary is approximately null. Also, the finite extent of soil mass has been decided on the basis of pressure bulb. Thus, the boundaries were put beyond the pressure bulb limit as a result the boundaries are not reflecting wave towards the model. Hence it has been concluded that, 30.5 m x 30.5 m extent of soil mass is behaving like infinite soil for the frame considered by Viladkar et al. [37] (Fig. 6 (a)). The mesh sensitivity study has been carried out on extent of soil mass and mesh size of 1017 x 1017 mm (Total no. of soil elements = 900) has been fixed for developed model. The mesh convergence study has been carried out on the basis of settlement for each mesh configuration. The boundary condition for the developed model is shown in Fig. 6 (b) i.e. hinged at bottom boundary and roller at vertical boundaries. In other words, it is said that the displacements at bottom boundary is restricted in horizontal and vertical direction (constraining both DoF). Whereas at vertical boundaries, the vertical displacement is allowed and horizontal displacement is restricted.

The footing settlement and bending moment in frame as well as combined footing for finite extent of soil mass (30.5 m x 30.5 m) are in good agreement with Viladkar et al. [37] results.



(a)



(b)

Fig. 6 (a) SSI Model by Viladkar et al. [37], (b) SSI FE Model used in Present Study

6.1. Detailed sensitivity analyses of soil boundary limits and mesh size

The detail sensitivity analysis for deciding the soil boundary limits and mesh sizes has been carried out as shown in Table 2. The soil boundary limits were decided from Boussinesq Method. To decide the soil boundary limits, 04 extent of soil mass were considered. For every soil mass the pressure on boundaries (i.e., bottom and vertical boundary) has been calculated from Boussinesq Method. The soil extent has been chosen in such a way that; the least soil pressure should act on the boundaries as well as the boundaries should not reflect wave back to the structure so that the true settlement will be observed.

Table 2. Sensitivity analyses of soil boundary limits and mesh size

Sr. No.	Extent of Soil Mass (m)	Pressure at boundaries calculated from Boussinesq Method (kPa)		Mesh Size (m)	No. of Elements	Δ/B Present Study	Δ/B Viladkar et al. [37]
		Bottom	Vertical				
1.	15.25 x 15.25 5B x 5B	0.0307	0.0054	3.05 x 3.05	25	0.0268	0.0300
				1.525 x 1.525	100	0.0275	
				1.017 x 1.017	225	0.0278	
				0.508 x 0.508	900	0.0278	
2.	21.35 x 21.35 7B x 7B	0.0156	0.0027	3.05 x 3.05	49	0.0275	0.0300
				1.525 x 1.525	196	0.0281	
				1.017 x 1.017	441	0.0285	
				0.508 x 0.508	1764	0.0285	
3.	27.45 x 27.45 9B x 9B	0.0094	0.0016	3.05 x 3.05	81	0.0278	0.0300
				1.525 x 1.525	324	0.0285	
				1.017 x 1.017	729	0.0291	
				0.508 x 0.508	2916	0.0291	
4.	30.5 x 30.5 10B x 10B	0.0076	0.0013	3.05 x 3.05	100	0.0291	0.0300
				1.525 x 1.525	400	0.0304	
				1.017 x 1.017	900	0.0310	
				0.508 x 0.508	3600	0.0310	

B is the width of footing and Δ is the footing settlement

From Table 2, it is observed that, for 15.25 x 15.25 m extent of soil mass, the pressure on the boundaries is about 1% that of the pressure applied on the structure. Due to such pressure on boundaries the confinement in soil mass increases and as a result the settlement is reduced for all mesh configurations with respect to Viladkar et al. [37] settlement (Linear elastic analysis). Thus, it is decided to increase the extent of soil, such that boundaries should not reflect the wave back to the structure. In other words, the boundaries are placed beyond the pressure bulb boundaries.

Thus, 7B x 7B, 9B x 9B and 10B x 10B soil masses were checked against boundary pressure and settlement criteria. The 9B x 9B soil extent shows good results for 1.017 x 1.017 m mesh but the boundary reflection is influencing the settlement. Hence the extent is further increased to 10B x 10B. The boundary pressure is showing approximately null value (around 0.1% of applied pressure) and settlement for 1.017 x 1.017 m mesh is also appropriately matching with Viladkar et al. [37]. Hence 10B x 10B extent of soil mass and 1.017 x 1.017 m mesh size has been considered in developed FE-SSI model.

6.2. Geometric, Material Properties and Loadings

Geometric and material properties are shown in Table 3, 4 and 5 as given by Viladkar et al. [37] for validation purpose.

Static - Uniformly Distributed Load = 0.24 N/mm for top and foundation beam (vertically downward)

Table 3. Geometrical Properties for Frame, Footing and soil

Sr. No.	Structure	Component	Size
1.	Frame	No. of Storey	01
		No. of Bays	02
		Storey height (mm)	3050
		Bay Width (mm)	3050
		Beam (mm)	270 x 270
		Column(mm)	270 x 270
2.	Foundation	Combined Footing Beam(mm)	270 x 270
3.	Soil	The extent of Soil Mass (m)	30.5 x 30.5

Table 4. Linear Elastic Material Properties for Structure and Soil

Sr. No.	Component	Elastic Modulus (N/mm^2)	Poisson's Ratio
1	Structural	21000	0.2
2	Soil Mass	3	0.3

Table 5. Non-Linear Material Properties for sand

Sr. No.	Description	Value
1	Relative Density	50%
2	Initial Tangent Mod. of sand 'Ei'	30 kg/cm^2
3	Modulus Number 'K'	305
4	Exponent 'n'	0.90
5	Failure Ratio 'Rf'	0.80
6	Cohesion 'C'	0
7	The angle of Internal Friction	39^0
8	Poisson's Ratio of sand	0.3

6.3. Results and Discussion

A plane strain linear and non-linear analysis has been carried out. The results in terms of footing settlement and bending moment in all members are represented in order to validate the present FE model. The results for Bending Moments in frame members and combined footings are shown in Table 6, 7 & 8 and graphically represented in Fig. 7, 8 and 9. (For member numbers kindly refer Fig. 6 (a)).

Table 6. Bending Moments (N-mm) in Frame Members (Linear Elastic Analysis)

Member	End	Viladkar et al. x 10^2	Present Study x 10^2	% Difference with respect to present study	NIA*
B1	1 (Inner)	678.4	707.9	4.17	2213.60
	2 (outer)	-2073.7	-2095.4	1.04	-919.20
B2	4 (Inner)	-3190.98	-3210.5	0.61	NA
	3 (outer)	-983.41	-1026.5	4.20	
C1	1 Top	0	0	0.00	0.00
	4 Bottom	0	0	0.00	0.00
C2	2 Top	2073.7	2095.4	1.04	919.20
	3 Bottom	983.4	1026.5	4.20	452.10

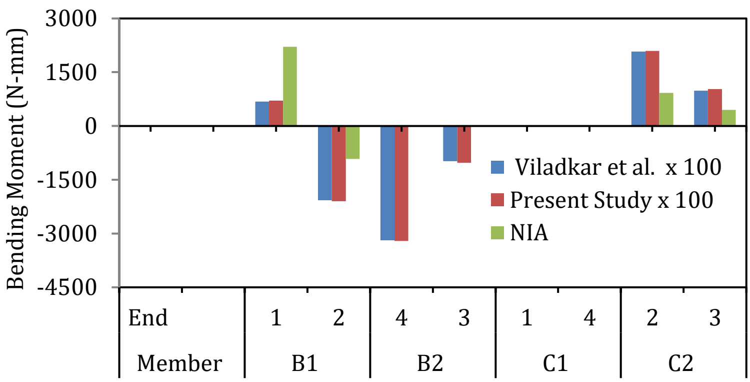


Fig. 7 Graphical representation of Bending Moments from Table 6

Table 7. Bending Moments (N-mm) in Frame Members (Non-Linear Elastic Analysis)

Member	End	Viladkar et al. x 10^2	Present Study x 10^2	% Difference with respect to present study	NIA*
B1	1 (Inner)	488.44	476.29	-2.55	2213.60
	2 (outer)	-2224.12	-2214.46	-0.44	-919.20
B2	4 (Inner)	-3310.00	-3336.42	0.79	NA
	3 (outer)	-1133.84	-1190.28	4.74	
C1	1 Top	0.00	0.00	0.00	0.00
	4 Bottom	0.00	0.00	0.00	0.00
C2	2 Top	2224.29	2214.46	-0.44	919.20
	3 Bottom	1134.07	1190.28	4.72	452.10

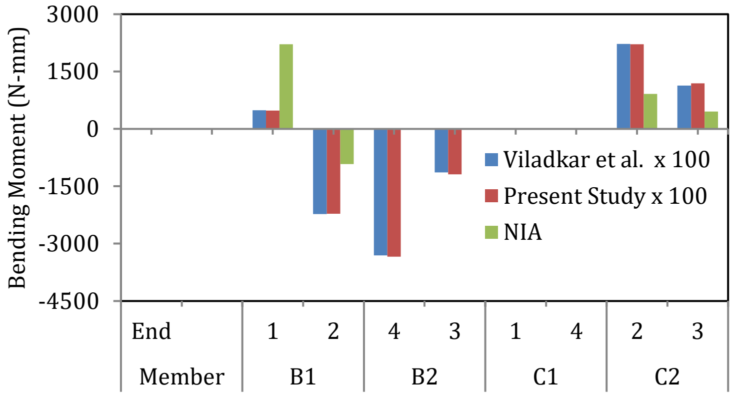


Fig. 8 Graphical representation of Bending Moments from Table 7

Table 8. Comparison of Bending Moments (N-mm) for LIA and NLIA in Present Study

Member	End	LIA**x 10²	NLIA*** x 10²	% Difference with respect to NLIA
B1	1 (Inner)	707.9	476.29	-48.62
	2 (outer)	-2095.4	-2214.46	5.37
B2	4 (Inner)	-3210.5	-3336.42	3.77
	3 (outer)	-1026.5	-1190.28	13.75
C1	1 Top	0	0.00	0.00
	4 Bottom	0	0.00	0.00
C2	2 Top	2095.4	2214.46	5.37
	3 Bottom	1026.5	1190.28	13.75

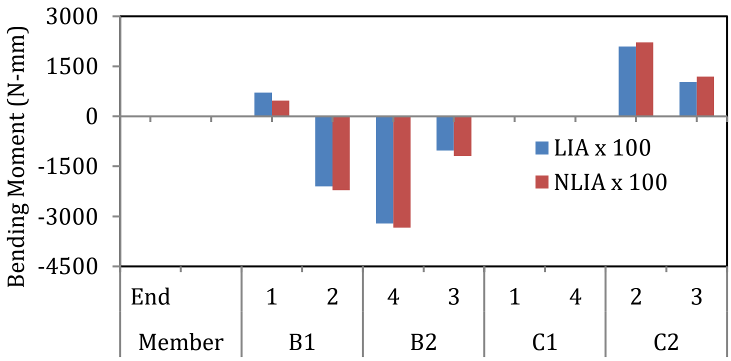


Fig. 9 Graphical representation of Bending Moments from Table 8

* NIA - Non-Interaction Analysis
**LIA - Linear Interaction Analysis
*** NLIA - Non-Linear Interaction Analysis

The variation of footing settlement in non-dimensional form along the width of footing from the center to end is plotted in Fig. 10. Where, 'x' denotes the distance from center to the edge of footing, B is the width of footing and Δ is footing settlement.

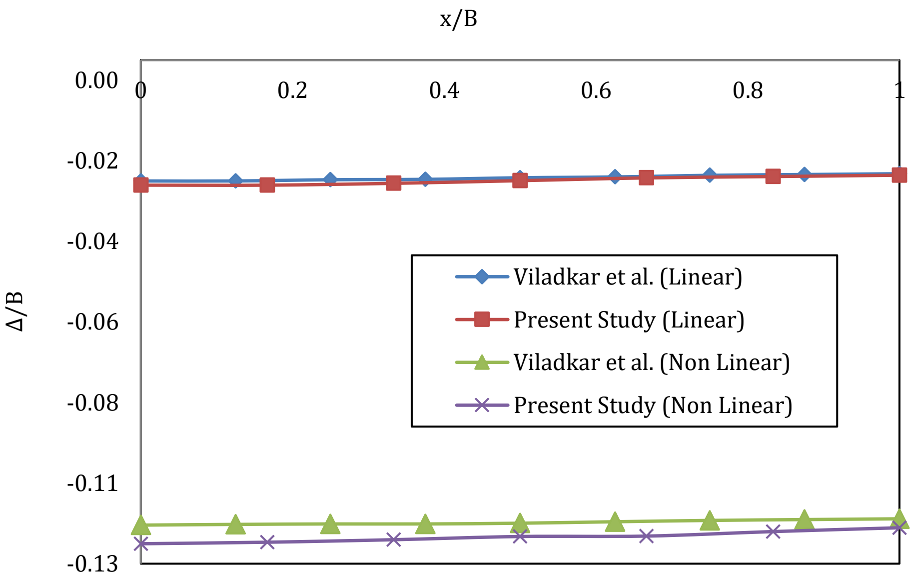


Fig. 10 Variation of Footing Settlement along Footing Width from the centre to end

The result in terms of bending moment and settlement from the present study shows good agreement with the available results of Viladkar et al. [37] model. Hence the developed FE-SSI model has been validated and further cases are considered to study the influence due to interface in FE modeling of SSI system.

7. Considered Cases

The developed FE model for SSI system has been validated in the section 6. In order to achieve the objectives of the present study, the following cases have been considered (Table 9).

The FE models used in all three cases are having the same geometrical properties as given in Table 3. The model with boundary conditions is shown in Fig. 6 (b). The structural part in all the cases have been modeled as linear elastic so the linear elastic material properties are used as shown in Table 4. Whereas, the soil (sand) [38] and interface has been modeled as linear as well as non-linear elastic. The non-linear material properties for sand and interface reported by Viladkar et al. [25] has been used for all the cases as given in Table 10 and 11 respectively.

Table 9. FE models considered for frame footing soil interaction system

Case No.	Component	Elements used (Ref: Section 3)	Constitutive Model (Ref: Section 4)	Loading	Interface Response
I	Structure	2 noded 1D isoparametric beam element	Linear Elastic	Vertical	Direct Contact (bonding)
	Soil	8 noded isoparametric plane strain element	Linear and Non-Linear		
II	Structure	2 noded 1D isoparametric beam element	Linear Elastic	Vertical and Lateral	Direct Contact (slip, bonding and de-bonding)
	Soil	8 noded isoparametric plane strain element	Linear and Non-Linear		
III	Structure	2 noded 1D isoparametric beam element	Linear Elastic	Vertical and Lateral	Modified interface (slip, bonding and de-bonding)
	Soil	8 noded isoparametric plane strain element	Linear and Non-Linear		
	Interface	5 noded isoparametric zero thickness element	Linear and Non-Linear		

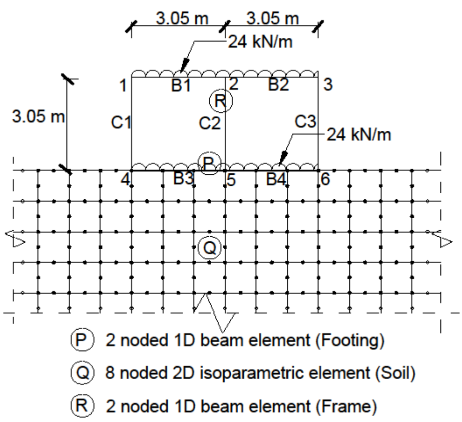
Table 10. Non-Linear Material Properties for Sand

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

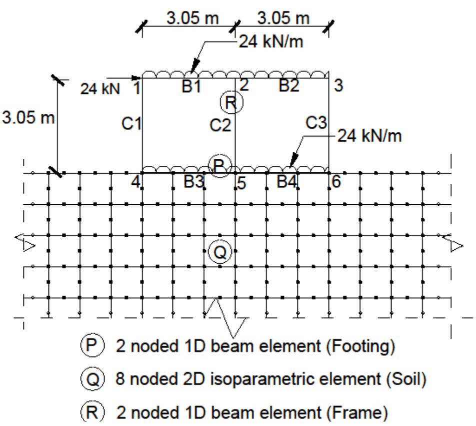
Table 11. Non-Linear Material Properties for Interface

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
8	Normal Stiffness (K_{nn})	10^8 kN/m^3

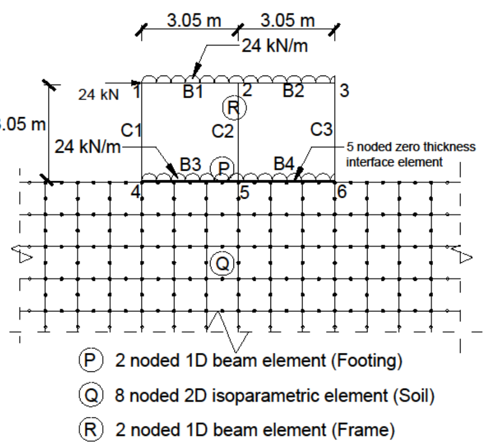
The static loading and member identification for all the cases are shown in Fig. 11 (a), (b) and (c) whereas the boundary conditions are shown in Fig. 6 (b).



(a) Case I



(b) Case II



(c) Case III

Fig. 11 Representation of FE Models with Loading and member identification

7.1. Result and Discussion

The plane strain FE analysis has been carried out for all 3 cases. For non-linear analysis, the total load has been applied into 7 load increment such as 30%, 15%, 15%, 10%, 10%, 10% and10% of the total load on the basis of sensitivity analysis. The analysis result (linear and non-linear soil) in terms of bending moment, footing settlement, lateral sway and base shear stress has been presented to study the influence of interface in SSI analysis. The study includes modified interface element with consideration of slip, bonding and de-bonding at soil-structure junction.

7.1.1 Bending moment

a. *for Case I*

For Case I, the structure is loaded as UDL only (vertically downward). Also, there is direct contact between soil and structure i.e., soil and structure is tied at intersecting nodes. The variation of bending moments clearly shows the necessity of interaction analysis (Table 12 and Fig. 12). Whereas the performance of structure improves further after considering non-linear analysis (Table 12 and Fig. 12).

Table 12. Bending moment comparison for NIA, LIA and NLIA for Case I

Member	End	NIA (kNm)	LIA (kNm)	% difference (NIA and LIA)	NLIA (kNm)	% difference (LIA and NLIA)
B1	1	9.19	17.17	-86.83	19.36	-12.75
	2	-22.13	-9.64	56.44	-6.89	28.53
B2	2	22.13	9.64	56.44	6.89	28.53
	3	-9.19	-17.17	-86.83	-19.36	-12.75
B3	4	NA	6.79	NA	9.50	-39.91
	5	NA	26.79	NA	26.72	0.26
B4	5	NA	-26.79	NA	-26.72	0.26
	6	NA	-6.79	NA	-9.50	-39.91
C1	1	-9.19	-17.17	-86.83	-19.36	-12.75
	4	-4.52	-6.79	-50.22	-9.50	-39.91
C2	2	0	0	0.00	0.00	0.00
	5	0	0	0.00	0.00	0.00
C3	3	9.19	17.17	-86.83	19.36	-12.75
	6	4.52	6.79	-50.22	9.50	-39.91

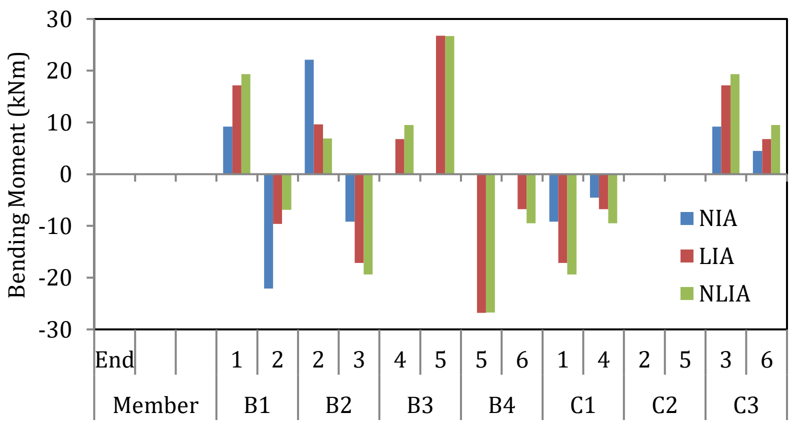


Fig. 12 Graphical representation of Bending Moments from Table 12

The bending moment (BM) comparison (Table 12 and Fig. 12) for Case I shows that there is redistribution of moments when compare LIA and NLIA with NIA. Also, it is observed that the center column is relieved from BM whereas edge columns are getting more moments. It is due to settlement of the footing. The results also find the importance of soil non-linearity on BM results, as the variation of -39% to 28% is observed. Such variation is due to the increased settlement in NLIA and continuous change of relative stiffness between soil and footing due to load increments. It is also observed that footing have the least pressure at center and maximum pressure at edges.

b. for Case II

In Case II, the static lateral load in addition to vertical load is acted on the structure. Also, the soil and structure are tied at intersection nodes (i.e., without interface as direct contact). The results of BM show the variation due to relative motion between structure and soil (Table 13 and Fig. 13). Again, the results show improvement in NLIA but reliability is getting affected due to tied contact at soil-structure junction.

Table 13. Bending moment comparison for NIA, LIA and NLIA for Case II

Member	End	NIA (kNm)	LIA (kNm)	% difference (NIA and LIA)	NLIA (kNm)	% difference (LIA and NLIA)
B1	1	0.151	7.33	-	9.56	-30.42
	2	-28.88	-18.13	37.22	-15.23	16.00
B2	2	15.442	0.98	93.65	-1.76	-
	3	-18.131	-27.1	-49.47	-29.36	-8.34
B3	4	NA	-1.3	NA	1.23	-
	5	NA	17.52	NA	17.60	-0.46
B4	5	NA	-36.35	NA	-36.04	0.85
	6	NA	-14.94	NA	-17.98	-20.35
C1	1	-0.151	-7.33	-	-9.56	-30.42
	4	8.359	1.3	84.45	-1.22	-
C2	2	13.438	17.15	-27.62	16.99	0.93
	5	14.978	18.83	-25.72	18.44	2.07
C3	3	18.131	27.1	-49.47	29.36	-8.34
	6	17.245	14.95	13.31	17.98	-20.27

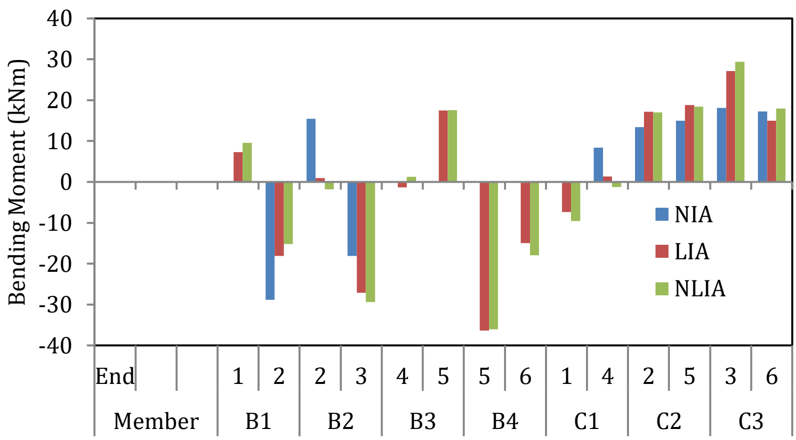


Fig. 13 Graphical representation of Bending Moments from Table 13

From Table 13 and Fig. 13, it is observed that the effect of lateral load in addition to vertical loads is dominant on column C2 and C3. As a result, a very high redistribution of BM in LIA is observed up to 93% and for some members, the reversible sign is also observed. As far as B1 and B2 are concerned (LIA), the edge 1 (where lateral load acts) is experiencing a very high increase in BM (indicated by '-'). In fact, due to the settlement of C1 as compare to fixed C1 in NIA, edge 1 is attracting very high moment with respect to NIA. Moreover, edge 2 is relieved from BM as corresponding edge 1 and 3 is getting higher values. In the case of LIA column members, the variation of -49 to 85% is observed. For NLIA, it is observed that the footing settlement and sway increases, as a result, the BM is increased up to 30%. In addition to this, foundation beam in NLIA shows reversible in the sign of BM at edge 4, whereas at edge 6, 21% BM is increased. It is happened due to lateral load, edge 4 is uplifted whereas edge 6 is sinking more (Fig. 16(a)).

c. for Case III

Case III is inclusive of interface. The interface is capable of slip, bonding and de-bonding at soil-structure contact. Also, the non-linear nature of interface has been considered to get acquainted with field conditions. As a result, Case III is more realistic as compare to earlier cases. The relative motion between structure and soil is taken care by interface hence; the performance of structure is improved and reliable as well. As a result, the true BM is observed from Table 14 and Fig. 14.

Table 14. Bending moment comparison for NIA, LIA and NLIA for Case III

Member	End	NIA (kNm)	LIA (kNm)	% difference (NIA and LIA)	NLIA (kNm)	% difference (LIA and NLIA)
B1	1	0.151	11.57	-	11.65	-0.69
	2	-28.88	-12.64	56.23	-12.52	0.95
B2	2	15.442	-4.08	-	-4.20	-2.94
	3	-18.131	-31.38	-73.07	-31.46	-0.25
B3	4	NA	3.53	NA	3.63	-2.83
	5	NA	16.85	NA	16.93	-0.47
B4	5	NA	-34.71	NA	-34.81	-0.29
	6	NA	-21.14	NA	-21.21	-0.33
C1	1	-0.151	-11.57	-	-11.65	-0.69
	4	8.359	-3.53	-	-3.63	-2.83
C2	2	13.438	16.71	-24.35	16.72	-0.06
	5	14.978	17.86	-19.24	17.87	-0.06
C3	3	18.131	31.38	-73.07	31.47	-0.29
	6	17.245	21.14	-22.59	21.22	-0.38

In Case 3, BM with the interface is given in Table 14 and graphically represented in Fig. 14. Due to incorporation of normal and tangential stiffness at footing soil interface, the resistance because of tied contact (without interface) between soil and footing is completely reduced. Hence the base shear stress is reduced and sway is allowed, as a result, true BM observed in LIA. Reversible BM sign is also observed at end 1 and 4, it is due to fact that, lateral load (at end 1) is lifting end 4 in LIA. It is also found that very less variation i.e. 3% is observed when soil and interface are considered as non-linear (NLIA). Thus the response of the structure is improved due to realistic numerical modeling of frame-footing-soil interaction system.

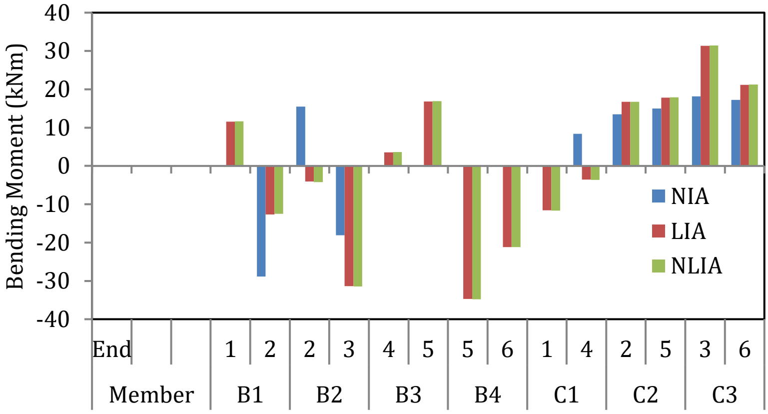


Fig. 14 Graphical representation of Bending Moments from Table 14

The comparison of BM for Case II and Case III is given in Table 15 and Fig. 15. The comparison is helpful in understanding the influence of interface on BM values.

Table 15. Bending moment comparison (with and without interface) for Case II and Case III

Member	End	LIA (without interface) (kNm)	LIA (with interface) (kNm)	% difference	NLIA (without interface) (kNm)	NLIA (with interface) (kNm)	% difference
B1	1	7.33	11.57	-57.84	9.56	11.65	-21.86
	2	-18.13	-12.64	30.28	-15.23	-12.52	17.79
B2	2	0.98	-4.08	-	-1.76	-4.20	-
	3	-27.1	-31.38	-15.79	-29.36	-31.46	-7.15
B3	4	-1.3	3.53	-	1.23	3.63	-
	5	17.52	16.85	3.82	17.60	16.93	3.81
B4	5	-36.35	-34.71	4.51	-36.04	-34.81	3.41
	6	-14.94	-21.14	-41.50	-17.98	-21.21	-17.96
C1	1	-7.33	-11.57	-57.84	-9.56	-11.65	-21.86
	4	1.3	-3.53	-	-1.22	-3.63	-
C2	2	17.15	16.71	2.57	16.99	16.72	1.59
	5	18.83	17.86	5.15	18.44	17.87	3.09
C3	3	27.1	31.38	-15.79	29.36	31.47	-7.19
	6	14.95	21.14	-41.40	17.98	21.22	-18.02

('-' indicates irreversible sign or very high difference)

The influence of interface on BM is found out from Table 15 and Fig. 15. The variation from -57 to 30 % and some irreversible sign in BM value of LIA (as compared to LIA without interface) is observed. Whereas the variation of -21 to 17% with some irreversible sign in BM value of NLIA (as compared to NLIA without interface) is observed. Thus the inclusion of interface has resulted increase in free sway and settlement as a realistic physical behavior. As a result, the BM values are giving better result considering interface stiffness values.

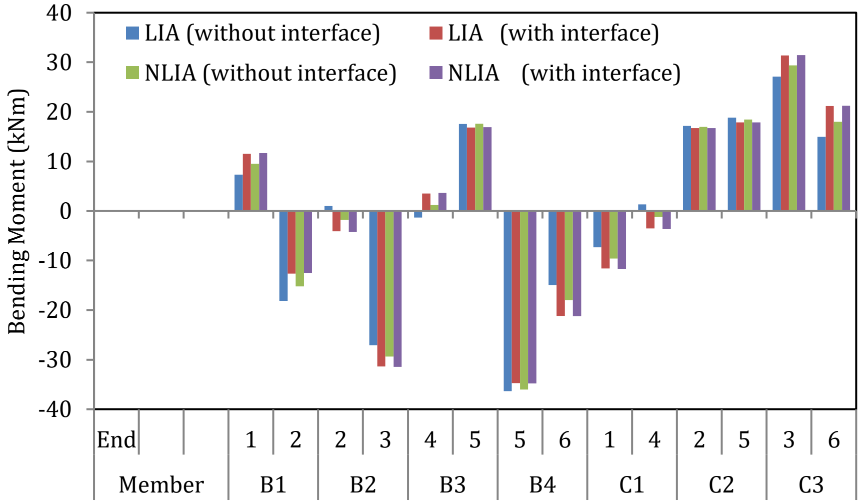
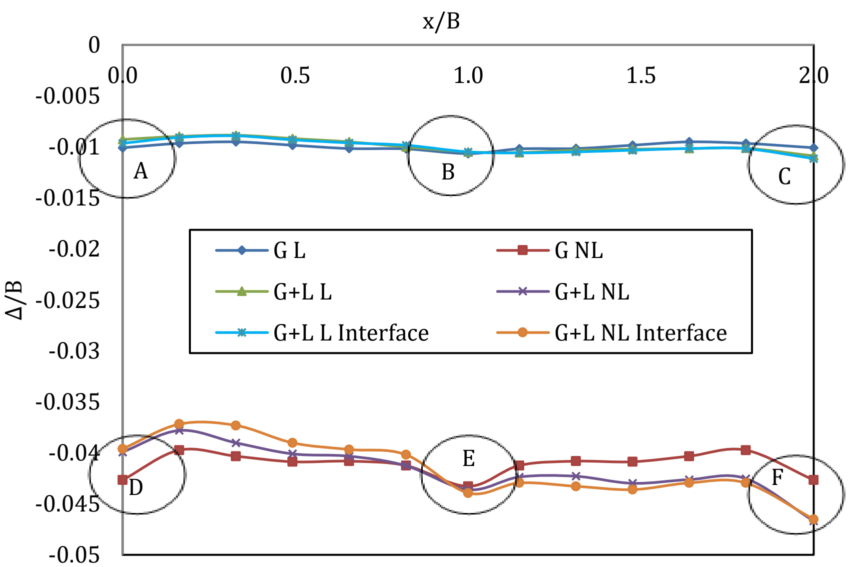


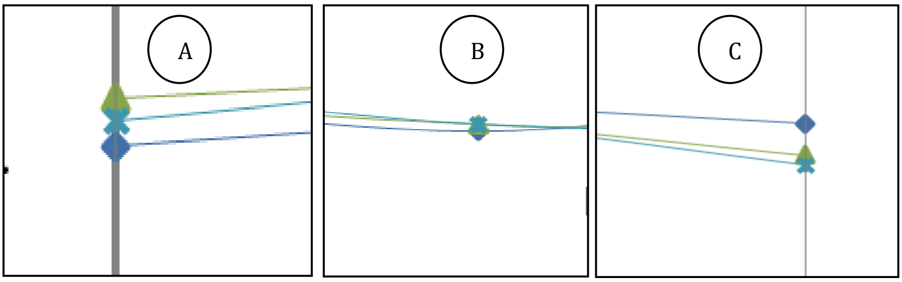
Fig. 15 Graphical representation of Bending Moments from Table 15

7.1.2 Footing Settlement

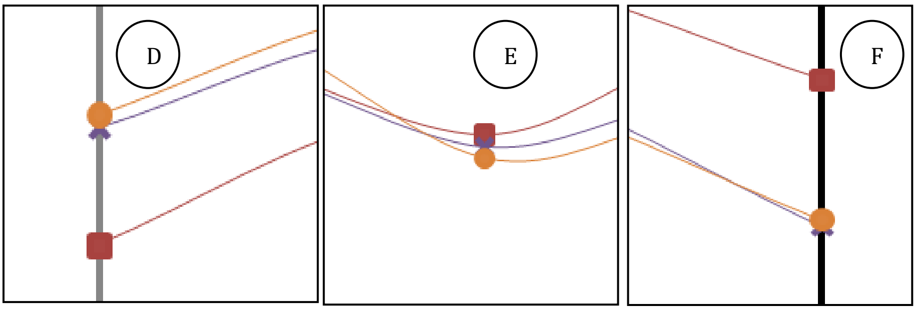
The variation in bonding and de-bonding at soil-structure contact is clearly observed from footing settlement results. Fig. 16 (a) shows the comparison of footing settlement for various cases. It is predominately observed that the values of settlement for non-linear analysis are 3.5 to 4 times that of linear analysis.



(a)



(b)



(c)

Fig. 16 (a) Non-dimensional representation of footing settlement for all the cases, (b) Close view of A, B and C, and (c) Close view of D, E and F

G L – Gravity load and linear analysis
G NL – Gravity load and Non-linear analysis
G+L L – Gravity + Lateral load and linear analysis
G+L NL – Gravity + Lateral load and Non-linear analysis
G+L L Interface – Gravity + Lateral load and linear analysis with linear Interface
G+L NL Interface – Gravity + Lateral load and Non-linear analysis with non-linear Interface
Δ – Footing settlement (mm)
B – Footing Width (mm)
x – Distance between end 4 and end 6 (mm)

The increase in settlement is due to lesser value of tangent modulus as compare to initial tangent modulus. As a result, stiffness of soil is reduced and settlement is increased.

It is also observed that, due to soil uplift pressure, the middle portion between two columns is looking like concave shape in all the cases. This is supposed to be a realistic response in SSI analysis. The similar kind of results has also depicted by Viladkar et al. [19].

The important consideration in interface element is to allow slip, bonding and de-bonding at soil footing interface. Thus, it is necessary to evaluate the behavior of 5 noded zero thickness interface element for such relative motions. From Fig. 16(a), Fig. 16(b) and 16(c), it is observed that (at end 4), there is de-bonding of 8% and 4.3% for 'G+L L' and 'G+L L Interface' cases respectively. Whereas, the de-bonding of 6.43% and 7.16% is observed for 'G+L NL' and 'G+L NL Interface' cases respectively. In addition to this, end 6 is found more sinking (bonding) as compare to 'G L' and 'G NL' cases. The extra sinking of 8% and 10.53% is found for 'G+L L' and 'G+L L Interface' cases respectively. Whereas sinking of 9.43 and 9% is found for 'G+L NL' and 'G+L NL Interface' cases respectively. Thus, it is noted that due to lateral loads the bonding and de-bonding has been observed in case II and case III. Moreover, the presence of interface has provided the appropriate values of bonding and de-bonding at footing-soil junction. It is also found that the resistance to slip, bonding and de-bonding due to tied contact (without interface) is completely reduced due to inclusion of the interface. Hence the value of de-bonding is increased by 11.35 % than 'G+L NL' case and bonding is increased by 31.62% than 'G+L L' case.

It is also found that, the presence of interface is necessary for laterally loaded structure. Whereas for only vertical loads, the interface may be neglected as there is full bond between structure and soil.

7.1.3 Footing Base Shear stress and Sway of the frame

The performance of interface for de-bonding and bonding has discussed through settlement and BM results. But the slip occurs due to interface is not clearly visible. The performance of interface for slip is very well seen through graphical representation of footing base shear stress and sway of the frame.

To evaluate the realistic performance of the structure subjected to lateral loads, the realistic modeling consideration has been adopted with the interface element. The response in terms of footing base shear stress and sway of the frame has been compared for with and without interface cases as shown in Fig. 17 and 18 respectively.

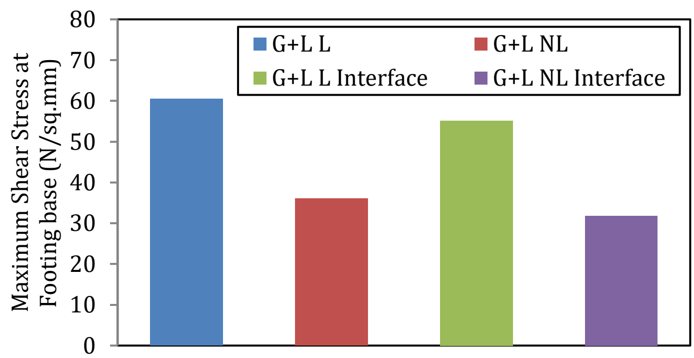


Fig. 17 Variation of maximum shear stress at the base of the footing

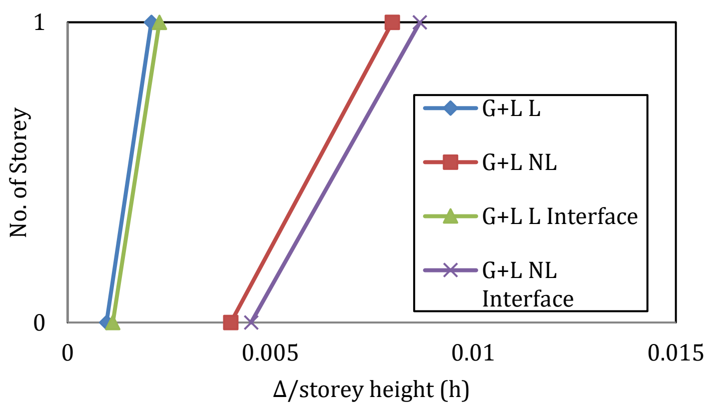


Fig. 18 Non-dimensional representation of Sway of the frame along the height

From Fig. 17, it is observed that the footing base shear stress is decreased after consideration of interface. It is also found that, the non-linearity of interface has further decreased the footing base shear stress as compare to linear results. It has happened due to reduction of shear stiffness along the footing base which results in more tangential displacement. It is also shown in Fig. 17 that the consideration of interface improves the performance of structure by reducing the footing base shear stress.

As the footing base shear stress is decreasing after consideration of interface, the slip at footing level and sway of the structure has been increased (slip increased by 13.82% and 11.08% for LIA and NLIA respectively and sway increased by 8.80% and 7.84% for LIA and NLIA respectively) as shown in Fig. 18. The sway in structure for non-linear analysis has found approximately 4 times than that of the linear analysis. It has also happened due to reduction in shear stiffness at base of the footing during incremental loading which results in increasing slip and sway. As a result, the realistic performance of the structure has been observed. The non-linearity of soil and interface is necessary for analysis of SSI problems.

8. Conclusions

Influence due to interface in FE modeling of SSI system has been studied using modified interface element. The realistic modeling of interface has been done by including slip, bonding and de-bonding at soil-structure contact. The interface non-linearity has also been considered to get acquainted with the field conditions. Thus, the appropriate influence due to interface has been found out by comparing BM, settlement, footing base shear stress and sway of the frame. Based on the analysis and results obtained, following conclusions are made,

- The FE model for SSI system with realistic interface behavior has been developed and validated successfully with available literature.
- Modified 5 noded zero thickness interface element has been successfully implemented in this study. The element has showed good compatibility with 2 noded 1D beam and 8 noded 2D soil elements. The execution of such interface element in frame-footing-soil interaction system subjected to lateral load is a novel contribution.
- The proposed model, due to the inclusion of interface has improved the mathematical performance of structure by reducing the base shear stresses and allowing the sway. Thus it is giving more realistic behavior of SSI problems.
- The response such as slip, bonding and de-bonding at soil-footing contact has been successfully evaluated by the modified interface element. Hence the proposed methodology is suitable for appropriate modeling SSI problems.
- The redistribution of BM as well as a reversible sign for some frame members has made SSI analysis a necessary study with realistic modeling considerations.
- The non-linearity of soil as well as interface in modeling of SSI system is necessary, as the settlement and sway has increased (about 4 times of linear analysis) drastically for non-linear interaction analysis.

The present study is limited for static loading conditions only. The methodology suggested in this study is useful for future research such as dynamic SSI analysis considering realistic interface modeling.

Acknowledgement

The author is acknowledging to the Director NIT Raipur, Head of the Department and Faculty members, Department of Civil Engineering, NIT Raipur for their continuous motivation, support and guidance to carry out this work.

References

[1] Terfaya N, Berga A, Raous M, Abou-bekr N. A Contact Model Coupling Friction and Adhesion: Application to Pile/Soil Interface. International Review of Civil Engineering. 2018; 9(1):1-11. https://doi.org/10.15866/irece.v9i1.14034

[2] Nde NM, Fokwa D, Mbessa M, Tamo TT, Pettang C. Numerical Study of the Interaction between a Reinforced Concrete Pile and Soil. Open Journal of Civil Engineering. 2020; 10: 259-269. https://doi.org/10.4236/ojce.2020.103022

[3] Tahghighi H, Mohammadi A. Numerical Evaluation of Soil – Structure Interaction Effects on the Seismic Performance and Vulnerability of Reinforced Concrete Buildings. International Journal of Geomechanics. 2020; 20(6): 1-14. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001651

[4] Rachamadugu R, Vikash G. Significance of Interface Modeling in the Analysis of Laterally Loaded Deep Foundations. Recent Advances in Computational Mechanics and Simulations, Lecture Notes in Civil Engineering, S. K. S. and M. Mukherjee, Ed. 2021: 199–209. https://doi.org/10.1007/978-981-15-8138-0_16

[5] Ichihara Y, Nakamura N, Moritani H, Choi B, Nishida A. 3D FEM Soil-Structure Interaction Analysis for Kashiwazaki – Kariwa Nuclear Power Plant Considering Soil Separation and Sliding. Frontiers in Built Environment. 2021; 7(June): 1-14. https://doi.org/10.3389/fbuil.2021.676408

[6] Qian XX, Yuan HN, Li QM, Zhang BY. Comparative study on interface elements, thin-layer elements, and contact analysis methods in the analysis of high concrete-faced rockfill dams. Journal of Applied Mathematics. 2013:1–11. https://doi.org/10.1155/2013/320890

[7] Ninic J, Meschke G. Beam – solid contact formulation for finite element analysis of pile – soil interaction with arbitrary discretization. International Journal of Numerical and Analytical Methods in Geomechanics. 2014; 38; 1453–1476. https://doi.org/10.1002/nag.2262

[8] Guo C, Lin P, Guo P, Wang F, Zhao L. A Weibull-based damage model for the shear softening behaviours of soil – structure interfaces. Geotechnical Research. 2021; 8(2): 54–63. https://doi.org/10.1680/jgere.20.00043

[9] Afrazi M, Yazdani M. Determination of the Effect of Soil Particle Size Distribution on the Shear Behavior of Sand. Journal of Advance Engineering and Computation. 2021; 5(2): 125–134. http://dx.doi.org/10.25073/jaec.202152.331

[10] Majedi MR, Afrazi M, Fakhimi A. A Micromechanical Model for Simulation of Rock Failure Under High Strain Rate Loading. International Journal of Civil Engineering, 2020. https://doi.org/10.1007/s40999-020-00551-2

[11] Majedi MR, Afrazi M, Fakhimi A. FEM-BPM simulation of SHPB testing for measurement of rock tensile strength. 54th US Rock Mechanics/Geomechanics Symposium, USA, 1-9, 2020.

[12] Barros RC, Vasconcelos LAC, Nogueira CL, Silveira RAM. Interface Elements In Geotechnical Engineering - Some Numerical Aspects and Applications. XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering P.O. Brazil., 1–20, 2017.

[13] Dhadse GD, Ramtekkar GD, Bhatt G. Finite Element Modeling of Soil Structure Interaction System with Interface : A Review. Archives of Computational Methods Engineering. 2020. https://doi.org/10.1007/s11831-020-09505-2

[14] Beer G. An Isoparametric Joint/Interface Element for Finite Element Analysis. International Journal for Numerical Methods in Engineering . 1985; 21: 585-600. https://doi.org/10.1002/nme.1620210402

[15] Nowroozi V, Hashemolhosseini H, Afrazi M, Kasehchi E. Optimum Design for Soil Nailing to Stabilize Retaining Walls Using FLAC3D. Journal of Advance Engineering and Computation. 2021; 5(2): 108-124. http://dx.doi.org/10.25073/jaec.202152.329

[16] Maheshwari P, Viladkar M. Strip footings on a three layer soil system: theory of elasticity approach. International Journal of Geotechnical Engineering. 2007; 1: 47-59. https://doi.org/10.3328/IJGE.2007.01.01.47-59
[17] Liu KX, Lee FH, Yong KY. A New Finite Element Model for Pile-Soil interaction. GeoTrans, USA, 441–451, 2004.
[18]Rao S, R KV, Allam MM. Representation of Soil Support in Analysis of Open Plane Frames. Computers and Structures. 1995; 55(6): 917–925.. https://doi.org/10.1016/0045-7949(94)00579-R
[19] Viladkar MN, Godbole PN, Noorzaei J. Modelling of interface for soil-structure interaction studies. Computers and Structures. 1994; 52(4): 765–779. https://doi.org/10.1016/0045-7949(94)90358-1
[20] Ai-shamrani MA, Ai-mashary FA. A Simplified Computation of the Interactive Behavior between Soils and Framed Structures. Journal of King Saud University - Engineering Sciences. 2003; 16(1): 37–60. https://doi.org/10.1016/S1018-3639(18)30779-7
[21] Lim J, han Song T, Seog BH. Formulation Method for Solid-to-Beam Transition Finite Elements. KSME International Journal. 2001; 15(11) 1499–1506. https://doi.org/10.1007/BF03185739
[22] Mao J. A finite element approach to solve contact problems in geotechnical engineering. International Journal of Numerical and Analytical Methods in Geomechanics. 2005; 29: 525–550. https://doi.org/10.1002/nag.424
[23] Aivazzadeh S, Verchery G. Stress analysis at the interface in adhesive joints by special finite elements. International Journal of Adhesion and Adhesives. 1986; 6(4): 185–188. https://doi.org/10.1016/0143-7496(86)90004-7
[24] Dalili Shoaei M, Huat BBK, Jaafar MS, Alkarni A. Soil-framed structure interaction analysis – A new interface element. Latin American Journal of Solids Structures. 2015; 12(2): 226-249. https://doi.org/10.1590/1679-78251130
[25] Viladkar MN, Zedan AJ, Saran S. Nonlinear elastic analysis of shallow footings subjected to eccentric inclined loads. Geomechanics and Geoengineering : An International Journal. 2015; 10(1): 45-56. https://doi.org/10.1080/17486025.2014.902117
[26] Pande GN, Sharma KG. On Joint / Interface Elements and Associated Problems of Numerical Ill-Conditioning. International Journal of Numerical and Analytical Methods in Geomechanics. 1979; 3(3): 293-300. https://doi.org/10.1002/nag.1610030308
[27] Noorzaei J, Viladkar MN, Godbole PN. Nonlinear Soil-Structure Interaction In Plane Frames. Engineering Computations. 1994; 11: 303-316. https://doi.org/10.1108/02644409410799308
[28] Day RA, Potts DM. Zero Thickness Interface Elements-Numerical Stability and Applications. International Journal of Numerical and Analytical Methods in Geomechanics. 1994; 18: 689-708. https://doi.org/10.1002/nag.1610181003
[29] Potts DM, Zdravkovic L. Finite element analysis in geotechnical engineering Theory. Thomas Telford, London, 1999, ISBN 0-7277-2783-4.
[30] Kaliakin VN, Li J. Insight into Deficiencies Associated With Commonly Used Zero-Thickness Interface Elements. Computers and Geotechnics. 1995; 17: 225–252. https://doi.org/10.1016/0266-352X(95)93870-O
[31] Mayer MH, Gaul L. Segment-to-segment contact elements for modelling joint interfaces in finite element analysis. Mechanical Systems and Signal Processing. 2007; 21: 724–734. https://doi.org/10.1016/j.ymssp.2005.10.006
[32] Chandrupatla TR, Belegundu Ashok D. Introduction to Finite Elements in Engineering, Fourth edition, New York, Pearson Education Limited, 2012.
[33] Dhadse GD, Ramtekkar GD, Bhat G. Response of Single and Multilayered Flexible Base for Static and Earthquake Loading Under Framed RC Structure. S. Adhikari et al. (eds.), Advances in Structural Technologies, Lecture Notes in Civil Engineering, Springer Singapore. 169–183, 2020. https://doi.org/10.1007/978-981-15-5235-9_13

[34] Dong W, Hu L, Yu YZ, Lv H. Comparison between Duncan and Chang's EB Model and the Generalized Plasticity Model in the Analysis of a High Earth-Rockfill Dam. Journal of Applied Mathematics. 2013; 2013; 1-12. https://doi.org/10.1155/2013/709430

[35] Lade PV. Overview Of Constitutive Models For Soils. Geo-Frontiers Congress 2005, Austin, Texas, United States, 1–34, 2005.

[36] Brinkgreve RBJ. Selection of Soil Models and Parameters for Geotechnical Engineering Application. Geo-Frontiers Congress 2005, Austin, Texas, United States, 69–98, 2005. https://doi.org/10.1061/40771(169)4

[37] Viladkar MN, Godbole PN, Noorzaei J. Soil-Structure Interaction in Plane Frames Using Coupled Finite-Infinite Elements. Computers and Structures. 1991; 39(5): 535-546. https://doi.org/10.1016/0045-7949(91)90062-Q

[38] Rouhanifar S, Afrazi M, Fakhimi A, Yazdani M. Strength and deformation behaviour of sand- rubber mixture. International Journal of Geotechnical Engineering. 2021; 15(9): 1078-1092. https://doi.org/10.1080/19386362.2020.1812193