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Effects and dynamic behaviour of soil - framed structure interaction

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Research Paper

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The effect and behaviour of soil - framed-structure interaction (SSI) under dynamic load conditions are presented in the paper. All civil engineering structures involve various types of structural elements that are in direct contact with soil. Hence, a new thin-layer interface element, based on the concept of the finite element method, is formulated. The formulation is elaborated using a combination of degrees of freedom of the top and bottom sides of the interface elements. The compatibility conditions of displacements between beam elements and quadrilateral soil elements are applied. Thus, a numerical program integrating the thin-layer interface element is developed for this purpose. The obtained results show that interaction between the soil and a framed structure has a considerable influence on the structural dynamic response of system components. Additionally, a parametric study has been elaborated to quantify the significance of interface behaviour on the soil and on the framed structure under dynamic load.

Key words:

soil-structure interaction dynamics, dynamic analysis, finite element method, soil, frame structure

Prethodno priopćenje

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Utjecaji i dinamičko ponašanje interakcije tla i okvirne konstrukcije

U radu se prikazuje utjecaj i interakcija tla s okvirnom konstrukcijom pod utjecajem dinamičkih opterećenja. Kod svih je građevina potrebna neka vrsta konstrukcijskih elemenata koji su u izravnom kontaktu s tlom. U ovom radu je razvijen novi tankoslojni element sučelja (kontaktni element) temeljen na metodi konačnih elemenata. Pritom je korištena odgovarajuća kombinacija stupnjeva slobode na gornjoj i donjoj strani kontaktnog elementa. Primijenjeni su uvjeti kompatibilnosti pomaka između grednih elemenata i četverokutnih elemenata tla. Za potrebe integriranja tankoslojnog kontaktnog elementa, razvijen je numerički program. Dobiveni rezultati pokazuju da interakcija tla i okvirne konstrukcije bitno utječe na strukturni dinamički odziv komponenata sustava. Provedeno je i parametarsko ispitivanje kako bi se kvantitativno odredio utjecaj kontaktnog elementa na tlo i okvirnu konstrukciju pri dinamičkom opterećenju.

Ključne riječi:

dinamika interakcije tla i konstrukcije, dinamička analiza, metoda konačnih elemenata, tlo, okvirna konstrukcija

1. Introduction

Framed structures rank among the structural systems that are widely used in civil, aeronautical, mechanical, and electrical engineering. Due to these various applications, the dynamic analysis of framed structures has attracted undivided attention of searchers and engineers. In general, columns of these structures are considered fixed at their foundations. The design of buildings in seismic zones usually involves the assumption that soil flexibility, which induces an increase in the fundamental period of the structure, can be neglected. This increase does not always lead to an attenuation of seismic amplitude. The soil – framed-structure interaction (SSI) can have a detrimental effect on the response of the structure. In addition, the simplification of the SSI effect in seismic codes can lead to poor design of structures. For these reasons, simplified procedures for the inclusion of SSI are proposed in American Seismic Regulations (FEMA).

Thus, the design of structural elements using this assumption does not reflect realistic behaviour due to the settlement, rotation of foundations, and interaction between the structure and the soil. These effects engender a transfer of loads between the soil and the structure known as the soil-structure interaction phenomenon, which has a significant impact on structural response, especially for systems founded on soft soils.

Numerous geotechnical problems involve the phenomenon of interaction between structures and soil, which is particularly pronounced in the case of important structures such as nuclear power plants and multi-story buildings founded on soft stratum. In numerical studies of this problem, it is necessary to model the structure, the soil, and the interface between them. An accurate modelling of the interface media under various loading conditions is an important factor for explaining the response of structures. Hence, to obtain pertinent results, it is necessary to select a robustness modelling and a rigorous constitutive law of the interface continuum [1]. In this domain, many SSI approaches have been presented:

- analytical modelling
- numerical modelling.

The first category includes classical approaches [2] in which a set of springs having only one degree of freedom is used. This method is considered to be straightforward, and it simplifies the solution of soil-structure interaction issues. Additionally, spring methods have been improved using dashpot elements [3] to make structural responses more accurate. However, this approach suffers a handicap due to discontinuity of the supporting medium and the neglect of shear deformations. To enhance this model, Boudaa [4] improved the one-parameter approach by taking into account shear deformations in the analysis. Also, Viladkar et al. [5] presented a discrete interface element to study the soil and beam behaviour. The analysis is intended to formulate the finite element that is compatible with the 3-noded bending beam element. Additionally, Mayer and

Gaul [6] established a discrete element that is more suitable for the solid-to-solid contact.

The second category involves various numerical approaches. With innovations in computer science and numerical methods, various simulations have been increasingly used to study the soil-structure interaction. Thus, the modelling of interaction is elaborated based on the dimensional concept of problems relating to static or dynamic loading. Moreover, various computational methods such as the finite difference method [7, 8], the finite element method (FEM) [9-11], and the boundary element method (BEM) [12, 13] have been employed to analyse the interaction problems.

The use of FEM has attained a major position in the study of complex interactive behaviour of structures. These complex problems call for rapid clarification of the interface between different bodies and for definition of important phenomena and effects on structural response. In this respect, Dinev [14] simplified the continuum behaviour by differential equation of the soil layer. Swamy et al. [15] presented a comparative study between interactive and noninteractive soil and frame structures, and pointed to the importance of interface modelling. In addition, Coutinho et al. [16] developed a link interface having 4-nodes with 2-degrees of freedom for each node in order to analyse the interaction phenomenon and strip footing. Large shear deformations at the interface medium have also been studied and analysed [17].

Our contribution to this research is a new interface element developed to study the dynamics of interaction between the soil and framed structures. The new thin layer interface element ensures compatibility conditions between the beam and soil elements. In literature, membranous interface elements are not compatible with beam elements employed as main elements in frames. The finite element developed in this study contains 4-nodes connected to the beam and quadrilateral soil elements. Therefore, the thin-interface element with varying degrees of freedom for each node is used to study dynamic response of framed structures, and to quantify contribution of the soil-structure interaction.

2. Modelling of contact problems

Many approaches and attempts have been made to model the soil-structure interaction phenomenon. Interface elements are largely used to model behaviour of the zone between the foundations and soil with proper mechanical properties. In this context, the approaches relating to the soil-structure interaction are classified in three categories: structural approach, continuum approach, and hybrid approach. The structural approach has a rigid base where the structure and the sub-grade are substituted with structural components. In the second approach, models are derived from partial differential equations governing the entire system as a continuum, while the hybrid approach is obtained by a combination of the first two approaches.

2.1. Winkler model

The soil-structure interaction model based on the Winkler approach is among the first analytical solutions that focus on the complexity of the soil structure interaction. Due to complexities of the SSI, many assumptions have been introduced in the structure - foundation soil interface to simplify modelling of the entire system. This approach suffers a handicap due to the discontinuity of the supporting medium and the neglect of shear in foundations [4, 18, 19]. In this context, the beam behaviour is governed by the fourth-order differential equation.

$$\frac{d^4 v(x)}{dx^4} + \frac{K_s}{EI} v(x) = \frac{q(x)}{EI} \quad (1)$$

where $v(x)$ is the downward deflection, while EI , K_s , $q(x)$ are the bending stiffness of beam, soil subgrade modulus, and external load, respectively.

The nonlinear behaviour of soil has prompted researchers to study more extensively the soil-structure interaction problems. Then, the variable value of the soil sub-grade modulus is integrated in the equation (1).

$$\frac{d^4 v(x)}{dx^4} + \frac{K_s(x)}{EI} v(x) = \frac{q(x)}{EI} \quad (2)$$

$K_s(x)$ is the nonlinear elastic coefficient of a variable Winkler foundation. This means that soil stiffness depends on the position considered along the major interface axis representing a non-homogeneous and nonlinear foundation. Structures have been used for many years on nonlinear soil, $K_s(x)$, to calibrate response of foundations, such as: behaviour of piles under static load [20] and under dynamic load [21]. These models take into consideration the soil-structure interaction phenomena by using one-dimensional nonlinear springs distributed along the soil-foundation contact. The limitation of this approach is essentially related to dimensional representation, so that loads acting in the horizontal direction have no effect on the response of springs. Harvath et al. [22, 23] introduced the sub-grade hybrid model replacing the multi-layered soil medium by an equivalent layer comprised between the upper and lower layers, separated by a perfect flexible membrane having a constant tension.

2.2. Continuum model

The elastic continuum model is considered to be homogenous, isotropic, and linearly elastic. Many parameters of the soil: elastic modulus, shear modulus, and layered soil thickness, have been introduced in the formulation [23]. Next, the two-parameter soil-foundation model is introduced to study the influence of shear deformations on the vertical and

horizontal responses of the soil-structure interaction [4, 5, 19]. Under static load, the equation governing the system response can be deduced as

$$(K_b^e + K_s^e + K_G^e)\{q_e\} = \{F_e\} - \{R_e\} \quad (3)$$

where K_b^e , K_s^e , K_G^e are stiffness matrices of the flexural beam element, sub-grade, and shear deformation, respectively. $\{q_e\}$, $\{F_e\}$ and $\{R_e\}$ are vectors of nodal degrees of freedom, nodal loads, and equivalent nodal loads of distributed load.

In this way, the influence of each layer's behaviour on the overall behaviour of soil is introduced through the sub-matrix

$$\begin{Bmatrix} T_t^i \\ T_b^i \end{Bmatrix} = \begin{bmatrix} K_{tt}^i & K_{tb}^i \\ K_{bt}^i & K_{bb}^i \end{bmatrix} \begin{Bmatrix} U_t^i \\ U_b^i \end{Bmatrix} \quad (4)$$

where U and T are displacements and tensions at the top and bottom of the considered layer, while K is the sub-matrix of the top and bottom layers.

2.3. Hybrid model

As described in the above section, the hybrid approach depends on the combination of structural and continuum models. Many studies have already been developed in this respect. As an example, a dynamic analysis of a windmill tower using SSI is elaborated in [24]. In this analysis, an innovative hybrid model is presented where the monopole and lattice tower, analysed using the continuum model (FEM Software), are coupled with the structural approach to describe behaviour of various types of soils.

Finally, the structural model is easy and simple but is lacking in accuracy. In addition, the continuum approach is more accurate for soil modelling, but presents major difficulties when it comes to implementation via a computer software. In this study, the continuum approach is used to model the soil-structure interaction.

3. Finite element formulation of soil structure interaction

External loads engender relative movement between the structure and the soil. The use of interface elements, respecting compatibility conditions, prohibits relative displacements between contact nodes. In this case, interface elements can be used to model the fine zone between foundations and soil. For this reason, many methods have been proposed to model discontinuous behaviour at the interface level using various interface elements (Figure 1).

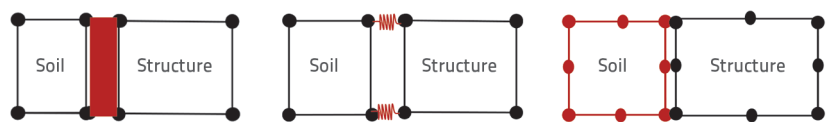


Figure 1. Soil-structure interaction examples

Accurate modelling of the interface elements is an important task for explaining the riddle of the soil-structure interaction behaviour. Therefore, the modelling-technique robustness and the constitutive law of the interfacial media have been of great importance in recent years due to innovations in numerical methods and thanks to development of high-power computing machines.

The finite element method is among numerical approaches largely used in this domain. Pertinent results show that it capable of providing advanced solutions to contact problems [25]. The simulation technique for mechanical discontinuity at the interface is highly significant. The continuum between the soil and foundations has been modelled in literature using many approaches of the soil-structure interface behaviour (Figure 1). Interface elements can be modelled using spring elements, 2-node or 3-node elements, or continuum medium with finer meshing, zero thickness elements, or thin-layer elements. 2-node or 3-node elements can assume the form of node-to-node elements that have been a common choice to model interface behaviour (Figure 1a). For some problems, interface behaviour can be modelled by refining conventional finite element meshes in the vicinity of the interface with suitable properties [26] (Figure 1b). In addition, it can be modelled by spring elements that can provide connection between foundations and soil (Figure 1c). Some elements used in the analysis of interaction between various bodies are described in the following section.

3.1. Zero-thickness interface element

Modelling of the contact region using zero-thickness elements was initially developed by Goodman [27]. This element has 4-nodes or 8-nodes with two degrees of freedom for each node. The formulation is based on relative displacements between both sides of interface elements (Figure 2). The nodal displacement vector in local coordinate system can be written

$$\{q_e\} = \langle u_i, v_i \rangle_{i=1,4}^t \tag{5}$$

where u_i and v_i refer to horizontal and vertical displacements of the i -node.

The relative displacement vector can be deduced as

$$\{u\} = \langle u_t, v_n \rangle^t \tag{6}$$

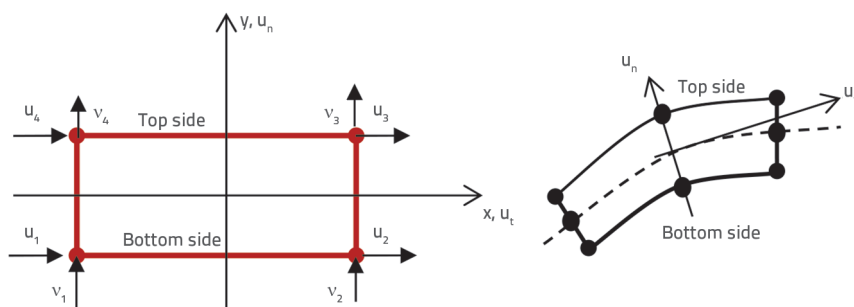


Figure 2. Zero-thickness interface element

where u_t and u_n are tangential and normal relative displacements that can be expressed as $u_t = u_{top} - u_{bot}$ and $u_n = v_{top} - v_{bot}$. When 2-nodes on each side of interface element are considered, the displacements u and v can be approximated using linear Gaussian interpolation functions. The displacement of the top and bottom nodes is expressed as:

$$\begin{Bmatrix} u_{top} \\ v_{top} \\ u_{bot} \\ v_{bot} \end{Bmatrix} = \begin{bmatrix} -N_1 & 0 & -N_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & -N_1 & 0 & -N_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & N_1 & 0 & N_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & N_1 & 0 & N_2 \end{bmatrix} \{q_e\} \tag{7}$$

The strain displacement matrix can be computed by

$$\{\epsilon\} = [B]\{q_e\} \tag{8}$$

with

$$[B] = \begin{bmatrix} -N_1 & 0 & -N_2 & 0 & N_1 & 0 & N_2 & 0 \\ 0 & -N_1 & 0 & -N_2 & 0 & N_1 & 0 & N_2 \end{bmatrix}$$

The stiffness matrix of an element can be determined as follows:

$$[K_e] = \int_L [B]^t [D^e] [B] dx \tag{9}$$

gdje je $[D^e]$ matrica konstitutivnog zakona, a L je dužina stranice. where $[D^e]$ is the constitutive law matrix and L is the length of the side.

In conclusion, more contact elements can be found in the zero-thickness interface family of elements that take into account additional complicated phenomena.

3.2 Thin-layer interface element

In addition to zero-thickness interface elements, thin-layer thickness elements have also been analysed in literature [6]. It has been shown that a small change in thickness can produce large results. Moreover, it has been suggested that a simple shear test can be carried out to determine thickness of the thin layer interface element [14]. In order to reduce disadvantages, Desai et al. [29] and Sharma [30] proposed a thin-layer interface element (Figure 3). Here, a solid element of small thickness was used to simulate behaviour of interfaces. Translational freedoms were

considered at common nodes from the interface level. In the parametric study, Desai [29] suggested that the thickness, t , of interface elements is $0.01 \leq t/L \leq 0.10$, with L as the width of foundations. Various modes of deformation were incorporated and a number of problems with displacement and hybrid finite element procedures were studied. Thin-layer interface elements have been successfully employed to study

the soil-structure interaction under static load, and have then been modified to enable study under dynamic load conditions. The behaviour of an interface medium involves a thin finite zone, rather than a zero-thickness interface element, as often assumed in many investigations.

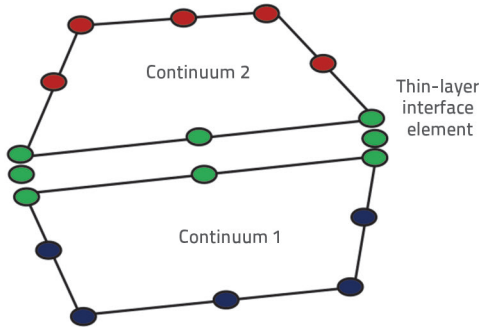


Figure 3. Thin-layer interface element

The thin interface element is treated in the finite element analysis like a solid finite element. The constitutive law of the interface element is

$$\{\sigma\} = [C^i]\{\varepsilon\} \tag{10}$$

where $\{\sigma\}$ and $\{\varepsilon\}$ are the stress and strain vectors, respectively, and $[C^i]$ is the elasticity matrix of the interface medium.

$$[C^i] = \begin{bmatrix} c_{nn}^i & c_{ns}^i \\ c_{sn}^i & c_{ss}^i \end{bmatrix}$$

where c_{nn}^i, c_{ss}^i are normal and tangential components of the thin interface element behaviour. c_{ns}^i, c_{sn}^i represent the coupling between normal and shear effects.

The behaviour of an interface element can be deduced using the stiffness matrix formulation as follows:

$$[K^i] = \int_V [B^i]^t [C^i] [B^i] dV \tag{11}$$

where $[B^i]$ is the transformation matrix of the interface element.

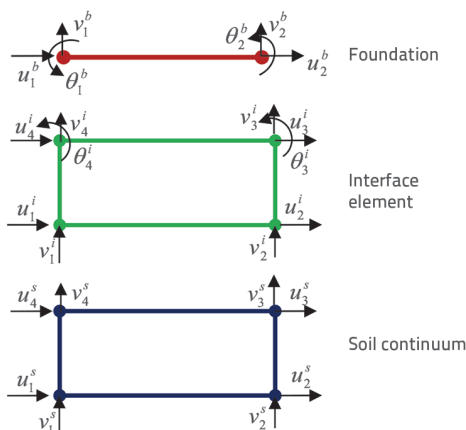


Figure 4. Thin-layer interface element

4. New thin-layer interface element

4.1. Formulation of the interface element

The finite element used in this paper is composed of (1) 1D-beam element, (2) 2D-interface element and (3) 2D-soil element. These elements must be integrated together to constitute the joint element that can be employed to analyse the soil-structure interaction under dynamic loading. The beam is a unidirectional bar element having 2-nodes with 3 degrees of freedom for each node, and the soil is meshed by quadrilateral elements Q4 having two degrees of freedom for each node (Figure 4).

Nodes of the developed thin-layer interface element are connected at the top side with those of the beam and at the bottom side with soil elements (Figure 5). In this case, each beam node has three degrees of freedom, but soil element nodes have only two degrees of freedom. So the new finite interface element appears in the analysis with 10 degrees of freedom.

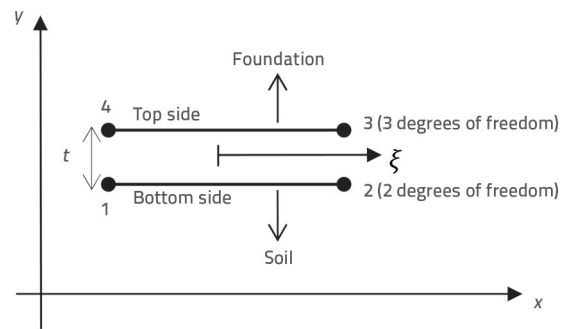


Figure 5. Thin-layer interface element

Displacements of common nodes of various elements must be assured to guarantee compatibility conditions, Figure 4 and Table 1.

Table 1. Displacement of thin-layer interface element nodes

Node	Horizontal displacement u	Vertical displacement v	Rotation θ
1	$u_1^i = u_4^s$	$v_1^i = v_4^s$	
2	$u_2^i = u_3^s$	$v_2^i = v_3^s$	
3	$u_3^i = u_2^b$	$v_3^i = v_2^b$	$\theta_3^i = \theta_2^b$
4	$u_4^i = u_1^b$	$v_4^i = v_1^b$	$\theta_4^i = \theta_1^b$

In static analysis, the response of the composed structure can easily be computed using the equation:

$$[K]\{u\} = \{F\} \tag{12}$$

In dynamic analysis, the equation (12) becomes

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\} \quad (13)$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping, and stiffness matrices, respectively. $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the acceleration, velocity and displacement of the system, and $\{F(t)\}$ is the external force vector.

Relative displacement components can be approximated as

$$\Delta U = \sum_1^n N_i(\xi) u_i \quad (14.1)$$

$$\Delta V = \sum_1^n N_i(\xi) v_i \quad (14.2)$$

$$\Delta \theta = \sum_1^n N_i(\xi) \theta_i \quad (14.3)$$

where n is the number of nodes, u_i , v_i and θ_i are the i -node degrees of freedom.

For a one-dimensional finite element linear analysis, shape functions of nodes 1 and 2 (Figure 2) have the following expressions:

$$N_1(\xi) = \frac{1}{2}(1-\xi) \quad (15.1)$$

$$N_2(\xi) = \frac{1}{2}(1+\xi) \quad (15.2)$$

At the interface level, deformations are assumed as relative displacements between the upper and lower nodes. Therefore, the strain vector can be expressed as follows:

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_t \\ \varepsilon_n \\ \varepsilon_r \end{Bmatrix} = \left\langle \frac{\Delta u}{t}, \frac{\Delta v}{t}, \frac{\Delta \theta}{t} \right\rangle^t \quad (16)$$

ε_t , ε_n and ε_r tangential, normal, and rotational deformations, respectively, and t is the element thickness

Substituting equation (14) into equation (15), the vector of deformation can be written as follows:

$$\{\varepsilon\} = \frac{1}{t} [N(\xi)] \{q_e\} \quad (17)$$

The shape function matrix can be established according to the nodal displacement vector with

$$[N(\xi)] = \begin{bmatrix} -N_1(\xi) & 0 & -N_2(\xi) & 0 & N_1(\xi) & 0 & 0 & N_2(\xi) & 0 & 0 \\ 0 & -N_1(\xi) & 0 & -N_2(\xi) & 0 & N_1(\xi) & 0 & 0 & N_2(\xi) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & N_1(\xi) & 0 & 0 & N_2(\xi) \end{bmatrix}$$

The displacement-strain relationship can be formulated as follows:

$$\{\varepsilon\} = [B(\xi)] \{q_e\} \quad (18)$$

where $[B(\xi)] = (1/t) [N(\xi)]$ is the displacement-deformation matrix.

Based on the total potential energy concept, the stiffness matrix can be deduced in intrinsic coordinate axis as

$$[K] = \int_{-1}^1 \int_{-1}^1 [B(\xi)]^t [C_e] [B(\xi)] |J| d\eta d\xi \quad (19)$$

$|J|$ is the Jacobian determinant and $[C_e]$ is the elasticity matrix containing three decoupled components in the local coordinate system.

$$[C_e] = \begin{bmatrix} C_s & 0 & 0 \\ 0 & C_n & 0 \\ 0 & 0 & C_r \end{bmatrix} \quad (20)$$

C_s , C_n and C_r are the shearing, normal, and rotational rigidity of the elastic foundation layer of soil used, respectively.

In general, the interface element can be inclined at an angle with respect to the global axis (Figure 6). Then, the elasticity stiffness matrix in global coordinates is

$$[C_g] = [T]^t [C_e] [T] \quad (21)$$

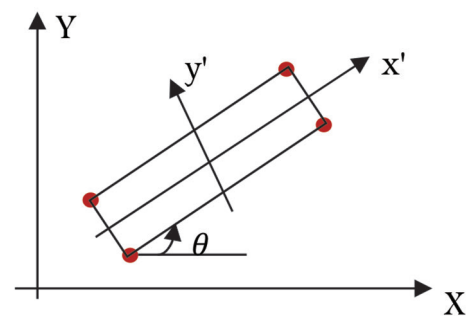


Figure 6. Interface element in global coordinate systems

The transformation matrix is:

$$[T] = \begin{bmatrix} \cos 2\theta & \sin 2\theta & 0 \\ -\frac{1}{2} \sin 2\theta & \cos^2 \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Then, the material stiffness matrix can be expressed in the global reference as

$$[C_g] = \begin{bmatrix} \cos 2\theta & -\frac{1}{2} \sin 2\theta & 0 \\ \sin 2\theta & \cos^2 \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_s & 0 & 0 \\ 0 & C_n & 0 \\ 0 & 0 & C_r \end{bmatrix} \quad (22)$$

$$\begin{bmatrix} \cos 2\theta & \sin 2\theta & 0 \\ -\frac{1}{2} \sin 2\theta & \cos^2 \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_1 & c_4 & 0 \\ c_4 & c_2 & 0 \\ 0 & 0 & c_3 \end{bmatrix}$$

In global coordinates, the strain vector can be written as

$$\begin{Bmatrix} \varepsilon_t \\ \varepsilon_n \\ \varepsilon_r \end{Bmatrix} = \begin{bmatrix} \cos 2\theta & \sin 2\theta & 0 \\ -\frac{1}{2}\sin 2\theta & \cos^2 \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \gamma_{xy} \\ \varepsilon_y \\ \gamma_\theta \end{Bmatrix} \quad (23)$$

The mass matrix can be evaluated in the same manner

$$[M] = \int_{-1}^1 \int_0^t [N(\xi)]^t [N(\xi)] \rho |J| d\eta d\xi \quad (24)$$

where ρ is the density of the material.

4.2. Characteristics of the interface medium

Most soils obey nonlinear constitutive laws for multiple reasons: the heterogeneity, the nonlinear sensitivity ...etc. In this work, a linear elastic assumption of the soil behaviour is used. Thus, the elastic continuum model can have the physical representation of the soil media [31, 32].

The foundation behaviour can be assessed in a flexible or rigid fashion by a dimensionless parameter called the system stiffness, P_s , [32, 33]. The normal rigidity of the elastic foundation layer can be written as follows:

$$C_n = \frac{1}{12} \frac{C_f}{P_s} \left(\frac{d}{L} \right)^3 \quad (25)$$

where C_f , d and L are the rigidity, thickness, and length of foundations, respectively. The system stiffness parameter, P_s , allows differentiation between the flexible and stiff behaviour of soil ($P_s = 0$: absolutely flexible, $0 < P_s \leq 0.01$: semi-flexible, $0.01 < P_s \leq 0.1$: semi-stiff and $P_s > 0.1$: stiff).

Adding, Karkon et al. [28] described shear stiffness of the elastic foundation layer as a function of soil properties (E_s , ν) and beam width, b , as

$$C_s = \frac{E_s}{4(1+\nu)} \frac{b}{\beta} \quad (26)$$

where β is a parameter characterizing distribution of displacement along the vertical direction.

Finally, the elastic rotational stiffness of the elastic foundation layer can be evaluated according to [34] using the following expression:

$$C_r = \frac{\pi b^2 L E_s}{16(1-\nu^2)} \left(1 + 0.22 \frac{b}{L} \right) \quad (27)$$

For different soil types, the values of C_n , C_s and C_r are given in Table 3, and they correspond to the data of the problem described in the following section.

5. Numerical examples

5.1. Data of the problem

To validate the developed program and to show the performance of the thin-layer interface element, two models are chosen:

- fixed base (Figure 7a)
- thin-layer interface element (Figure 7b).

The numerical program takes into account multiple finite elements: beam element describing the plane frame, interfacial element simulating the interaction zone, and continuum elements representing the soil under foundations.

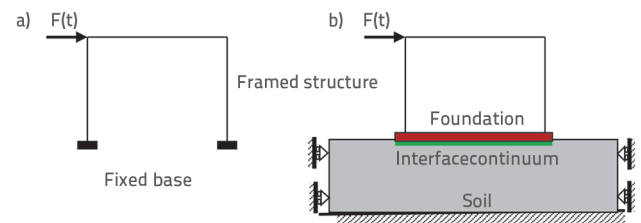


Figure 7. a) Fixed-base model; b) interface element model

In this study, limit boundaries of vertical and base sides were restrained at a satisfactory length corresponding to very small horizontal displacements. The thickness of interface elements is selected equal to 5 cm [29]. To simulate the response of plane frames subjected to dynamic loading conditions, a sinusoidal dynamic force $f(t) = 500\sin((\pi/0,6)t)$ is applied at the top of the frame. The foundation is assumed to be resting on three types of soil: hard soil, medium soil, and soft soil, which are treated as plane strain problems. The small-strain modulus values of various soil types are shown in Table 2.

Table 2. Mechanical characteristics of soils used

Soil used	Young's Modulus [kN/m ²]	Poisson's coefficient	Density [kN/m ³]
Hard soil	60000	0.30	18
Medium soil	30000	0.35	18
Soft soil	20000	0.40	18

The concrete frame has 5m in span and 3m in height. The cross-section of the beam is $0.4 \cdot 0.4$ m², while the Young's modulus and Poisson's ratio are $3.2 \cdot 10^7$ kN/m² and 0.2, respectively. Using equations (25-27), equivalent mechanical properties of soils are expressed through their rigidities, as shown in Table 3.

Table 3. Rigidity of equivalent springs [28, 32-34]

Soil used	C_s [kN/m]	C_n [kN/m]	C_f [kN/m]
Hard soil	$69.230 \cdot 10^3$	$8 \cdot 10^4$	10^{10}
Medium soil	$34.615 \cdot 10^3$	$3.5 \cdot 10^4$	10^8
Soft soil	$23.077 \cdot 10^3$	10^4	10^6

5.2. Analysis using modal analysis

The results obtained using this simulation for the system called Soil and Framed-Structure With Interface Elements (SFSIWIE) (Figure 7b) and for the Fixed-Base analysis (FB) (Figure 7a), are analysed. Thus, a modal analysis is conducted for both types of structures by computing the fundamental period of vibrations. In the first step, the fundamental period was found to be 0.0142 sec for the FB frame, while it was 0.129 sec for the SFSIWIE frame, which is approximately 10 times more. Thus, the neglect of soil-structure interaction underestimated the fundamental period of vibrations. Figure (8) shows the period ratio of vibration of FB frame and SFSIWIE frame for various numbers of storeys using modal analysis.

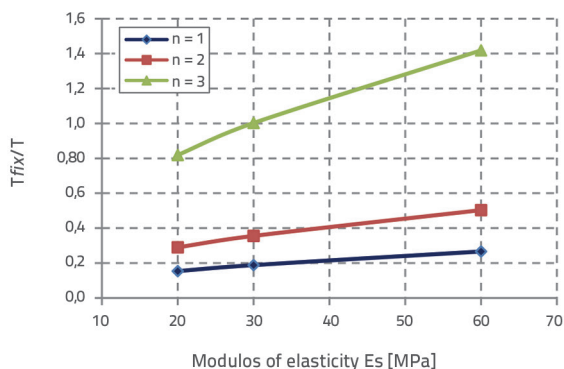


Figure 8. Relative period of FB and SFSIWIE frames

So, the (T_{fix}/T) ratio highly depends on the number of stories and the soil type (Figure 8). This variation becomes very pronounced when the number of stories is large and the elastic modulus is significant.

In the second step, the dynamic analysis is carried out to compute harmonic response of the FB frame and the SFSIWIE frame. The time history displacement in the horizontal direction at the top of the superstructure is elaborated for the fixed-base and flexible base conditions, and the effect of interaction is included in the analysis (Figure 9). So, SFSIWIE displacements using medium soil as example are clearly superior to FB displacements for the applied duration of load. The displacement field shows similar profile with some phase lag. The integration of interface elements compared to the fixed-base model contributes mainly to the behaviour of the SFSIWIE frame, and the differences between them became essentially notable at peak levels. At these levels, the difference between responses is found to be about 2.5 times.

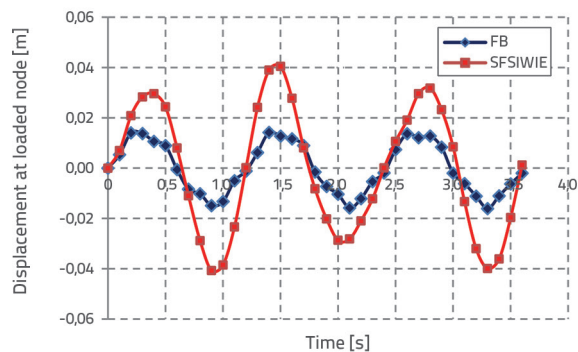


Figure 9. SFSIWIE-frame and FB-frame responses

In another section, three categories of soil described by their Young’s modulus are selected, which vary from 20MPa (soft soil), 30MPa (medium soil) to 60MPa(hard soil) (Table 3). Figure 10 shows the framed-structure response (loaded node) under harmonic load using the SFSIWIE system.

In general, soil properties affect the structural dynamic response during application of dynamic load. The influence of soil type seems to be rather small in the beginning and increases over time. This confirms that duration of the loading process also influences dynamic response of structures (Figure 10).

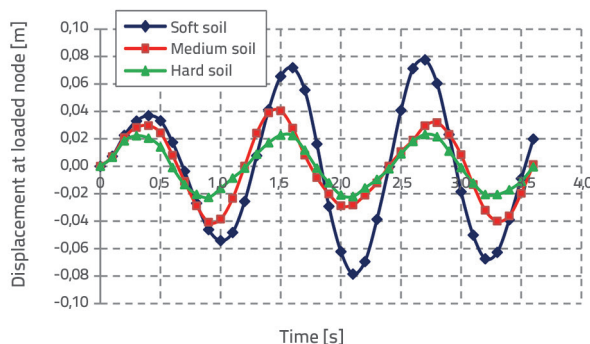


Figure 10. Dynamic influence of soil properties

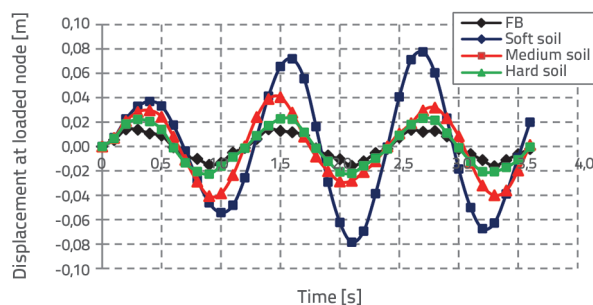


Figure 11. Structural response

Figures 11-12 show time history of horizontal displacement at the top of the superstructure and at the interface node, respectively. For different soil types, horizontal displacements at the top of the superstructure considering interface elements are very important compared to interface-node displacement.

For example, at $t = 2.75$ sec, the displacement at the top of the frame is found to be 8 cm, and the corresponding value at the interface is amounts to 6.1 cm. Thus, the displacement at the top of the frame is by approximately 31.14 % higher.

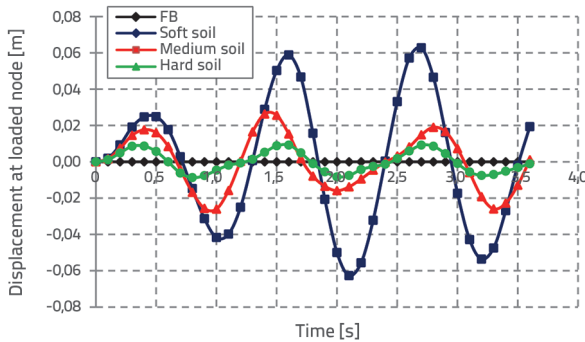


Figure 12. Interface response

5.3. Analysis using finite element method

5.3.1. Analysis with interface elements

The frame, the interface region, and the soil foundation mesh is shown in Figure 13. Under the foundation profile, the mesh is sufficiently refined and moderate meshes have been used in the rest of the continuum. In this case, three computing points are selected: frame node (A), interface node (B) and soil node (C) (free field) to study the influence of soil types on the frame, interface and soil.

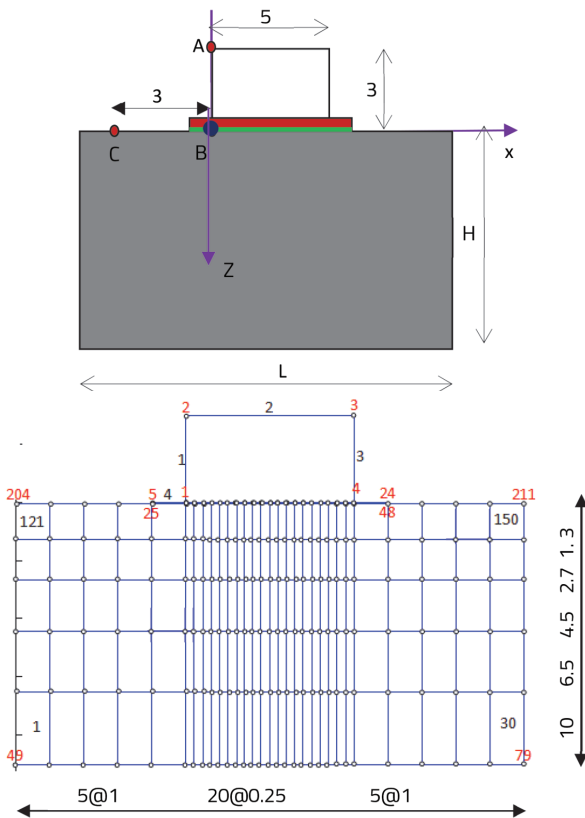


Figure 13. Meshing of frame, interface medium and soil (dim. in m)

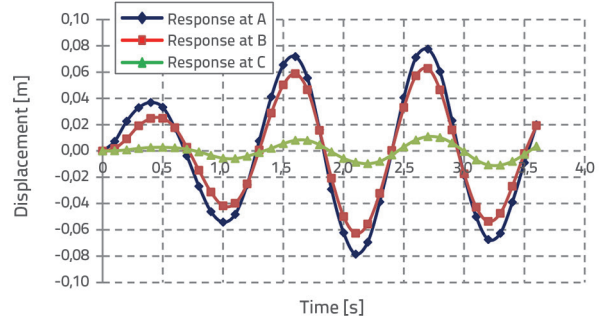


Figure 14. Dynamic responses of A, B and C nodes for soft soil

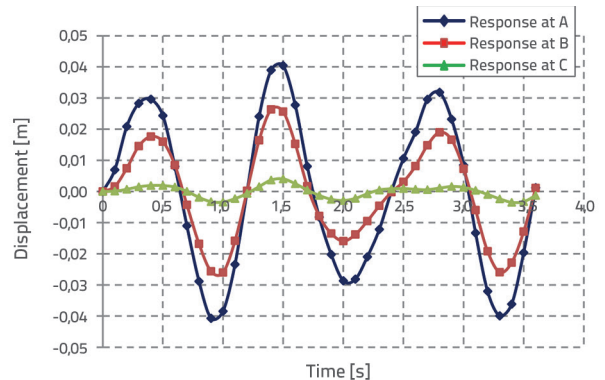


Figure 15. Dynamic responses of A, B and C nodes for medium soil

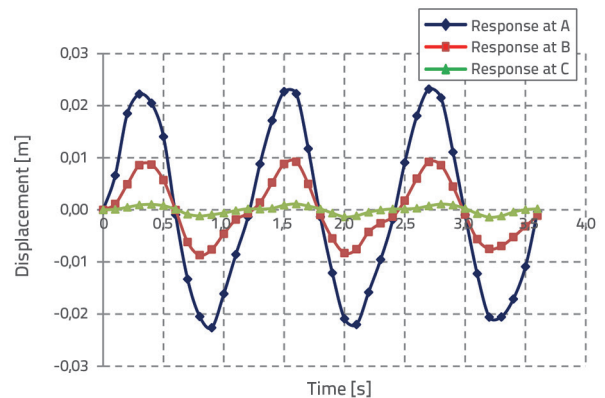


Figure 16. Dynamic responses of A, B and C nodes for hard soil

The comparative study has been elaborated to clarify the effect and the influence of soil type on the frame-structure, interface media and free field. The results obtained with this simulation for the system using interface elements (SFSIWIE) can be divided into:

1. Influence of soil type on the superstructure

The responses at the top of superstructure have been studied for various soil types. Thus, the time history analysis for these soil types has been carried out and the peak displacement profile has been studied. The obtained results show that it is necessary to reinforce soft soil by a substitute in order to improve mechanical characteristics of soils under foundations (Figure 14-16).

Table 4. Maximum displacement of superstructure

Soil type	Vršna vrijednost	1	2	3
Hard soil	peak displacement	0.022	0.022	0.023
	percentage in change			
Medium soil	peak displacement	0.03	0.041	0.032
	percentage in change	36.36 %	86.36 %	39.13 %
	percentage average	53.95 %		
Soft soil	peak displacement	0.038	0.07	0.08
	percentage in change	72.72 %	118.18 %	247.82 %
	percentage average	146.24 %		

Table 5. Maximum displacement of the interface

Soil type	Vršna vrijednost	1	2	3
Hard soil	peak displacement	0.008	0.009	0.0085
	percentage in change			
Medium soil	peak displacement	0.018	0.028	0.02
	percentage in change	125 %	211.11 %	135.29 %
	percentage average	157.13 %		
Soft soil	peak displacement	0.038	0.07	0.08
	percentage in change	375 %	677.77 %	841.17 %
	percentage average	631.31 %		

In addition, it can be observed that when the stiffness of the soil increases, the difference of frame displacement considering SSI decreases for the hard soil (Table 4).

2. Influence of soil type on the interface

Figures (14-16) show that dynamic response of the interface media is identical to that of the superstructure. In this case, the soil type has an important mutual effect on the interface continuum and on the superstructure (Table 5).

Moving from medium soil to soft soil, the average displacement varies from 53.95 % to 146.24 % for the superstructure, and so it is 2.7 times greater. However, it changes from 157.13 % to 631.31 % for the interface media, and so it is by approximately 4 times greater (Tables 4 and 5).

3. Influence of soil type on the free field

From figure (14-16), it can be seen that each soil type has a very small effect on the free-field nodes when these nodes are far from foundations. This numerical computation validates the hypothesis of kinematic conditions of lateral sides.

5.3.2. Analysis without interface elements

In this case, the analysis of SSI is elaborated without using the thin-layer interface element (SFSIWIE); a perfect link between the framed-structure and the soil (SFSIWITIE) is considered. As a result, Figure 17 shows a histogram of the fundamental period of vibration versus soil type. The obtained results show that: (1) the dynamic response of a framed structure can be very sensitive to the SSI model,

(2) the flexibility of the SSI increases natural period of the structure, and (3) the period of the fundamental mode of vibration depends on soil type.

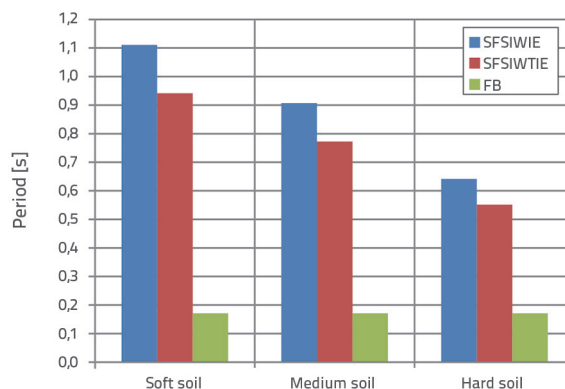


Figure 17. Period-soil type histogram

6. Conclusions

A new thin-layer interface finite element is formulated to study the soil-structure interaction problem under dynamic-load conditions. In this case, the effect and the behaviour of soil – framed structure are studied and evaluated with and without interface element. The following conclusions can be made based on the results obtained in this study:

- The developed new thin-layer interface finite element can be used to solve contact problems with various degrees of freedom.

- The fundamental natural period of structure integrating SSI effect is greater compared to the same structure with fixed-base, and at least 10 times greater if the underlying soil is soft.
- The period ratio is an inherent property of a building and its surrounding. A precise estimation of modes of vibration was possible, with foundation flexibility effects included.
- To provide for an accurate response of the structure, the effect of SSI needs to be integrated under dynamic loading conditions.
- Mechanical properties and idealisation of the supporting soil affect directly the dynamic response of frame nodes and interface nodes. Dynamic characteristics of the structure built on hard soil exceed by 53.95 % and 146.24 % dynamic characteristics of the same structure built on medium and soft soil, respectively. Moreover, soil properties affect the response of the interface that is estimated to about 157.13 % for medium soil and 631.31 % for soft soil.
- The incorporation of interface elements using the SFSIWIE model improves the response of frame compared to the fixed base model.

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