MODELING OF LATERALLY LOADED PILES USING EMBEDDED BEAM ELEMENTS

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Summary: *Realistic modeling of pile groups requires the use of complex nonlinear 3D simulations, usually with full discretization of pile continuum. In order to reduce the complexity of these models, as well as the computation time, in past years an embedded beam element has been formulated and implemented into FEM computer codes such as PLAXIS 3D. This concept was originally intended for modeling axially loaded piles and pile groups, while its performances under lateral loading conditions are not fully investigated. This paper presents the overview of different modeling techniques of laterally loaded pile groups using FEM. The possibility of using embedded beam model for this problem, as well as its limitations, have been discussed.*

Keywords: *embedded beam, lateral load, pile group, FEM, soil-structure interaction*

1. INTRODUCTION

Lateral deflection behavior of piled foundations is important design parameter in the case of engineering structures subjected to earthquake impact, wave or wind actions etc. There are also examples of piled foundations subjected to a long term static lateral loading such as foundations of retaining walls or building walls supporting the arched roof structures [1]. Also, this loading case can be the governing factor for the design of structural connections between the piles and raft in piled raft foundations [2]. Inside the pile group piles are usually arranged in rows, where *leading row* and *trailing rows* can be recognized (Fig. 1). Piles in

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trailing rows tend to exhibit less lateral resistance because of the interaction with the failure surface of the piles in front of it, and this effect is known as ”shadowing” [3]. Group interaction becomes less significant as pile spacing increases and overlapping decreases.

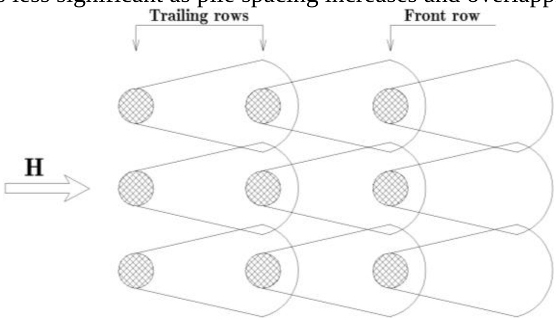

Figure 1. Front and trailing rows in pile group with shear zone overlapping

The analysis of laterally loaded pile group is a 3D problem and high soil nonlinearity and complex interactions between structural elements are governing factors that lead to the necessity of use of modern numerical methods for the correct problem solution. In load transfer methods (e.g. p-y curves [4]) piles are modeled as elastic beams supported by a set of discrete nonlinear springs that represent the surrounding soil. Group interaction effects in this case are usually taken into account by scaling down resistances in trailing rows by appropriate loading multiplier [3]. In continuum based methods the soil is represented by a discretized continuum whose behavior is described by an appropriate constitutive law. Up to now, Finite Element Method (FEM) is recognized as the most powerful tool [5], and in past years an embedded beam (EB) concept [6] was introduced as an improvement of FEM analysis of piles and implemented into different FEM computer codes. This concept was originally intended for modeling the axially loaded piles and pile groups. Verifications of this approach were reported for different geotechnical problems: compression pile test [7, 8], tension pile test [9], vertically loaded pile group [8, 10, 11, 12] and piled raft [10, 12], soil reinforcements [10], rock anchors [11], disconnected piled rafts [13]. However, performances of the EB for modeling of pile groups under lateral loading haven’t been fully investigated. Up to author’s knowledge, Sadek and Shahrour [6] used EB for analysis of single and two inclined micropiles subjected to static lateral loading. Dao [14] compared the EB single pile model with the volume pile model for the case of external lateral loading, as well as the loading induced by lateral soil displacements. Analysis of closely spaced pile groups under lateral loading (especially group interaction factors) was recently performed by Keller [15] for the case of single pile and 3-piles row. This paper presents a short overview and study of different modeling techniques for laterally loaded pile groups using FEM and PLAXIS 3D code, with main focus on EB element as recently introduced modeling concept.

2. FULL SOLID FEM PILE MODEL

The well known method for FEM modeling of pile foundations corresponds to a full discretization of pile volume using 3D finite elements. This concept allows the precise modeling of the pile geometry, which is important for real simulation of pile-soil interaction along pile shaft. The pile material behavior is described by a linear elastic model, while pile-soil contact is modeled using special zero-thickness interface elements. These elements simulate a weaker and more flexible soil zone around the piles. Interface elements' behavior is described by linear elastic-perfectly plastic Mohr-Coulomb model, where the elastic zone is limited by value of the maximum shear stress τ which can be mobilized at the contact of the pile shaft and the soil. Normal stresses in the soil are also limited by tension cut-off criterion. The main interface property is the strength reduction factor (R_{inter}) that reduces the soil shear strength parameters c and φ into interface strength parameters c_i and $φ_i$. Suitable values of R_{inter} can be found in the literature for different soil types, and usual value is about 0.5 (referred to 2/3φ) [16]. Note that the interface stiffness parameters are also reduced by R_{inter}. Interfaces can simulate the slipping/gapping between the pile and the soil by producing relative displacements in both axial and perpendicular directions. These displacements are related to interface stiffness parameters and the interface "*virtual thickness*" (imaginary zone with reduced soil properties). However, interface virtual thickness should not be too large, because it would produce large and unrealistic elastic displacements around the pile [16], so R_{inter} remains the main factor for the model calibration. The main problem is the excessive computation time because of the large number of finite elements that is used for modeling the pile geometry and the interface surface. What can also be an issue in this case is the calculation of pile beam internal (section) forces, which is by default done by integration of stresses along the pile axis. Latter problem can also be solved by adding the elastic beam element with very small bending stiffness through the center of the pile [14], which will not influence the system stiffness matrix. This allows the pile bending line to be calculated and internal forces are then determined using real pile bending stiffness. This modeling approach can take the most of the problem aspects into considerations, and remains the most precise.

3. EMBEDDED BEAM ELEMENT IN PLAXIS 3D

The embedded beam approach was introduced by Sadek and Shahrour 2004 [6]. In this concept pile volume isn't discretized with solid elements, but replaced with advanced formulation. EB is a beam element that is inserted (embedded) at arbitrary direction into existing FE mesh of soil volume elements (e.g. 10-node tetrahedron in PLAXIS). EB element in PLAXIS is 3-node element with 6 DOF per node (3 translations and 3 rotations). Upon insertion of EB new "virtual" nodes are generated inside existing soil volume elements at penetration points (Fig. 2), and they don't affect the discretization of soil continuum. As an improvement of initial formulation [6], an elastic zone is assumed around the EB element in PLAXIS 3D (Fig. 2), where plasticity in soil elements is disabled. Although EB doesn't occupy the volume, elastic zone bounds the space occupied by real pile, and its size is governed by pile diameter D. In comparison with full soil model, the main difference is the fact that the pile-soil contact is modeled along the pile axis, instead of pile circumference. Pile-soil interaction is modeled with special interface 3-node spring elements in axial and lateral directions that "connect" the EB nodes with virtual soil FE nodes. These elements are different from the interface elements used in full solid pile model. Interface stress components t_s, t_n, t_t, as well as at the pile tip interface spring, are shown in Fig. 2. Skin interface behavior is described by linear elastic constitutive law:

$$\begin{Bmatrix} t_s \\ t_n \\ t_t \end{Bmatrix} = \begin{bmatrix} K_s & 0 & 0 \\ 0 & K_n & 0 \\ 0 & 0 & K_t \end{bmatrix} \begin{Bmatrix} u_s^{pile} - u_s^{soil} \\ u_n^{pile} - u_n^{soil} \\ u_t^{pile} - u_t^{soil} \end{Bmatrix} \tag{1}$$

where K_s is elastic stiffness in direction of pile axis, and K_n, K_t are elastic stiffness in lateral direction (perpendicular to pile axis). Latter vector in Eq. 1 contains the displacements of pile and soil in orthogonal directions (s, n, t). Interface normal stresses t_n and t_t will always remain elastic (they are not limited by failure law), while the value of shear stress t_s is limited by ultimate traction value T_{max}. Pile foot resistance is defined in almost similar way, by linear elastic-perfectly plastic spring in pile axial direction. Base force is limited with value F_{max}:

$$F_{foot} = K_{foot}\left(u_{foot}^{pile} - u_{foot}^{soil}\right) \le F_{\max} \tag{4}$$

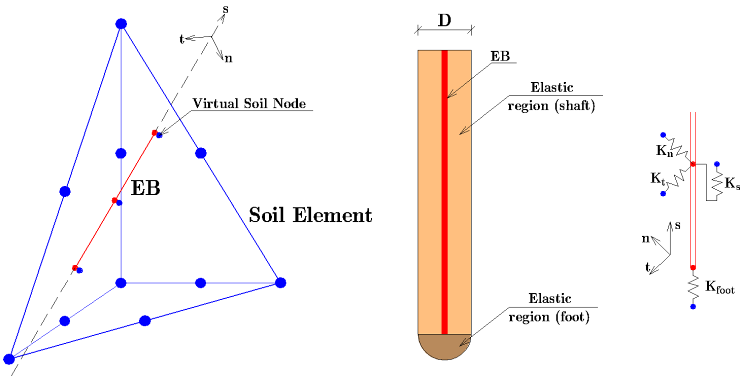

Figure 2. Embedded beam element

Relative displacements (u_{rel}) at pile-soil interface are only related to the values of the interface stiffness K_s, K_n and K_t. Like in the case of the full solid model, the generation of large elastic displacements at pile-soil interface should be preserved. In order to do this, interface stiffness K_s, K_n and K_t must be higher than the soil stiffness properties (e.g. oedometer modulus $E_{oed,soil}$). According to [16], interface stiffness in PLAXIS 3D are set to the following values:

$$K_s >> G_{soil} = \frac{E_{soil}}{2\left(1+\nu_{soil}\right)}$$
$$K_n = K_t = \frac{2\left(1-\nu_{soil}\right)}{1-2\nu_{soil}} K_s >> \frac{2\left(1-\nu_{soil}\right)}{1-2\nu_{soil}} \frac{E_{soil}}{2\left(1+\nu_{soil}\right)} = E_{oed,soil} \tag{2}$$

Note that stiffness values are not user-defined values, but the values that are automatically set by PLAXIS 3D code, so the governing calibration factors for the model interface stiffness are the stiffness properties of the surrounding soil. What is very important is the fact that the T_{max} and F_{max}, which separate linear elastic and perfectly plastic interface behavior using failure criterions, are user input values. These values define the total EB bearing capacity as sum of T_{max} and F_{max} [16]. There are several ways to enter T_{max} in PLAXIS, and the most important is *layer-dependant* option, where T_{max} is related to (reduced) soil strength parameters. Only in this case pile bearing capacity is result of calculation, while otherwise it is an input value and must be carefully chosen. Ability of the EB to resemble behavior of pile group subjected to lateral loading, and especially the pile interaction factors, will be analyzed in the next section.

4. COMPARISON OF MODELING TECHNIQUES

Comparison of described modeling techniques (EB vs. volume pile model - VP) is presented on simple idealized example of laterally loaded 2x2 pile group with c-c (center to center) pile spacing of 4D. Piles are 10 m long, with diameter of 0.5 m. Two different types of soil (loose and dense sand) are considered. Numerical simulations were performed as displacement control tests with prescribed displacement of 0.2D at the top of the piles, applied in 8 equal increments. In order to simplify the model and focus on group interaction effects, pile cap was not modeled, and instead the prescribed displacement was applied on all piles at the same amount. This simulates the rigid translation of pile cap, without contact with the soil. The cases of fully rigid interface (R_{inter}=1), as well as softer interface (R_{inter}=0.5) are investigated. Soil behavior is modeled using elastoplastic Hardening Soil (HS) model [17] and piles are modeled as linear elastic (LE). Constitutive parameters are shown in Table 1.

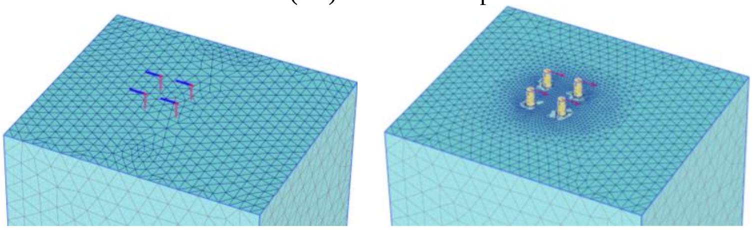

Figure 3. EB and VP pile group models

Table 1. Material model parameters

Material			Loose sand	Dense sand	Concrete (pile)
Material model			HS	HS	LE
Unsaturated weight	γ_{unsat}	kN/m^3	17	20	25
Stiffness	E	kN/m^2	-	-	30x10^6
	E_{50}^{ref}	kN/m^2	20000	40000	
	E_{oed}^{ref}	kN/m^2			
	E_{ur}^{ref}	kN/m^2	60000	120000	
Poisson ratio	υ_{ur}	-	0.2		0.2
Power	m	-	0.5		
Reference pressure	p^{ref}	kN/m^2	100		
Cohesion	c'	kN/m^2	0		
Friction angle	φ'	°	30	35	
Dilatancy angle	ψ	°	0	5	
Lateral pressure coefficient	K_0	-	1-sinφ'		
Failure ratio	R_f	-	0.9		

Note that the EB actually doesn't occupy any volume, so the weight of the EB (concrete) should be entered as reduced value, in order to preserve the values of initial vertical stresses after insertion of the piles. Maximum traction T_{max} is calculated using layer dependent option and soil interface factor R_{inter}, while the maximum pile tip force is adopted in high value of F_{max}=10000 kN, in order to reduce its impact on the model behavior. The pile installation process is totally neglected in the example (soil properties are unchanged due to installation process disturbances).

Interaction between the piles inside group and total group efficiency can be easily expressed using pile interaction factors for each pile α_i and group interaction factor GW, which is the mean value of α_i. Pile interaction factor α_i is defined as:

$$\alpha_i = \frac{H_i}{H_{SP}} \leq 1 \tag{5}$$

where H_i is lateral force of i-th pile inside the group and the H_{SP} is the force of equivalent single pile for the same deflection. Group interaction factor GW is defined as:

$$GW = \alpha_{i,mean} = \frac{\sum_{i=1}^{N} \alpha_i}{N} = \frac{\sum_{i=1}^{N} \frac{H_i}{H_{SP}}}{N} = \frac{\sum_{i=1}^{N} H_i}{N \cdot H_{SP}} = \frac{H_{GROUP}}{N \cdot H_{SP}} \leq 1 \tag{6}$$

According to research by Kotthaus [18], α_i and GW are displacement dependent, and decrease with increased displacement level, as well as with smaller pile spacing.

5. RESULTS AND DISCUSSION

Load-displacement curves for single pile models in dense and loose sand are given in Fig. 4.

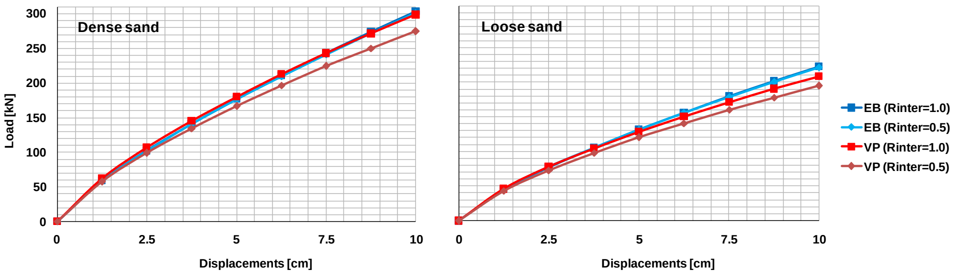

Figure 4. Load-displacement curves of single piles

The results in Fig. 4 show that interface properties (R_{inter}) don't influence the lateral behavior of EB models, while the VP models are influenced as expected. This is associated with the formulation of the EB interface, where only the shear stress in axial direction is governed by interface input parameters. It can also be observed that the EB single pile model agrees very well with the VP model with rigid interface, while the weaker pile-soil contact cannot be resembled with EB interface parameters.

The match between the EB models and VP model with rigid interface is better in the case of dense sand than in the loose sand. This is probably associated with the difference in the FE meshes of VP and EB models, which lead to different plastic zones in the models, and plastic behavior is higher in loose sand models.

These differences, even not very large, should be investigated in further research. The main difference in the finite element meshes is the fact that the zone around volume pile contains the finer FE mesh, while from the practical point of view, EB finite element mesh should be without any refinement [16].

Load-displacement curves for piles inside pile group are given in Figures 5 and 6. Difference in bearing capacity between front and trailing row piles can be clearly seen in both EB and VP models, which means that both models can qualitatively resemble well known pile group behavior.

Again, the EB model is not influenced by the EB interface properties. Slight disagreement between the EB front row pile and EB single pile looks unrealistic (forces in front row pile are higher than forces in single pile), and this is probably due to different FE meshes of these two models. However, while the EB and VP single pile models with the rigid interface showed almost the same behavior, in the case of pile group the difference is observed. These differences are higher for the trailing row.

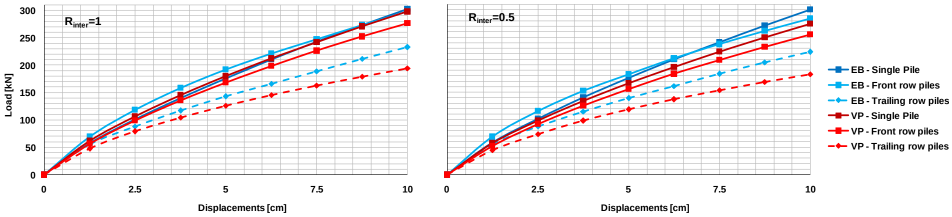

Figure 5. Load-displacement curves of single pile and group piles in dense sand

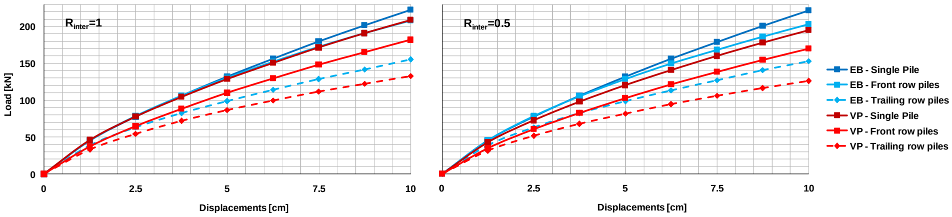

Figure 6. Load-displacement curves of single pile and group piles in loose sand

Pile interaction factors α_i and total group interaction factors GW are given in Figures 7-9.

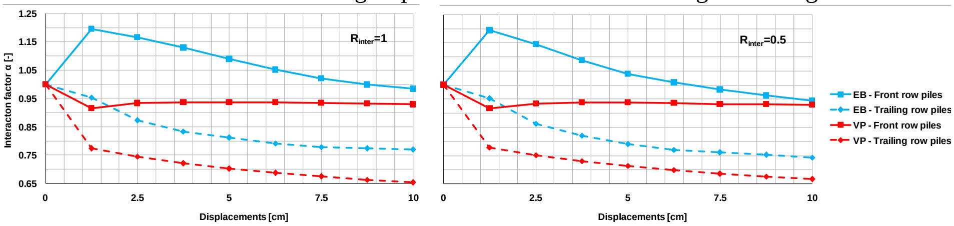

Figure 7. Interaction factors for pile group in dense sand

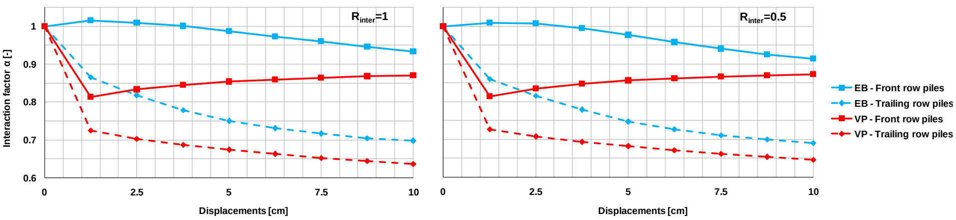

Figure 8. Interaction factors for pile group in loose sand

The above mentioned differences in FE meshes in pile group and single pile models lead to unrealistic values of interaction factors α_i and GW higher than 1 (case of EB models in dense sand for small displacements level). These values must be further investigated from the EB model mesh-sensitivity point of view. In the case of loose sand, EB models show expected decreasing interaction factors. Differences in interaction between the EB and VP models decrease as the loading level increases and these differences are higher for trailing rows. At higher loading states the EB and VP models can predict the pile group efficiency in almost similar way (the interaction factors and GW are closer). However, the main issue with the VP model is the fact that the VP models show, in general, the increase of interaction factors for front row piles. Although this increase is not very large, this behavior is not fully realistic and should be further investigated. In presented example the EB model can better predict the pile group interaction behavior than the VP model, according to group interaction factors described by Kotthaus [18].

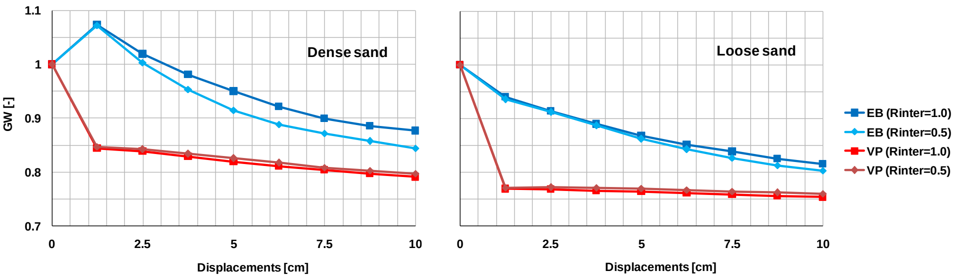

Figure 9. Group interaction factors

From Fig. 9 we can observe that the interface strength parameters don't influence the total group interaction effects for both EB and VP models, which means that for the group interaction prediction interface properties are not the governing factor for model calibration.

6. CONCLUDING REMARKS

Two different pile modeling techniques were analyzed. It was shown that the pile group behavior can qualitatively be resembled by EB formulation, but there are differences in obtained results between the EB and VP models, which are higher for trailing group rows. Differences in group interaction effects decrease with the increase of loading level.

Transversal forces in the laterally loaded piles are not influenced by interface properties in the EB model. Due to EB interface formulation, T_{max} and R_{inter} will only influence the pile response under axial loading. However, when transversal pile forces become large, plasticity will occur in the surrounding soil elements, outside the elastic zone. Interface strength parameters don't influence the total group interaction factors for both EB and VP models. In the case of rough pile-soil contact (R_{inter}=1), EB can better match the VP model under lateral loading.

The fact that EB doesn't take into account the sliding between the pile and the surrounding soil in lateral directions can be the main disadvantage of this modeling concept. Since the real circumference of the pile is not modeled, pile installation effects cannot be taken into account. However, real soil-structure interaction can be distinctly affected by the installation depending in the pile type (e.g. bored piles or driven piles), which can lead to the problems with the EB model calibration with real measurements. For shown idealized example, EB model can be better for pile group interaction prediction than VP model, but there are some unrealistic results which are probably associated with the difference in FE meshes. Based on published research [13] and presented example, EB models are sensitive to FE mesh coarseness. This is probably because of a different level of approximation governed with different number of virtual nodes that are generated in different FE meshes. Presented study was performed on the models with relatively coarse mesh. In order to keep the accuracy of the results and decrease computation time, in further research the influence of the FE mesh coarseness on the precision of EB models must be investigated. The possibilities of introducing additional interface elements from VP models into EB models (say "hybrid" model), without increasing the computation time should also be investigated, so the cases of weaker pile-soil interfaces can also be modeled with EB models. Further research should lead to modeling guidelines for laterally loaded pile groups using PLAXIS 3D EB elements.

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МОДЕЛ ЛАТЕРАЛНО ОПТЕРЕЋЕНИХ ШИПОВА ПОМОЋУ ”УМЕТНУТИХ” ГРЕДНИХ ЕЛЕМЕНАТА

Резиме: *Тачно моделирање група шипова захтева примену сложених нелинеарних 3D симулација, често са потпуном дискретизацијом шипова. У циљу смањења сложености оваквих модела, као и потребног рачунарског времена, последњих година формулисан је “уметнути” гредни елемент, који је имплементиран у рачунарске програме Методе коначних елемената, као што је PLAXIS 3D. Овај концепт првобитно је био намењен за моделирање аксијално оптерећених шипова и група шипова, док његове перформансе под латералним оптерећењем нису у потпуности истражене. У овом раду дат је кратак приказ различитих техника моделирања латерално оптерећених група шипова коришћењем Методе коначних елемената. Анализирана је могућност примене “уметнутих” гредних елемената за решење овог проблема и приказана су ограничења овог модела.*

Кључне речи: *“уметнути” гредни елемент, латерално оптерећење, група шипова, МКЕ, интеракција тла и објекта*