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PUSHOVER ANALYSIS OF MDOF SYSTEM WITH SSI EFFECTS AND ACCORDING TO FEMA 440

Mladen Cosic(1

(1 *Magister of Technical Sciences, Diploma Civil Engineer, PhD student, personal address: Marka Milanovica 17, 15300 Loznica, Serbia;* *mladen165@inffo.net*

Summary

This paper discusses the analysis of soil-structure interaction using Displacement Modification Method, which was developed within the concept of FEMA 440 regulations. This method belongs to a group of static seismic methods, and uses the model of nonlinear behaviour of structures. To assess the effects of soil-structure interaction applied multi-parametric analysis of kinematics and damping effects of the ground or soil. The research was conducted also, on a model where the impact of introducing foundation structure and soil. The soil is modeled as a homogeneous, elastic, isotropic half-space (HEIS), while the connection of foundation structure-HEIS achieved using contact gap elements. In all analysis were introduced development of geometric nonlinearity, while development of material nonlinearity introduced by the concentrated plastic hinge model.

Key words

soil-structure interaction, pushover analysis, target displacement

ПУСХОВЕР АНАЛИЗА НА МДОФ СИСТЕМ СО ССИ ЕФЕКТИ И СПОРЕД ФЕМА 440

Mladen Cosic(1

Резиме

Овој труд се дискутира за анализа на почвата-структура интеракција со користење Дисплацемент Модифицатион Метход, кој беше развиен во рамките на концептот на ФЕМА 440 прописи. Овој метод припаѓа на група на статички сеизмички методи, и користи моделот на нелинеарни однесувањето на структури. Да се проценат ефектите на почвата-структура интеракција применети мулти-параметрична анализа на кинематика и амортизирањето ефекти на земјата или почва. Истражувањето беше спроведено, исто така, на пример, каде што влијанието на воведувањето на основа структура и почвата. На почвата е моделирана како хомогена, еластична, изотропна половина-простор (ХЕИС), додека врската на фондација структура-ХЕИС постигнато со користење на контактни јазот елементи. Во сите анализи беа воведени на развојот на геометриски не се линеарноста, додека развојот на материјал не се линеарноста воведени од страна на концентриран пластични панта модел.

Клучни зборови

почвата-структура интеракција, пусховер анализа, целни поместување

1. INTRODUCTION

In last two decades was formulated and updated the research on the improvement of new methods based on static analysis of the seismic influence and non-linear mathematical model of structues (NSPA- Nonlinear Static Pushover Analysis). NSPA analysis is implemented in ATC 40 [1] and FEMA 273/356 [2, 3] regulations, and FEMA 440 [4] have shown further improvement in the case of structure and soil interaction (SSI- Soil-Structure Interaction). The general procedure for determining a level of the target displacement is based on concept of Coefficient Method according to FEMA 356, which was modified and presented as Displacement Modification Method DMM in FEMA 440.

When is considering the interaction of foundation and soil in seismic areas, important is the knowledge of behavior of soil under static and dynamic loads and a wide range of changes of parameters related to the seismology, seismic geotechnical problems, geology and soil mechanics and applied mechanics in general. SSI analysis of problems of interaction in order to obtain reliable and economical solution at the same time, refers to definition: effects of seismic load, dynamic characteristics of the soil, stability of foundations in seismic conditions and modeling structure-foundation-soil for SSI interaction.

2. SOIL-STRUCTURE INTERACTION ACCORDING TO FEMA 440

There are three primary categories of SSI effects [4]: introduction of flexibility to the soil-foundation system (FFE- Flexible Foundation Effects), filtering of ground motions transmitted to the structure (KIE- Kinematic Interaction Effects) and dissipation of energy from the soil-structure system through radiation and hysteretic soil damping (FDE- Foundation Damping Effects).

The basic classical model (RBM- rigid based model) which does not introduce SSI interaction treated fundation and soil as absolutely rigid. This system has excited by the free movement of surface soil (FFM- Free Field Motion) with conventional damping. Structural systems that take into account vertical elements (reinforced concrete walls, frames) may be especially sensitive to even small rotation and translation, which does not take into account with assumption of the rigid based model. According to the FEMA 440 [1] regulations for the nonlinear static seismic analysis, SSI interaction is modeled by introducing flexibility into the system of foundation structure-soil. This model of interaction is called model with flexible base (FBM- Flexible Base Model). In a given model is introduced the impact of structural components of foundation and geotechnical components of foundation. The first component is introduced modeling of flexible foundation structure, while the second component is introduced modeling of spring components with an appropriate stiffness to replace the impact of soil. Also, in this model is used a resulting acceleration record that comes to the surface of the soil with 5% damping as the conventional initial value. Compared to the model that has absolutely rigid foundation structure occurs increase a period of vibration of structure, changes in the distribution of forces in the cross sections and can be taken into account the impact of foundation structure. Further improvement can be done by introducing filtering effects that SSI interaction can have on the character and intensity of ground motion experienced by the structural model. Kinematic interaction results from the presence of relatively stiff foundation elements on or in soil that cause foundation motions to deviate from FFM. Two effects are commonly identified: base-slab averaging and embedment effects. The base-slab averaging effect can be visualized by recognizing that the instantaneous motion that would have occurred in the absence of the structure within and below its footprint is not the same at every point. The embedment effect is associated with the reduction of ground motion that tends to occur with depth in a soil deposit. Both base-slab averaging and embedment affect the character of the foundation-level motion (FIM- Foundation Input Motion) in a manner that is independent of the superstructure. The effects can be visualized as a filter applied to the high-frequency (short-period) components of the FFM (high T-pass filter). The next situation is introduction of FDE that are another result of inertial SSI interaction in addition to foundation flexibility. Foundation damping results from the relative movements of the foundation and the supporting soil. It is associated with radiation of energy away from the foundation and hysteretic damping within the soil. The result is an effective decrease in the spectral ordinates of ground motion experienced by the structure.

In practical analysis foundation damping is linked to ratio of fundamental period of the system on FBM model to that of a RBM model. The foundation damping is combined with the conventional initial structural damping to generate a revised damping ratio for the entire system, including structure, foundation, and soil. Ground motions imposed at the foundation of a structure can differ from those in the free field due to averaging of variable ground motions across the foundation slab. These effects belong to the group of KIE effects and they are important for buildings with relatively short fundamental periods (<0.5s), large plan dimensions or basements embedded 3m or more in soil materials. A ratio of response spectra RRS factor is used to represent KIE effects as ratio of the response spectral ordinates imposed on the foundation FIM to the free-field spectral ordinates FFM. Two phenomena should be considered in evaluating RRS: base slab averaging RRS_{bsa} and foundation embedment e. The RRS_{bsa} effect occurs at the foundation level for mats or spread footings interconnected by either grade beams or reinforced concrete slabs. The only case in which RRS_{bsa} effect should be neglected is in buildings without a laterally connected foundation system and with flexible floor and roof diaphragms. Foundation embedment effects should be considered for buildings with basements when the depth of basements is greater than about 3m. KIE effects can effectively cover by the procedure defined in [5]:

- evaluate the effective foundation size $b_e=\sqrt{ab}$, where a and b are the full footprint dimensions of the building foundation in plan view,
- evaluate the RRS from base-slab averaging RRS_{bsa} as a function of period T:

$$RRS_{bsa} = 1 - \frac{1}{14.1}\left(\frac{b_e}{T}\right)^{1.2} \geq \text{ the value for } T \geq 0.2\text{s}, \qquad (1)$$

- if the structure has a basement embedded a depth e from the ground surface, evaluate an additional RRS from embedment RRS_e as a function of period T:

$$RRS_e = \cos\left(\frac{2\pi e}{Tnv_s}\right) \geq 0.453, \text{ or the } RRS_e \text{ value for } T \geq 0.2\text{s, where:} \qquad (2)$$

  v_s shear wave velocity for site soil conditions, taken as average value of velocity to a depth of e below foundation, n shear wave velocity reduction factor for the expected PGA: PGA=0.1g: n=0.9, PGA=0.15g: n=0.8, PGA=0.2g: n=0.7, PGA=0.3g: n=0.65,
- evaluate the product of RRS_{bsa} times RRS_e to obtain the total RRS for each period of interest. The spectral ordinate of the FIM at each period is the product of the FFM spectrum and the total RRS.
- to generate the complete spectrum for FIM, repeat previous steps for different periods.

Kinematic interaction effects should be neglected for soft clay sites (class E), while embedment effects can be neglected for foundations embedded in firm rock (classes A and B). Shear wave velocity in a function of soil class according to the FEMA 273 [2] are: A: $v_s>1524\text{m/s}^2$, B: $762<v_s<1524$, C: $366<v_s<762$, D: $183<v_s<366$, E: $v_s<183\text{m/s}^2$. The effects of foundation damping are represented by a modified system-damping ratio. The initial damping ratio for the structure neglecting foundation damping is referred to as β_i and is generally taken as 5%. The final value of the damping coefficient is β_0 which takes into account the SSI interaction, so that a change of β_i in β_0 affects the correction of elastic response spectrum. Determination of foundation damping factor β_f is carried out by:

- evaluate the linear periods for the structural model assuming a RBM model T_{fix} and a FBM model T_{flex}, using soil spring stiffness according to FEMA 356 [3].
- determine foundation damping factor β_f as:

$$\beta_f = a_1\left(\frac{T_{flex,eff}}{T_{fix,eff}} - 1\right) + a_2\left(\frac{T_{flex,eff}}{T_{fix,eff}} - 1\right)^2, \qquad (3)$$

- while the damping coefficient β_0 which takes into account the SSI interaction is determined as:

$$\beta_0 = \beta_f + \frac{\beta_i}{\left(\frac{T_{flex,eff}}{T_{fix,eff}}\right)^3} . \qquad (4)$$

3. PUSHOVER ANALYSIS OF MDOF SYSTEM ACCORDING TO FEMA 440

Based on previously presented FEMA 440 concept, parametric analysis was performed for 8-storey 4-field frame system. For the analysis of frame in terms seismic effects is used beam's linear finite elements, while the nonlinear effects were included using geometric and material nonlinearities. First made NSPA analysis of MDOF systems, and then using the DMM method solved target displacements. Based on the conducted NSPA analysis pushover curves were developed. Effect of SSI interaction is incorporated in the analysis of target displacement. Response spectra (Figure 1.) for analyze of system was introduced by FEMA 273 [2] with the normalized ordinate at a value of 1. In relation to the FFM response spectra, acceleration spectra with kinematic interaction effects FFM+KIE and foundation damping effects FFM+KIE+FDE are generated. Effect of foundation embedment *e* can be seen comparing the chart (Figure 1.a, b) for different values of *e*=0 and *e*=9m for constants: soil C: v_s=600m/s^2, PGA=0.3g, *n*=0.65, β_0=0.1. Reduction of values in constant acceleration is up to 50%. For stiffer buildings with lower periods of vibration are significantly reduction the acceleration, if there is existence of a ground floor e=9m. Influence of FDE effects was discussed over β_0 coefficient, which is varied within the limits of the possible values for the MDOF reinforced concrete frame system [6]. Preliminary and later detailed multi-parametric research has found that the impact of FDE effects, within the examined values, is dominant in relation to the KIE effects for frame systems.

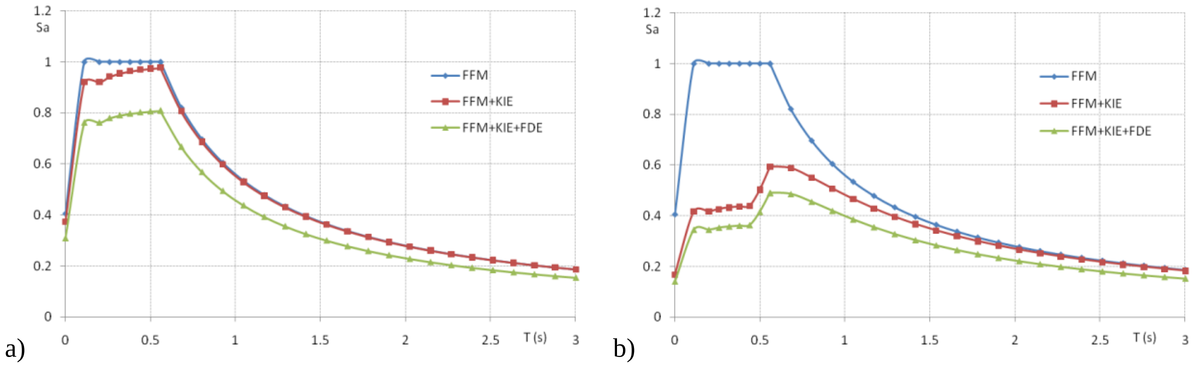

Figure 1 Elastic spectrum FFM, kinematics effects spectrum FFM+KIE, and kinematics and damping effects spectrum of the foundations FFM+KIE+FDE for soil C: v_s*=600m/s*^{2}*, PGA=0.3g: n=0.65,* β_0*=0.1: a) e=0, b) e=9m*

Слика 1 Еластичен спектар ФФМ, на спектарот поправена кинематичка ефекти ФФМ+КИЕ и на спектарот поправена кинематичка ефекти и амортизирането почва ФФМ+КИЕ+ФДЕ за почвата Ц: $в_с$*=600м/с*^{2}*, ПГА=0.3г: н=0,65,* β_0*=0,1: а) е=0, б) е=9м*

On the basis of the applied response spectra, developed pushover curves and demand curves levels of target displacements TD are determined. Target displacements envelope TDE curve is constructed linking such separated discrete values of TD [7]. TDE envelope represents a possible state of global drifts for one multi-storey frame in a function of soil types and different levels of damping β_0. Taking into account the SSI interaction, changes of parameters are considered: β_0€(5, 10, 15, 20, 25, 30)%, soil types €(A, B, C, D, E) according to the FEMA 273 for *e*=3m, PGA=0.3g, *n*=0,65 (Figure 2.). Minimum value of global drifts are within the limits of 0.2-0.4% and are related to soil type A, while maximum values are more different, and are related to soil type E. Such a large range of value points to the differences in behavior of structure founded on different types of soil, regardless of the type of structural system. Change of the total shear force is much smaller than change of displacements, or drifts, because the system has considerably less stiffness in non-linear domain.

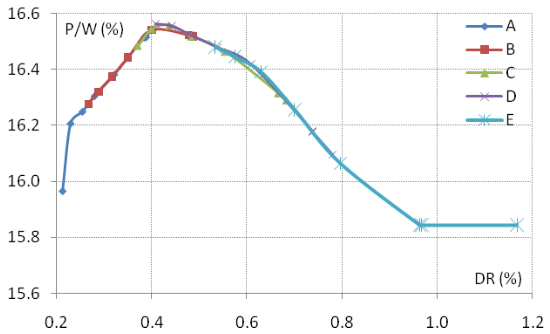

Figure 2 Target displacements envelope of multi-storey MDOF frame (PGA=0.3g, n=0.65, e=3m)
Слика 2 Целна преместувања коверт на многоетажна МДОФ рамка (ПГА=0.3г, н=0,65, е=3м)

Since TDE envelope designed for different types of soil and different levels of damping β_0, in certain situations TD values overlap. Because of this inability of the visual perception of discrete values, in particular are designed: pushover curves without SSI interaction, target displacements without SSI interaction and target displacements taking into account SSI interaction for different types of soils and levels of damping β_0 (Figure 3.a-e). On the basis of conducted research and obtained target displacements toward DMM method, can be said that discrete values of the total seismic forces lie on the pushover curve. In a case of soil type E: TD, SSI, β_0=0.1 and TD, no SSI (Figure 3.e) obtained target displacements are higher than realized displacements from pushover curve.

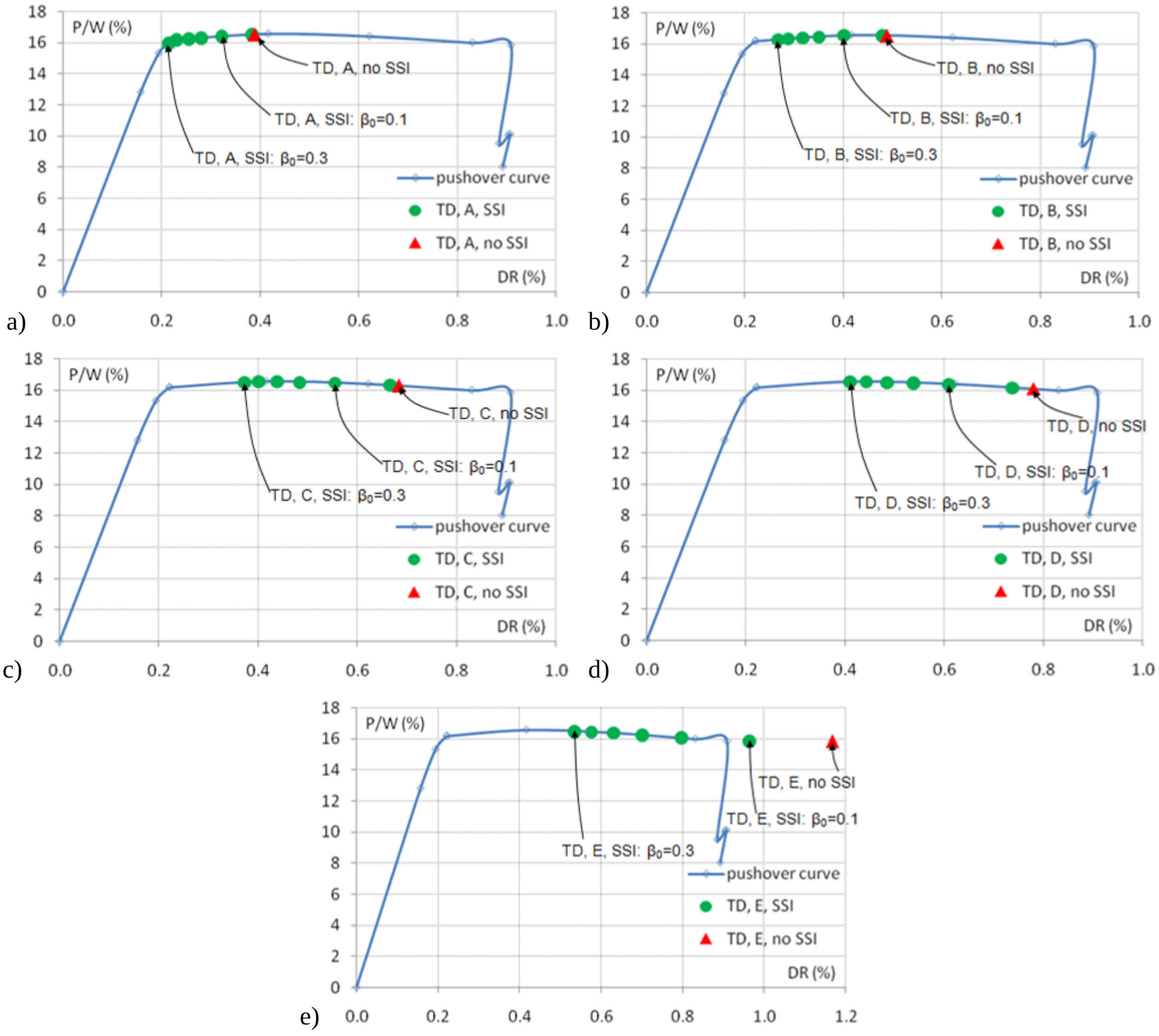

Figure 3 Pushover curve and target displacements for soil: a) A, b) B, c) C, d) D, e) E
Слика 3 Пусховер крива и целните преместувања за почвата: а) А, б) Б, ц) Ц, д) Д, е) Е

4. PUSHOVER ANALYSIS OF MDOF SYSTEM WITH HEIS

The research was conducted also on a model with the impact of introducing foundation structure and soil. In this calculated model deformation and displacement of structure during an earthquake depends of the interaction of three related systems: the same construction (MDOF multi-storey frame), the foundation structure (foundation beams or plate) and the geological environment where is the foundation structure (Figure 4.) [8].

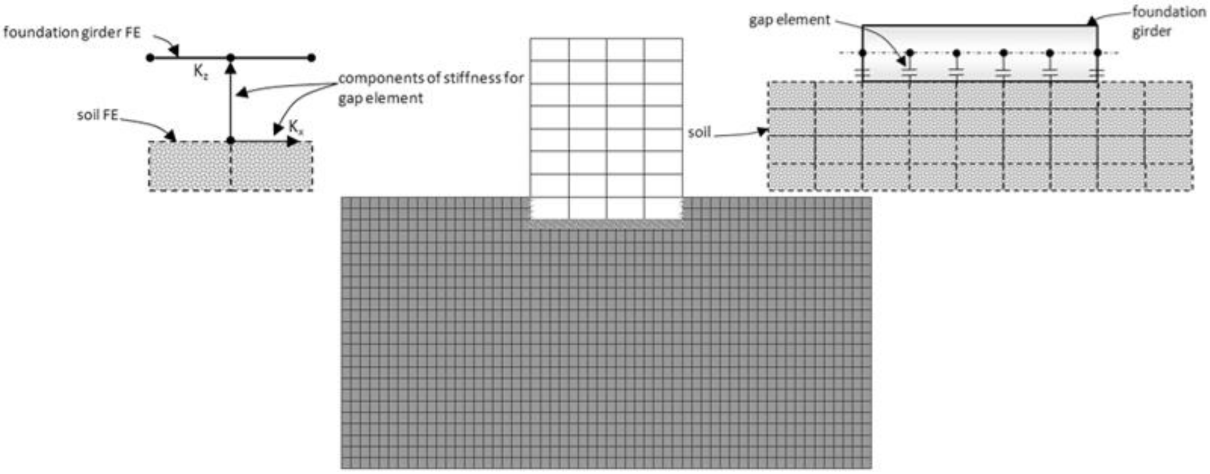

Figure 4 Numerical model of MDOF multistorey frame and HEIS
Слика 4 Нумерички модел на МДОФ многоетажни рамка и ХЕИС

Since finite element method applied to analysis, there is elimination of soil finite elements in the area of underground levels to form the basic structure type foundation girder. In this way it takes into account the impact of underground part which aims to simulate MDOF system behavior in real terms. The foundation structure is formed as a foundation girder which is modeled using linear finite elements and the soil using plate finite elements. The foundation structure-soil contact is achieved using gap elements and thereby eliminates tension stresses. To establish continuity of connection to the foundation structure-soil, it is applied a discrete contact element that connects nodes of finite elements [9]. Each contact element has six components of stiffness: one axial, two shear, two rotational and one torsional. In order to establish compatibility of deformation of the foundation girder-soil contact, it is necessary to take into account that the component of stiffness in direction of connection K_Z has a large value ($K_Z=10^{10}$kN/m). The horizontal component of contact element is stiffness for a case when the friction force occurs between the foundation girder and soil. Contact element features two states: active (contact is established, very high stiffness) and inactive (contact is not established, very low stiffness) [10] (Figure 5.). Applying contact elements in modeling transitional zone of the foundation girder-soil, it is necessary to apply geometric nonlinear incremental-iterative analysis. Due to nonlinear behavior (change of state following a major change of stiffness) of contact element, there may be serious difficulties in ensuring convergence of nonlinear solutions [11]. Since applied contact nodal element, it is necessary to fulfill a requirement on length of finite elements in a contact zone, respecting a sufficient number of contact elements so as not to violate a compatibility of deformation.

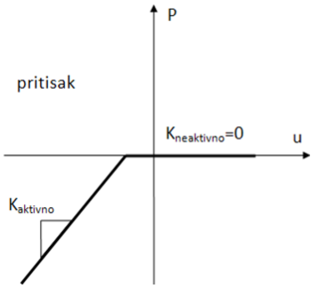

Figure 5 Force-displacement chart for gap element active on pressure
Слика 5 Сила-поместување дијаграм за празнината елемент активно работи на притисок

For the behavior of soil in this study was approved homogeneous, elastic and isotropic half-space HEIS [12]. As discussed to be used plane frame, for soil used plane strain. In process of approximation considered soil domain is modeled with surface two-dimensional finite elements. These finite elements are mathematic two-dimensional, because considerations related to the coordinate system defined by two axes. These axes determine the mid plane or mid surface that shares a thickness of surface finite element. The paper deals with a 1m thickness slice of soil, where is finite element approximated by a constant thickness. In case of a plane strain can be assumed that points of cross section, which is sufficiently far from the base, remain after deformation in plane. Cross section points will have only component of displacement in plane x, y (plane of discussed model), and this displacement will be independent of position of point with respect to z axis (perpendicular to plane of discussed model) [13].

The survey was conducted on the MDOF model without introducing the soil (no HEIS) and with introducing influence of soil to the procedure previously described (E=100MPa and E=10MPa) (Figure 6.). Computational models that are introduced with HEIS model of soil to analyze have a lower value of initial stiffness, as the soil is treated as elastic deformable environment. On the other hand, capacity is substantially lower for these models compared to the model without HEIS. If analysis will be perform on isolated structural elements, such as columns on HEIS, then came to fore only impact of reduction of initial stiffness, with no reduction of capacity [14]. By modeling the entire complex MDOF structure, foundations, transitional zone and soil as HEIS change place on all three key levels: stiffness, strength and ductility.

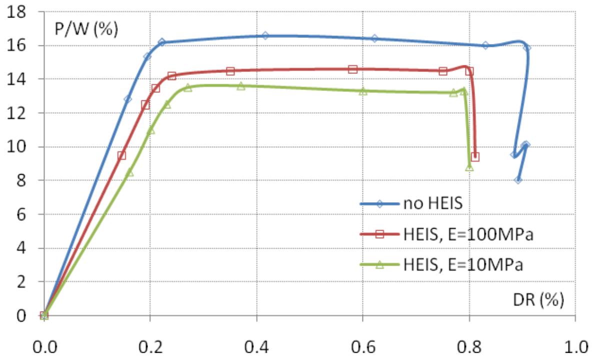

Figure 6 Pushover curves for model without HEIS and with HEIS
Слика 6 Пусховер криви за модел без ХЕИС и со ХЕИС

For a large number of frames with different number of storey and (non)regularity was found significantly less post-elastic stiffness ($K_N \approx 0$), compared to initial elastic stiffness [15]. The study of MDOF model with SSI interaction and without introducing HEIS, found that situation for all computational levels of target displacements are on pushover curve. Therefore, there is no reduction in the capacity due to a change of soil type and damping β_0, compared to value of pushover curves without SSI interaction. Here problem appears that real level of total shear force at the base of MDOF system with HEIS model of soil for the analysis of SSI interaction, is less than of MDOF model without HEIS (Figure 7.).

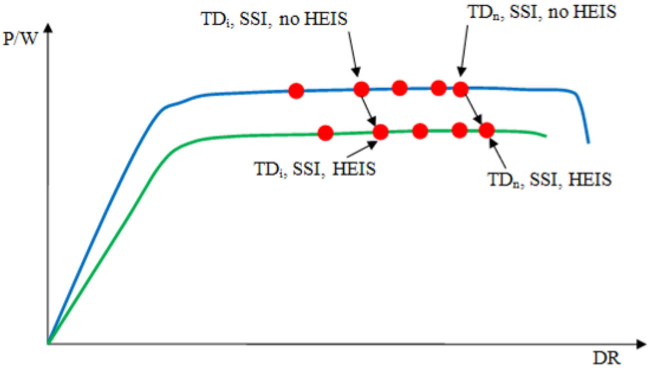

Figure 7 Target displacements for model without HEIS and with HEIS
Слика 7 Целните преместувања за модел без ХЕИС и со ХЕИС

5. CONCLUSIONS

The research found that the introduction of SSI interactions can significantly affect the increase in global drift, and partial correction of the total force at the base of the system. Sensitivity changes of the total force at the base is much smaller than the change of displacements, because the non-linear domain of the system has significantly less stiffness, even in certain situations, stiffness is equal zero, so that the small increase of seismic load can produce much larger deformations.

Numerical analysis of the MDOF multi-storey system with HEIS model of soil, compared to the model without soil, determined the difference in initial stiffness and total value of shear force at base. This difference indicates the difference in a level of target displacement of these two different approaches for modeling. As it is not always possible to conduct analysis and modeling using the HEIS model of soil, it is recommended that in order to simplify the participation of soil components introduce elastic supports. For these elastic supports is necessary to define the components of stiffness values and also if it is possible to introduce a limit state of load. So, the response of MDOF system will be much better described in linear and nonlinear domains for SSI interaction.

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