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COMPARATIV NONLINEAR ANALYSIS SOIL-PILE INTERACTION 2D FRAME

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ABSTRACT
A comparative non-linear static and dynamic analysis of NSA and NDA 2D frames of buildings funded on piles is presented in this paper. The model involved a linear-non-linear pile-soil interaction, using link elements. The soil was modeled using multiple (linear) plastic connecting elements, as well as with p-y curves, on both sides of the pile. P-y curves only transfer (receive) compression, and were modeled according to Cox, Reese and Matlock for submerged sand, and piles with a diameter 60 cm.

KEYWORDS: Dynamic soil-pile interaction (DSPSI), non-linear dynamic analysis (NDA), pushover non-linear static analysis (NSA), multiline plastic link elements, p-y curves.

KOMPARATIVNA NELINEARNA ANALIZA INTERAKCIJE ŠIP-TLO 2D RAMA

REZIME
U radu je sprovedena komparativna nelinearna statička i dinamička analiza NSA i NDA 2D rama zgrade fundiranog na šipovima. U modelu je uljučena i linearno-nelinearna interakcija šip-tlo korišćenjem link elemenata. Tlo je modelovano sa više(linijskim) plastičnim veznim elementima, kao p-y krivama, sa obe strane šipa. P-y krive prenose (primaju) samo pritisak, a modelovane su prema Koksu, Risu i Matloku za potopljen pesak, i šipove prečnika 60cm.

KLJUČNE REČI: Dinamička interakcija tlo-šip DSPSI, nelinearna dinamička analiza NDA, pušover nelinearna statička analiza NSA, višelinijski plastični link element, p-y krive.

INTRODUCTION

A comparative non-linear static and dynamic analysis of NSA and NDA 2D frames of buildings funded on piles is presented in this paper. The model involved a linear-non-linear pile-soil interaction, using link elements. The soil was modeled using multiple (linear) plastic connecting elements, as well as with p-y curves, on both sides of the pile. P-y curves only transfer (receive) compression, and were modeled according to Cox, Reese and Matlock for submerged sand, and piles with a diameter 60 cm

2D FRAME MODEL WITH PILES

Outer piles of a facade frame were funded using a group of 3 piles, whereas the inner ones were funded on a group of four piles. Façade frame was "condensed" by inserting all pile elements via projection along the direction perpendicular to the frame middle plane. In this way, it is possible to draw the frame model using two dimensions. The group of 3 circular piles consists of a part made of one pile, and another part made of two condensed piles. Hence, in this "condensed" model, only two out of three piles are introduced, one of which is an individual pile, whereas the other is a double pile, figure 1 (i.e. a single pile was introduced to the model, whose Frame element cross-section, stiffness and mass were multiplied by 2, in SAP 2000 software, within the Set Modifiers module. This part is obtained through the following menu and path: Define/Section Properties/Frame Section/Frame Property/Property Modifiers/Set Modifiers). In accordance with this, the p-y curves of the "double" pile also have the double value of stiffness.

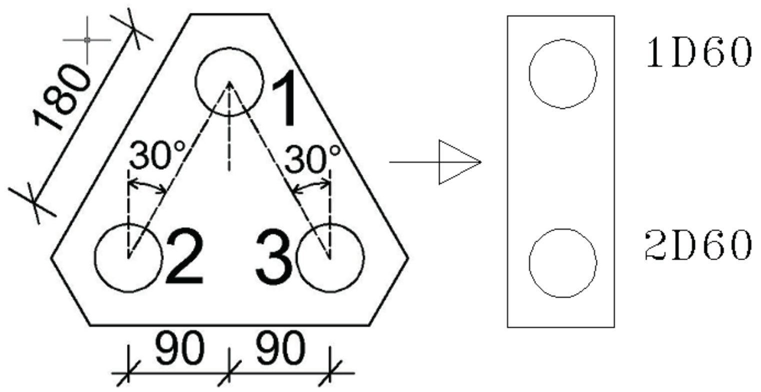

Figure 1 „Condensation" principle of a group of 3 piles (1D60 – individual pile, 2D60 – double pile).
Slika 1 Princip „kondenzacije" grupe od 3 šipa u ravansku grupu od 2 šipa. 1D60 - samosatalni šip, 2D60 - dvostruki šip

The 3D frame was dimensioned in terms of earthquake conditions using SAP 2000 v14 software, including the effects of the perpendicular direction and torsion (with 5% eccentricity), for a behavior factor of 5.85. A façade 2D frame with its corresponding loads was then taken out of a model dimensioned in this way. The span between the frames was

8m, which was also the distance between the pile axes, in both directions, since the structure in question was symmetrical along two axes. The height of the first storey was 5m whereas in the case of the remaining 6 storeys, it was 3.1 m. The model is similar to the models shown in (Folic, 2017). The difference is that the p-y curves mentioned in (Folic, 2017) are given for piles with a diameter of 1.2 m. In addition, the aforementioned paper contained several different models, with and without the pile-soil interaction. The geometry of a single frame model adopted in this paper, can be seen later, in the plastic hinges state analysis section.

PUSHOVER NON-LINEAR STATIC ANALYSIS

The pushover (PO) analysis involves the determining of curves which show the dependence of control node displacement u_{max} (typically at the top of the frame) from the Base Shear (BS) force, for an adopted shape of load distribution along the height. It is assumed that the adopted form of load remains unchanged for all intensity levels, along with the structure's deformed shape. Gradual increase of the load intensity is performed in steps, along with the opening of plastic hinges up to a point where the structure becomes a mechanism. When constructing pushover curves, the use of several different shapes of load distributions are recommended, along with the ones prescribed by the regulations given in EC8. In this paper, the following shapes of load distributions along the frame height were applied:

- Constant distribution (const).
- Linear variable (lin).
- Proportional to the shape of the first eigen-tone (1 mode) and
- Proportional to the distribution of (corresponding) masses (acc).

In addition, different types of PO curve displays can be applied, and in the case of SAP 2000, the following ones are available:

1. Resulting base shear force according to the observed displacement (MD),
2. ATC 40 spectrum capacity method,
3. FEMA 356 coefficients method,
4. FEMA 440 equivalent linearization method and
5. FEMA 440 displacement modification method.

In the following sections of the paper, the PO curves were determined using SAP 2000 v14 software (using the above mentioned point 1, "manually"), but not with the Display/Show Static Pushover Curve option, since in this case the diagram is not visible enough, reading of values from it is insufficiently accurate and appropriate manipulations cannot be performed. Thus, the above process was performed using the path Display/Show Plot Function, i.e. by using the function diagram U_{max}/BS. In addition, the PO curve was also determined according to the FEMA 356 procedure (point 3). PO curves according to the function diagram (point 1) are given in figures below (2-6).

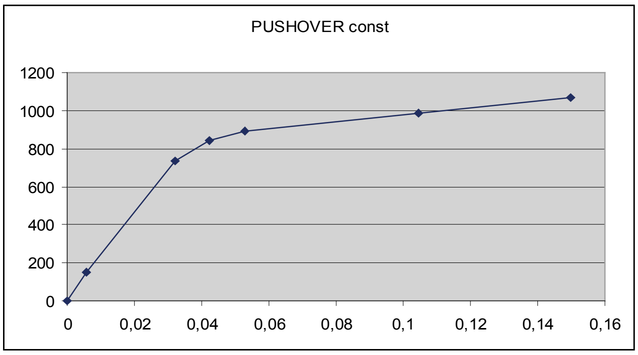

Figure 2 PushOver curve. Constant load shape with high BS=1069 kN, u_{max}=14,97 cm.
Slika 2 Pušover kriva. Konstantna raspodela opterećenja po visini. Sila u osnovi BS=1069 kN, maksimalno pomeranje u_{max}=14,97 cm.

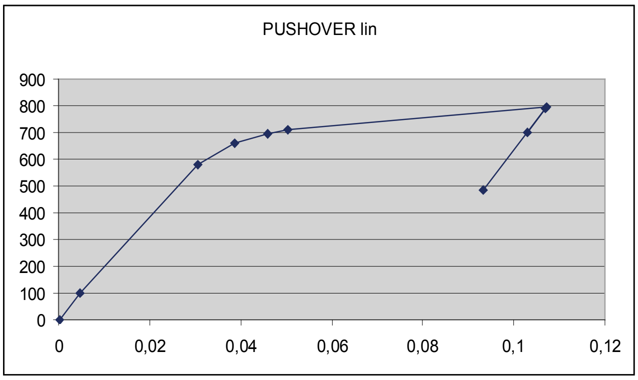

Figure 3 PushOver curve. Linear distributed load shape with high BS=793,1 kN, u_{max}=10,73 cm
Slika 3 Pušover kriva. Linearna raspodela opterećenja po visini BS=793,1 kN, u_{max}=10,73 cm

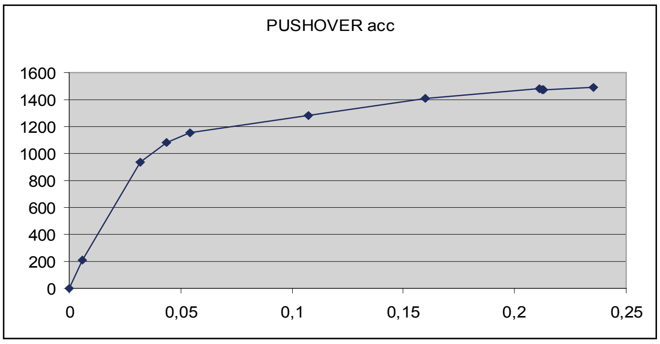

Figure 4 Push Over curve. Load shape distributed Acc proportional mass with high BS=1493 kN, u_{max}=23,54 cm.
Slika 4 Pušover kriva. Raspodela opterećenja proporc. masama BS=1493, kN, u_{max}=23,54 cm

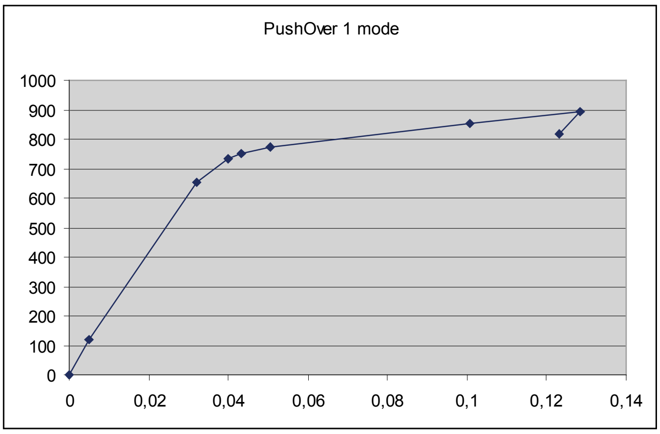

Figure 5 PushOver curve. Load shape distributed proportional 1 mode BS=893,9 kN, u_{max}=12,83 cm.
Slika 5 Pušover kriva. Raspodela opterećenja 1 mode BS=893,9 kN, u_{max}=12,83 cm.

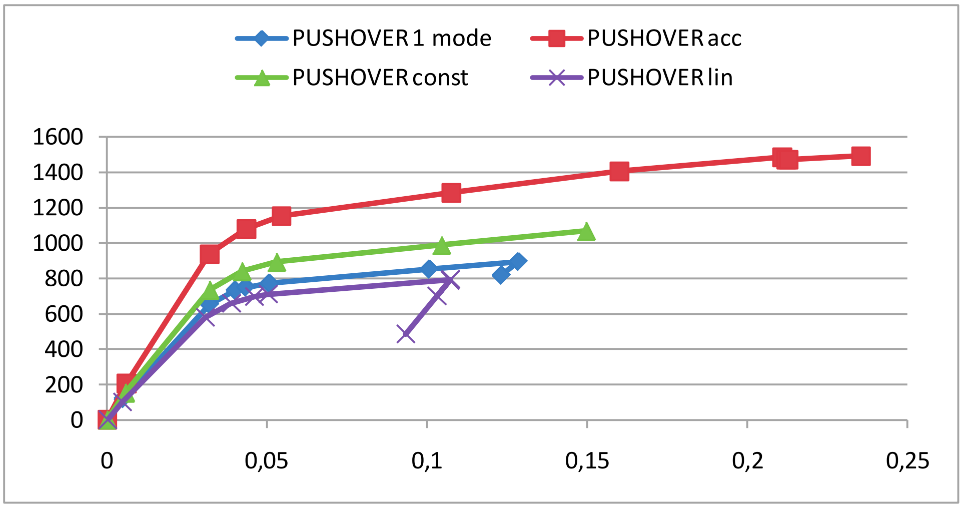

Figure 6 Sum diagram Push Over curves, for 4 shapes load distributed: lin, 1 mode, const i acc.
Slika 6 Zbirni dijagram Pušover krivih za 4 oblika raspodele opterećenja: lin, 1 mode, const i acc.

In the sum diagram, for PO curves compared in this way, there is a noticeable difference of maximum control node displacement, depending on the load shape, along with a difference in initial stiffness. A more detailed analysis data are given in table 1.

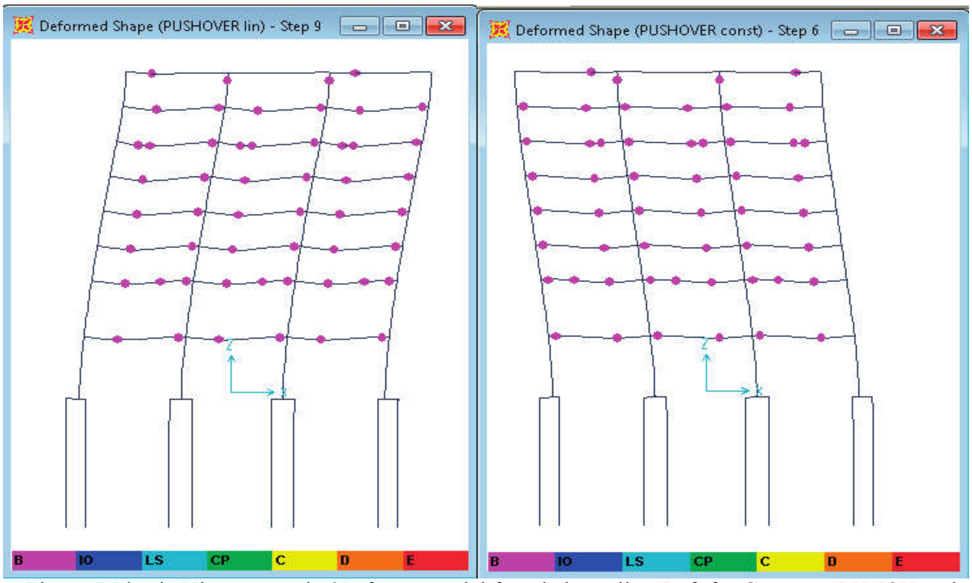

Figure 7 Plastic Hinges state in 2D frame model founded on piles. Left for Constant, PH 53Y and right Linear distributed load on high PH 52Y. All Plastic hinge states: Yield.
Slika 7 Stanje plastičnih zglobova, u modelu 2D rama sa šipovima, levo za Constant, PH 53Y I desno za Linearnu raspodelu opterećenja PH 52Y. Svi plastični zglobovi su stanja: Yield.

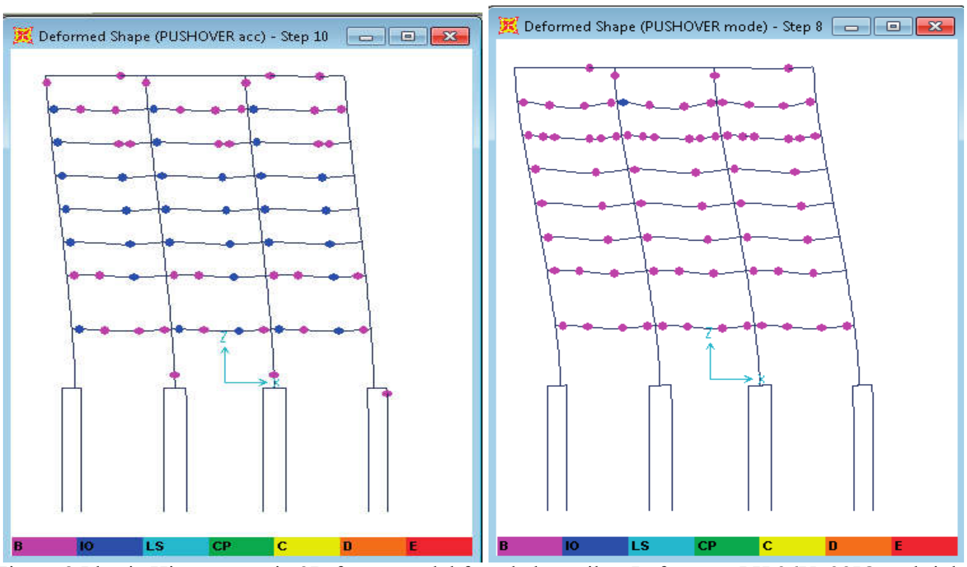

Figure 8 Plastic Hinges state in 2D frame model founded on piles. Left const. PH 36Y, 32IO and right Linear distributed load shape PH 72Y, 1IO. 1PlH state 1Y in pile.
Slika 8 Stanje plastičnih zglobova, u modelu 2D rama sa šipovima, levo za Konstantnu PH 36Y, 32IO i desno Linearnu raspodela opterećenja po visini PH 72Y, 1IO. 1PlH stanje 1Y u šipu.

NONLINEAR DYNAMIC ANALYSIS

Non-linear dynamic analysis was performed for the ElCentro accelerogram, for peak PGA values 0.20, 0.25 and 0.30 g. Node displacement at the top and the base shear were considered. The states of plastic hinges (fracture) were checked at the end of each earthquake.

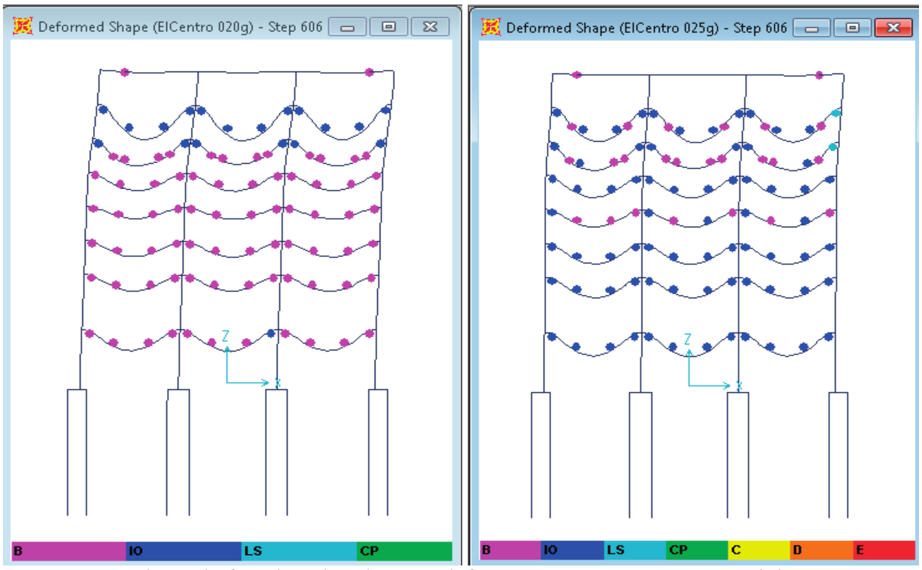

Figure 9 State at the end of earthquake ElCentro, left PGA 0,20g PH 79Y, 19IO, right PGA 0,25g PH 71Y, 25IO and 2LS.

Slika 9 Stanje na kraju zemljotresa ElCentro, levo PGA 0,20g PH 79Y, 19IO, desno PGA 0,25g PH 71Y, 25IO i 2LS.

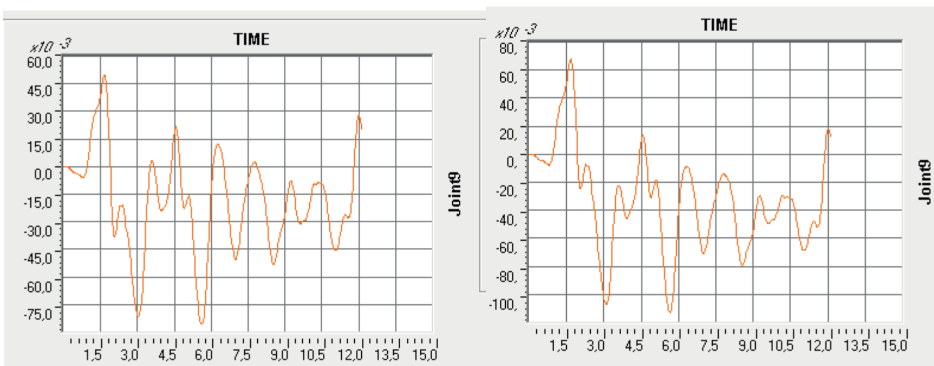

Figure 10 Displacement diagram node at the top of the building, due to earthquake acc. ElCentro: left PGA 0,20g, U_{max}=8,56cm, right PGA 0,25g, U_{max}=11,29 cm

Slika 10 Dijagram pomeranja čvora u vrhu zgrade tokom alcelerograma ElCentro levo PGA 0,20g, U_{max}=8,56cm, desno PGA 0,25g, U_{max}=11,29 cm

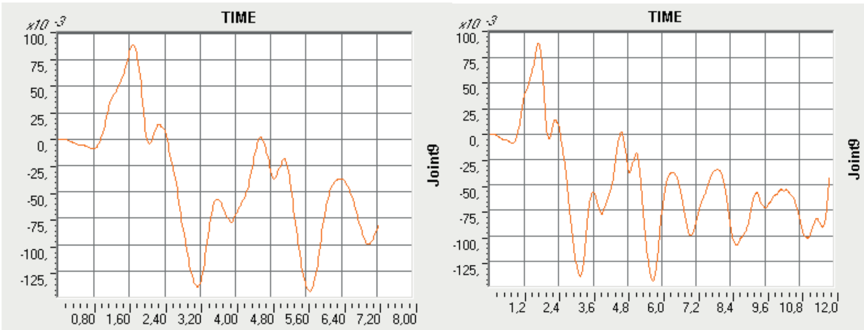

Figure 11 Top node displacement of building due to earthquake El Centro PGA 0,30g, U_{max}=14,47 cm left break on t=7,2sec, right on 11,86 sec.

Slika 11 Pomeranja čvora u vrhu zgrade tokom alcelerograma El Centro PGA 0,30g, U_{max}=14,47 cm levo prekid na t=7,2sec, desno na 11,86 sec.

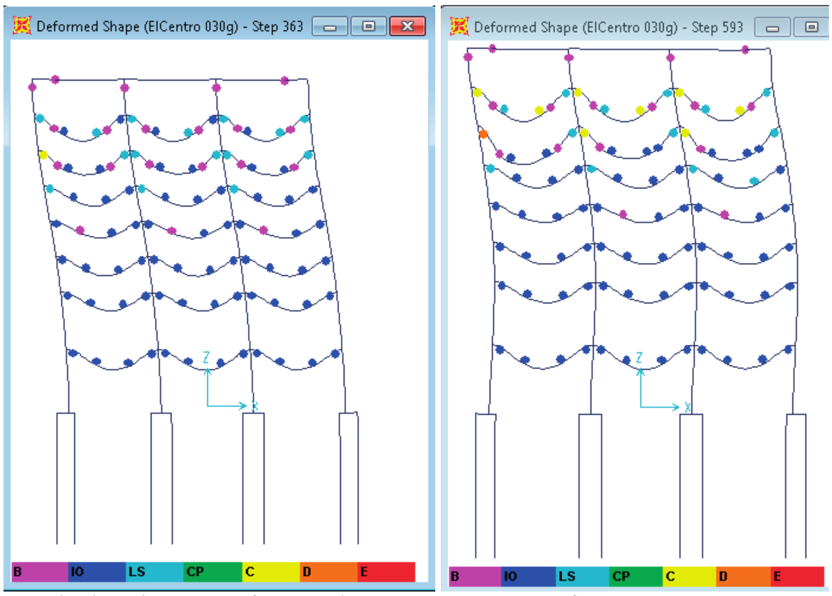

Figure 12 Plastics Hinge state after acc El Centro PGA 0,30g; Left at 7,2sec PH 20Y, 65IO, 15LS, 1C. Right at 11,86 sec PH 17Y, 62IO, 13LS, 8C and 1D.

Slika 12 Stanja plastičnih zglobova nakon dejstva akcelerograma El Centro PGA 0,30g; Levo u trenutku 7,2 sec PH 20Y, 65IO, 15LS, 1C. Desno u t=11,86sec PH 17Y, 62IO, 13LS, 8C and 1D.

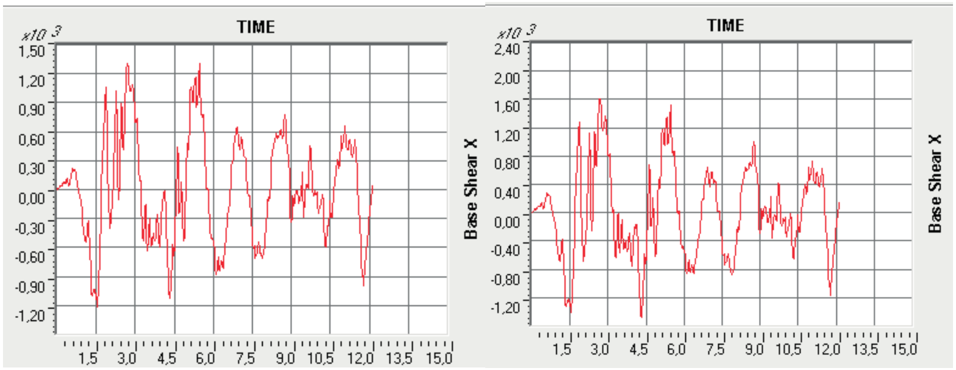

Figure 13 Base Shear ElCentro: left PGA 0,20g, BS_{max}=1312, kN, right PGA 0,25g BS_{max}=1615, kN, Base Shear

Slika 13 Sila u osnovi za ElCentro: levo PGA 0,20g, BS_{max}=1312, kN, desno PGA 0,25g BS_{max}=1615, kN, Sila u osnovi

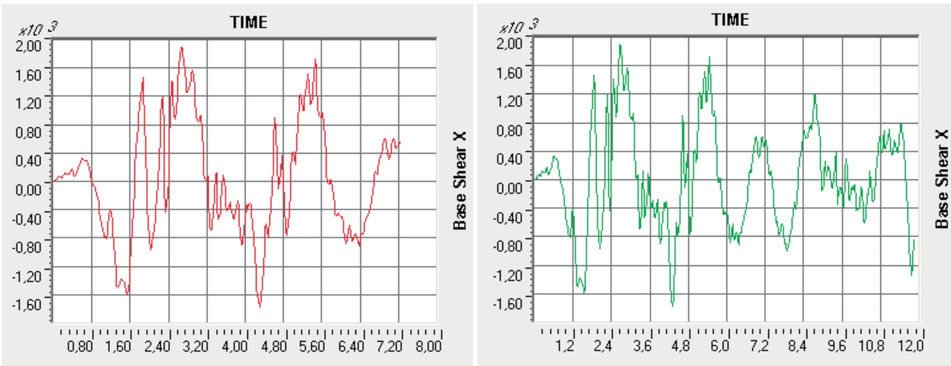

Figure 14 Base Shear for ElCentro PGA 0,30g, BS_{max}=1899 kN

Slika 14 Sila u osnovi ElCentro PGA 0,30g, BS_{max}=1899 kN

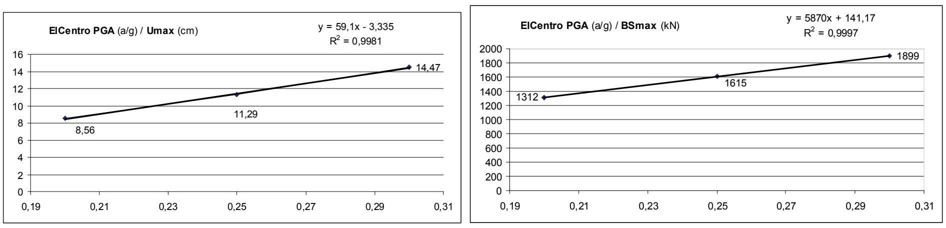

Figure 15 Linear regression Left PGA (a_{max}/g) vs U_{max} (cm) displacement, Right PGA (a_{max}/g) vs BSmax (kN) Base shear. Strong linear dependent R^2: left 0,9981 and right 0,9997.

Slika 15 Linearna regresija Levo PGA (a_{max}/g) vs U_{max} (cm) pomeranje, Right PGA (a_{max}/g) vs BSmax (kN) Sila u osnovi. Jaka linearna zavisnost R^2: levo 0,9981 i desno 0,9997.

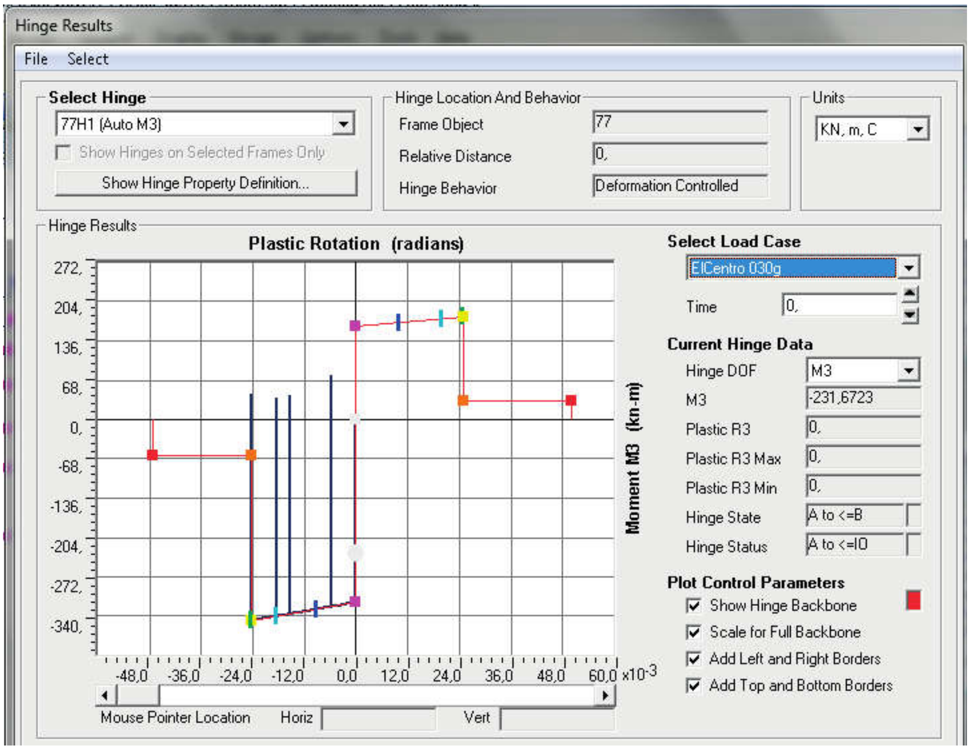

Figure 16 Results for state plastic hinge 77H1 for TH El Centro PGA 0.30g. Node in tip 6 floor, left end by the column on previous figure, where collaps state was reached.
Slika 16 Rezultat stanja plastičnog zgloba 77H1 za TH El Centro PGA 0.30g. Čvor u podu šestog sprata, na prethodnim slikama krajnji levo uz stub, dostiže stanje kolapsa.

RESULTS OF NSA AND NDA ANALYSES

Table 1. Comparative analysis of max top node displacements and Base Shear. In TH according with PGA.
Tabela 1. Komparativna analiza maksimalnih pomeranja čvora u vrhu i sila u osnovi u zavisnosti od oblika opterećenja. Kod vremenske analize u zavisnosti od PGA

	PGA g	El	Centro		Raspodela	opterećenja	
	0,20g	0,25g	0,30g*	PO lin	PO const	PO acc	PO 1 mode
BS (kN)	1312	1615	1899	793,10	1068,65	1492,66	893,87
Umax (cm)	8,56	11,29	14,47	10,73	14,97	23,54	12,83
FEMA 356 C							
BS (kN)				798,67	1076,10	1504,40	900,60
Umax (cm)				27,3	26,9	24,3	28,4

* cut off at 7,2 sec; FEMA 356 C - Site class C; Pushover= PO; F35B060G10K33900 sand

As can be seen in comparative analysis in table 1, there is a slight difference in maximmum displacements in pushover curves for the FEMA356 method, depending on the load shape. In addition, maximum base shear forces were deterined according to FEMA356 and the function diagrams („manually“) have shown insignificant difference, whereas this was not the case with displacements. In the case that curves are determined according to function diagrams (Display/Show plot function in SAP2000), noticeable deviations may be obtained for maximum displacements.

PO analysis is also used with method N2, for the purpose of determining of the equivalent system with one degree of freedom (SDOF), as well as for transition from MDOF (multiple degrees of freedom) to SDOF. This transition is performed by using the assumed shape of displacement (and load) vector Φ and its corresponding products obtained by multiplying with the mass matrix m. The same transformation factor Γ is used for base shear and displacements (Čaušević, 2010).

$$\Gamma = \frac{\Phi^T m 1}{\Phi^T m \Phi} = \frac{\sum m_i \Phi_i}{\sum m_i \Phi_i{}^2} = \frac{m*}{\sum m_i \Phi_i{}^2}$$

CONCLUSION

When it comes to determining of seismic performances of a structure using the pushover analysis, it is important to determine the point at which the structure becomes a mechanism. The analysis of the change in number and states of plastic hinges with the increase in displacements (in steps) of PO curves using SAP software cannot "easily" determined (point 1 mentioned in this paper). Better displays of PO curves can be obtained by using ETABS software, although this can be achieved in SAP2000 as well (especially in the case of engineering structures) if alternative procedures are taken into account. PO analysis is applied within the N2 method in order to determine the target structure displacement, as an intersection point of the seismic requirements (through spectrum response) and the seismic capacity of structures. The relatively simplified procedure for determining of the effects of non-linear static NSA and dynamic NDA soil-pile-structure interaction was presented in this paper. In order to obtain a more comprehensive insight about the structure's performance, it is necessary to apply several different models, load shapes, types and scales of accelerograms, procedures and software packages, with and without interactions.

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