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Izvorni naučni članak

ANALYSIS OF INTERACTION OF 2D RC FRAME MODEL USING P-Y CURVES UPON PILES

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ABSTRACT

The paper presents a seismic analysis of a 2D reinforced concrete (RC) frame founded on piles. The soil-pile interaction is represented by the so-called *p-y* curves. At the base, the piles may be both fixed or elastically supported. *P-y* curves are determined according to Rees, Cox and Matlock model for sand. Using SAP 2000, *p-y* curves are applied on both sides of the pile, as the link elements. Link elements are assumed as a multi-linear plastic type, i.e. as hysteresis envelopes according to the Takeda model. The linear part of the link element corresponds to initial stiffness of the *p-y* curve. Curves are exposed to compression only and to almost negligible tension. In the analysis of seismic action, the curve coefficients for a repeated, i.e. cyclic load were assumed. In such a way, numerical model asymptotically simulates the real actions and seismic response of structures in dynamic interaction of the pile-structure-soil system. This model offers many options for further development and study of seismic performance.

KEY WORDS: dynamic interaction, soil-pile-structure, *p-y* curves, link elements, 2D frame

ANALIZA INTERAKCIJE 2D MODELA AB OKVIRA PRIMENOM P-Y KRIVIH NA ŠIPOVIMA

REZIME

U radu je prikazana seizmička analiza 2D rama fundiranog na šipovima. Interakcija šip-tlo se obuhvata *p-y* krivama. Šipovi u bazi mogu biti uklješteni ili elastično oslonjeni. *P-y* krive su određene prema Rees, Cox i Matlock modelu za pesak. Primenom SAP 2000, *p-y* krive su nanete na šip obostrano, kao link elementi. Link elementi su usvojeni kao više-linearni plastični tip, odnosno kao histerezisne anvelope prema Takeda modelu. Linearni deo link elementa odgovara inicijalnoj krutosti *p-y* krive. Krive su izložene samo pritisku i skoro zanemarljivom zatezanju. U analizi seizmičkog dejstva izabrani su koeficijenti krive za ponovljeno, ciklično, opterećenje. Time se modelom asimptotski simuliraju realna dejstva i seizmički odgovori konstrukcije u dinamičkoj interakciji sistema šip-konstrukcija-tlo. Ovaj model pruža niz mogućnosti za dalji razvoj i proučavanje seizmičkih performansi.

KLJUČNE REČI: dinamička interakcija, konstrukcija-šip-tlo, *p-y* krive, link elementi, 2D ram

INTRODUCTION

Many researchers dealt with the soil-structure interaction, directly or indirectly, in recent period (Meymand, 1998), (JSCE, 1997), (Pando, 2013), (Milović and Đogo, 2009), (B. Folić, 2017) etc. A broad review of most significant research was presented in the paper (B. and R. Folić, 2018), with detailed analyses. In this paper the model of a reinforced concrete (RC) 2D frame with RC piles is presented (figure 1 left). Also, the method of calculation and implementation of *p-y* curves for dynamic (time history) analysis and the soil-structure-pile interaction (DSPSI) is presented too. The global displacements of a 2D frame and storey drifts under various seismic actions are analyzed. Also, the effects in link elements, caused by the seismic action (El Centro), are studied for various peak accelerations. The diagrams of displacements and forces of coupled link elements at certain depths are analyzed.

APPLIED METHODOLOGY (ABOUT THE MODEL AND P-Y CURVES)

Non-linear static analysis and time history analysis (differential equations of motion) are used in the analysis of 2D numerical model, which was extracted from the regular symmetrical 3D model of a building. The facade frame with four columns and the interior frame are analyzed. On the facade frame, Figure 1, there are corner columns and edge columns. The edge columns of the facade frame are founded on a group of 3 piles, and the interior ones on the groups of 4 piles each. The facade frame is "condensed" by inserting all pile elements using a projection normally to the middle plane of the frame (Folić B. and Folić R. 2018). Span (axial spacing) of each segment is 8 meters.

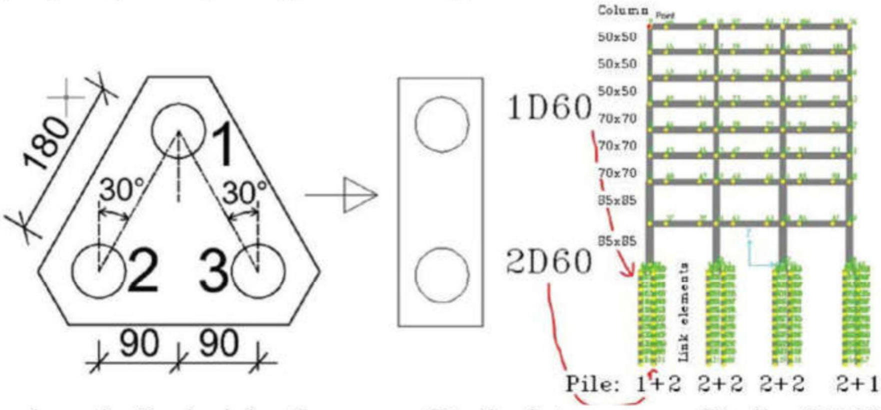

Figure 1. „Condensation" principle of a group of 3 piles into a group of 2 piles (1D60 – individual pile, 2D60 – double pile).

Slika 1. Princip „kondenzacije" grupe od 3 šipa u grupu od 2 šipa (1D60 samostalni šip, 2D60 dvostruki)

The diagrams of change of initial modules of lateral soil reaction k_0, in the function of the ground water table, which are used in determination of *p-y* curves, are presented in the Fig. 2. Using a backward control determined errors of approximate formulae and they are provided in table 1. The curves of dependence of k_0 on the angle of interior friction are provided in Figure 2 right, and the scale is linear. Even though the scale for φ on the axis in Fig. 2 resembles a logarithmic scale, it is difficult to determine the accurate dependence because of the deformation of the available images. The deformations in the upper section of Fig. 2 are so extensive that they would make this part of the analysis pointless. For determination of more accurate formulae, it is necessary to have a more precise diagram and a larger number of points for curve fitting.

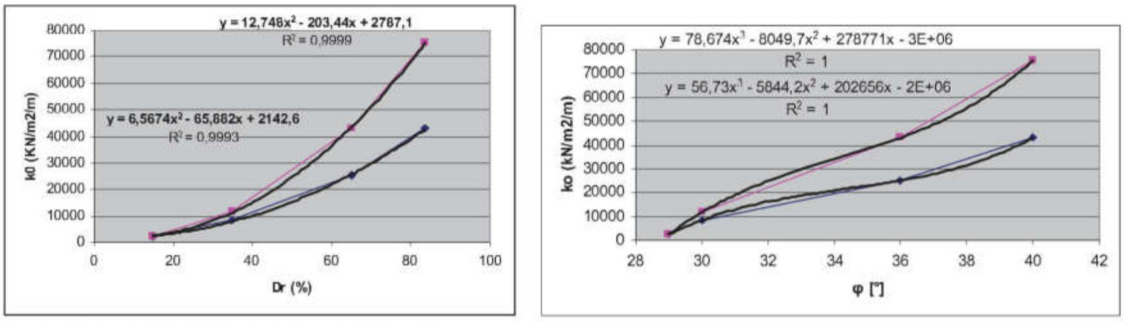

Figure 2. Left: Initial module of the lateral soil reaction as the function of the ground water table; Right: dependence upon the angle of internal friction, with formulae for approximate calculation.
Slika 2. Levo: Početni modul horizontalne reakcije tla k_0 u zavisnosti od nivoa podzemne vode; Desno: zavisnost od ugla unutrašnjeg trenja, sa formulama za približan proračun.

Table 1. Coefficient of lateral reaction for sand. Initial slope of *p-y* curve as a function of relative density and the level of underground water
Tabela 1. Koeficijent horizontalne reakcije tla za pesak. Početni nagib *p-y* krive u funkciji relativne zbijenosti i nivoa podzemne vode

Dr (%)	Dry ko (kN/m2)	Submerged ko (kN/m2)			Δ[%]	Δ[%]
20	3817,5	3451,9				
25	5668,6	4600,2				
27,5	**6833,2**	**5297,4**	6790	5430	0,64	-2,44
30	8157,1	6076,8				
35	11283,0	7881,8				
40	15046,3	10015,2				
45	19447,0	12476,9				
50	**24485,1**	**15267,0**	24430	16307	0,23	-6,38
55	30160,6	18385,5				
60	36473,5	21832,3				
65	43423,8	25607,5				
70	51011,5	29711,1				
75	**59236,6**	**34143,1**	61000	33900	-2,89	0,72
80	68099,1	38903,4				

NON-LINEAR STATIC ANALYSIS - PUSHOVER (NSA)

In the case of the pushover analysis, cyclic *p-y* curves are also used, because during the pushover analysis the loading is quasi-static rather than static. This quasi-static load attempts to produce the effect upon the structure which should be as similar as possible to the effects caused by an earthquake. Therefore, a larger number of lateral load distributions along the building height are used. Figure 3 presents four pushover curves due to four different forms of lateral load distribution along the height.

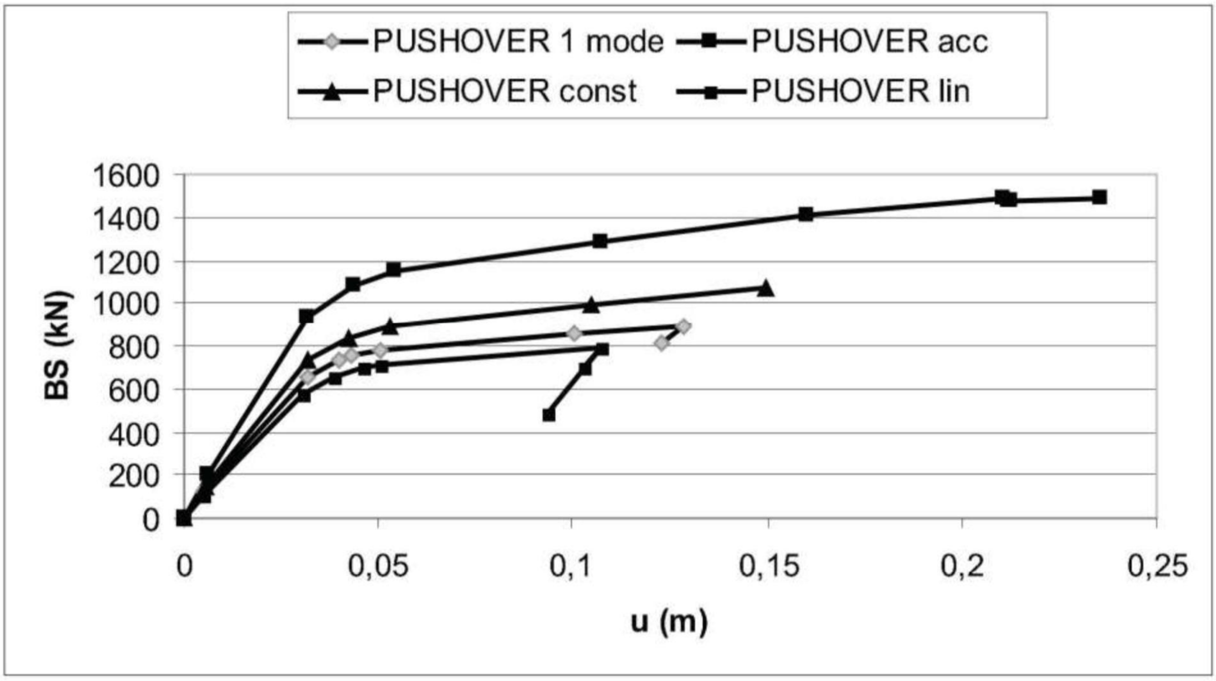

Figure 3. Collective diagram of pushover curves due to four shapes of load distribution: linear, the first natural mode, constant (const) and proportional to masses (acc).
Slika 3. Zbirni dijagram pušover krivih za četiri oblika raspodele opterećenja: linearno, prvi svojstveni oblik, konstantno (const) i proporcionalno masama (acc)

In Figure 3, one can observe considerable differences of base force and displacements, depending on applied distribution of load. The lowest base forces and displacements are observed for the linear distribution (lin), and the highest due to load distribution which is proportional to masses (acc). BS_{lin}=793.10 kN, u_{max}=10.73 cm; BS_{acc}=1492.66 kN, u_{max}=23.54 cm. The closest to the mean value are: 1 mode and constant by height - BS_{const}=1068.65 kN, BS_{1mode}=893.87 kN. (arithmetic, eg. ((Σx_i, i=1,…n)/n) BS_{mv}=1062,07 kN; u_{mv} =15,52 cm).

NONLINEAR DYNAMIC ANALYSIS (NDA)

Nonlinear dynamic (time history) analysis is performed using the El Centro accelerogram with peak values of PGA: 0.20, 0.25 and 0.30 g (with $g=9.81 m/s^2$). The displacement of the joint at the top is considered (Fig. 4) and the corresponding total seismic base force. Plastic hinge state (PHS) is checked at the end of each earthquake (Fig. 5).

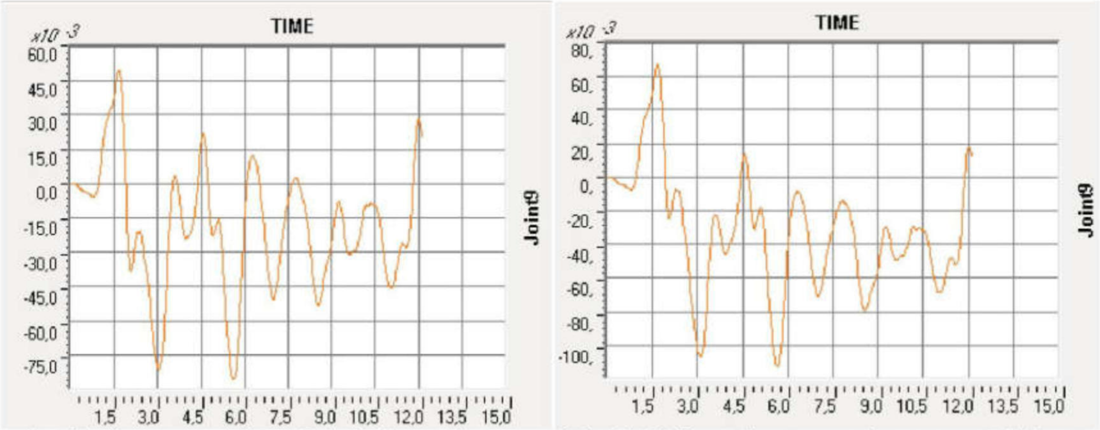

Figure 4. Displacement plot of the joint at the top of the building, due to accelerogram El Centro: left PGA 0.20g, *Umax* =8.56cm, right PGA 0.25g, *Umax* =11.29 cm Linear roof beam.
Slika 4. Dijagram pomeranja čvora u vrhu zgrade tokom akcelerograma El Centro levo PGA 0,20g, *Umax*=8,56cm, desno PGA 0,25g, *Umax* =11,29 cm. Linearna krovna greda.

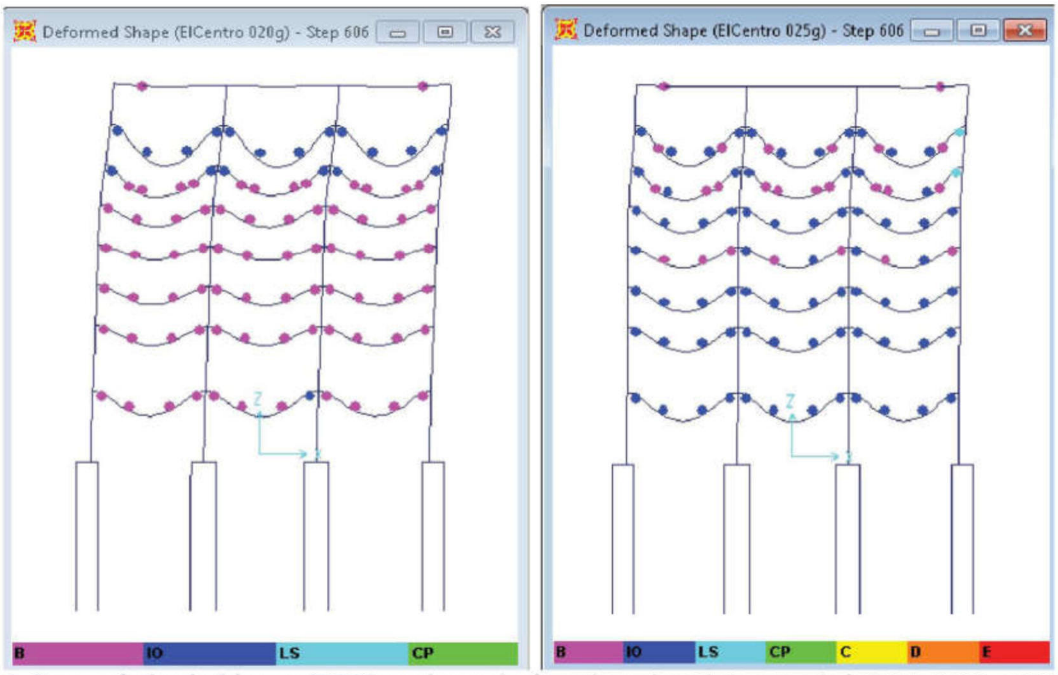

Figure 5. State of plastic hinges (PHS) at the end of earthquake El Centro, left PGA 0.20g PHS: 79Y, 19 IO; right PGA 0.25g PHS: 71Y, 25 IO and 2 LS. Linear roof beam
Slika 5. Stanje plastičnih zglobova (PHS) na kraju zemljotresa El Centro, levo PGA 0,20g PHS: 79Y, 19 IO; desno PGA 0,25g PHS: 71Y, 25 IO i 2 LS. Linearna krovna greda

DRIFTS OF COLUMNS FOR DIFFERENT PGA VALUES OF TIME HISTORY ANALYSES

For calculation of drifts of individual columns, a non-linear roof beam was assumed. With a non-linear (NL) roof beam, extreme values of column drifts during the action of El Centro accelerogram for PGA 0.20, 0.25 and 0.30 g are calculated. The results for PGA 0.20 are presented in Figure 6a, for the value 0.25 in Figure 6b, and for PGA 0.30 in Figure 6c.

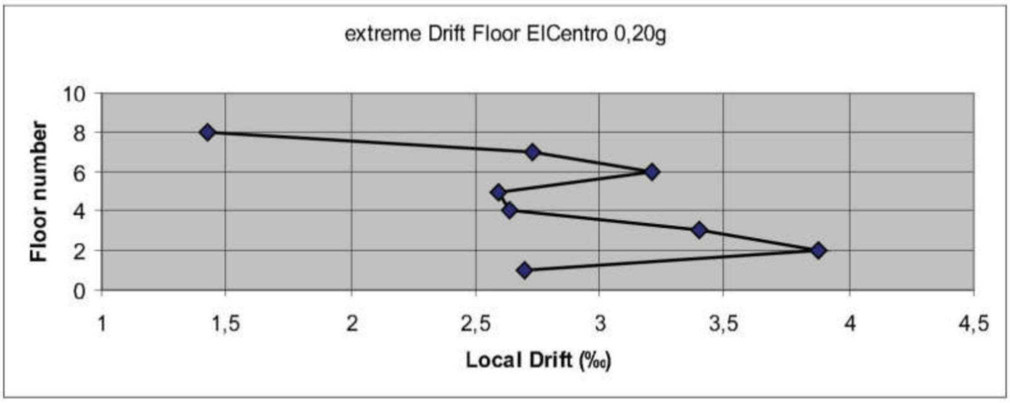

Figure 6a. Extreme floor drifts due to El Centro 0.20g. Allowed values exceeded
Slika 6a. Ekstremni spratni drift za El Centro 0,20g. Prekoračene dozvoljene vrednosti

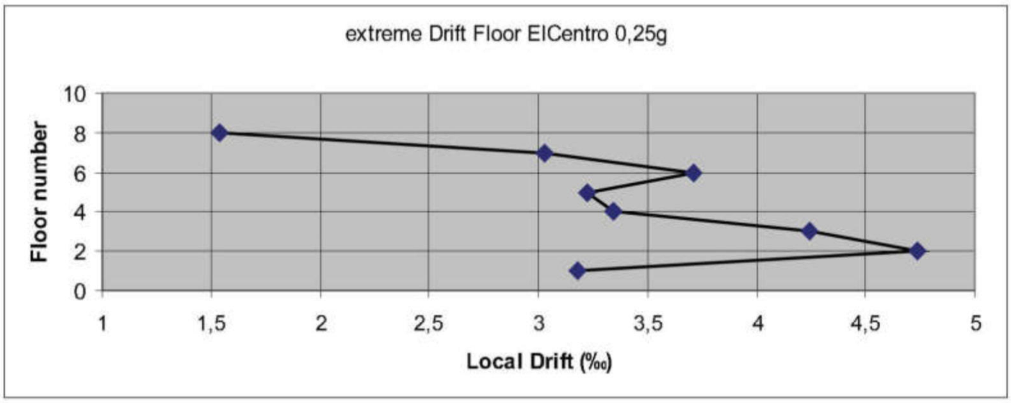

Figure 6b. Extreme floor drifts due to El Centro 0.25g. Allowed values exceeded
Slika 6b. Ekstremni spratni drift za El Centro 0,25g. Prekoračene dozvoljene vrednosti

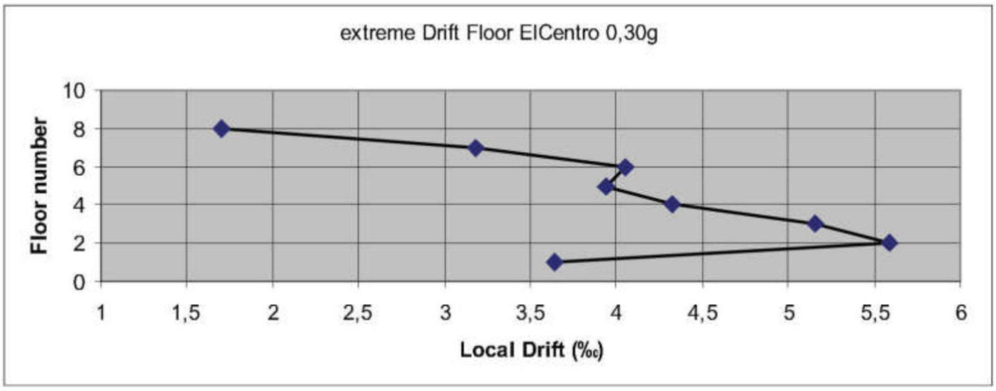

Figure 6c. Extreme floor drifts due to El Centro 0.30g. Allowed values exceeded
Slika 6c Ekstremni spratni drift za El Centro 0,30g. Prekoračene dozvoljene vrednosti

Comparing the values presented in Fig. 6c with those presented in Figs. 6a and 6b, some difference in shape of diagrams is observed.

EFFECTS IN LINK ELEMENTS DURING NDA (TH) DUE TO ACTION OF EL CENTRO

Analysis of link elements is done for the left edge pile, marked with arrow in Figure 1. As a result of this analysis, Fig. 7 presents diagrams of displacements and forces of coupled pairs of link elements No. 1 and 2 (at depth of 1 m), for PGA 0.20g. These coupled link elements are joined at the same node of the pile. In addition to non-linear analysis, the absolute work of coupled link elements was also considered. The absolute work is a positive value of the action of a force along the path (by multiplying the corresponding values from diagrams in Fig. 7a with those in 7b). In Fig.7b it may be observed that the soil link elements react only in compression, so the sign of the force is always negative.

A diagram of the cumulative absolute work of coupled link elements is presented in Fig. 8. The absolute work is necessary so that the positive and negative work would not be annulled during summing up. The negative work is a consequence of multiplying the force in a link element with a negative sign with the positive sign of its displacement. In Fig. 8, steeper sections of the cumulative curve are notable, representing the places where the intensity of accelerogram is "piling up", which affects the work of the link elements. It is actually a dissipation of seismic energy in the soil, at about 1 m bellow the ground surface.

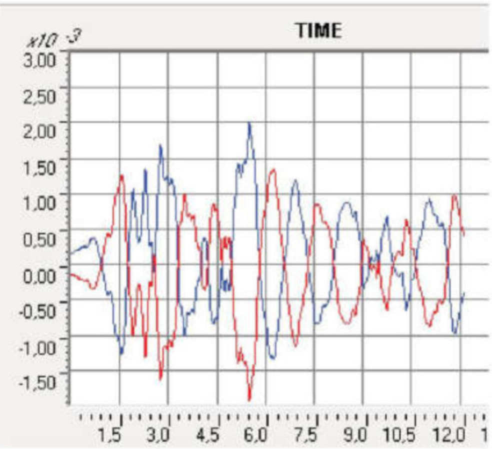

Figure 7a. Link1 and 2, level -1.0 m. PGA 0.20g. El Centro, NDA. Displacement: max 0.201cm. min 0.194 cm.

Slika 7a. Link 1 i 2, nivo -1,0 m. PGA 0,20g El Centro NDA. Pomeranje: max 0,201cm. min 0,194 cm

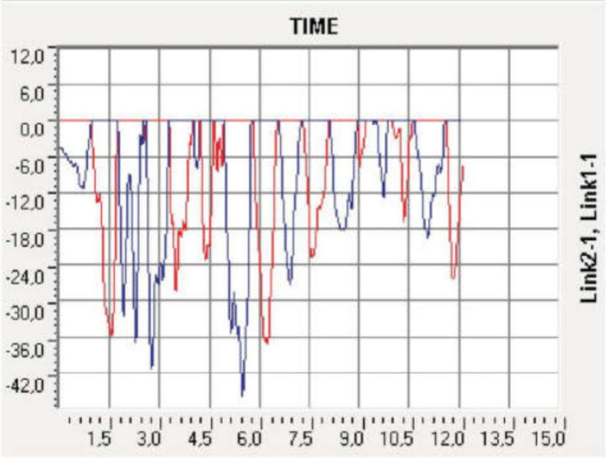

Figure 7b. Link 1 and 2, level -1.0 m. PGA 0.20g El Centro, NDA. Force: max 45.88 kN

Slika 7b. Link 1 i 2, nivo -1,0 m. PGA 0,20g El Centro NDA. Sila. max 45,88 kN

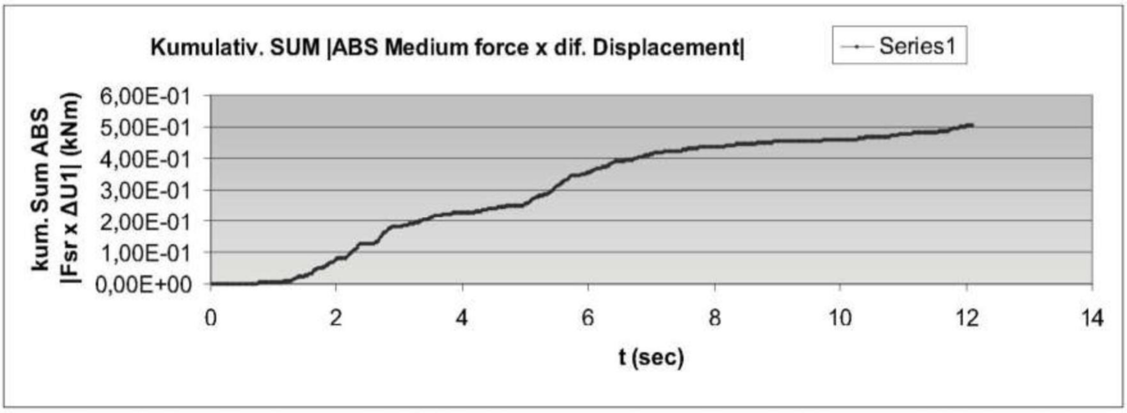

Figure 8. Cumulative absolute work of link elements under action of El Centro. Link 1 and 2, at 1.0 m below the ground surface. PGA 0.20g El Centro, NDA.
Slika 8. Kumulativni apsolutni rad link elemenata tokom dejstva El Centro. Link 1 i 2, nivo 1,0 m ispod površine tla. PGA 0,20g El Centro, NDA.

By numerical tests (Folić B and R., 2018), for PGA 0.30g, it was determined that the maximum displacements of link elements at the first three meters under the surface, range between 2,8 mm and 0,4 mm. Despite such small displacement, over 95 % of seismic energy of the link elements of this pile is dissipated at this depth. It is a depth of five pile diameters (3m/0.60m=5D). It is in agreement with the highest effects upon the coefficients A and B of the theory of *p-y* curves for the static and repeated load. The percentage of seismic energy dissipation along the pile length, jointly for both link elements, is provided in Figure 9. Figure 10 presents energy dissipation separately for the left and for the right link elements.

The table 2 presents a detailed analysis of forces, displacements, work and cumulative work of link elements during the action of El Centro and PGA=0.30g.

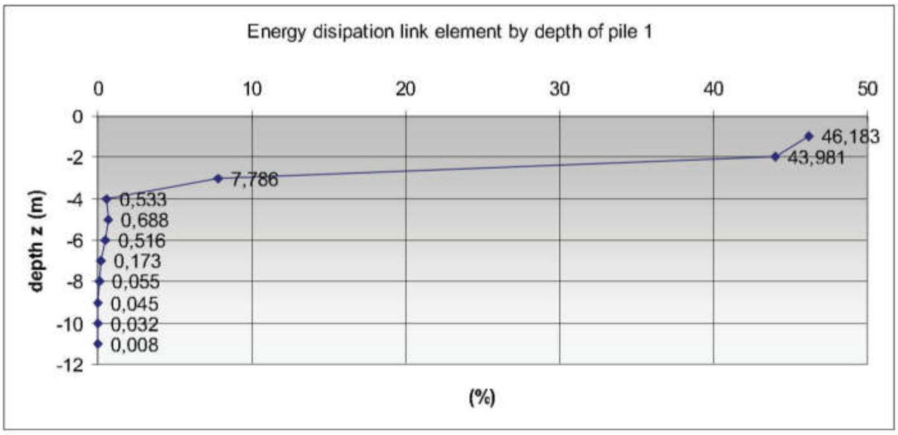

Figure 9. Percentage (%) of energy dissipation of link elements along depth bellow soil surface for pile 1
Slika 9. Procenat (%) disipacije energije za link elemente po dubini ispod površine terena za šip 1

In Fig. 10 one may observe the asymmetry of energy dissipation of link elements situated on the left and right side of a pile. The energy dissipation at 1 m of depth for this pile and accelerogram is about 50% higher for the left side than for the right (59.9/40.1).

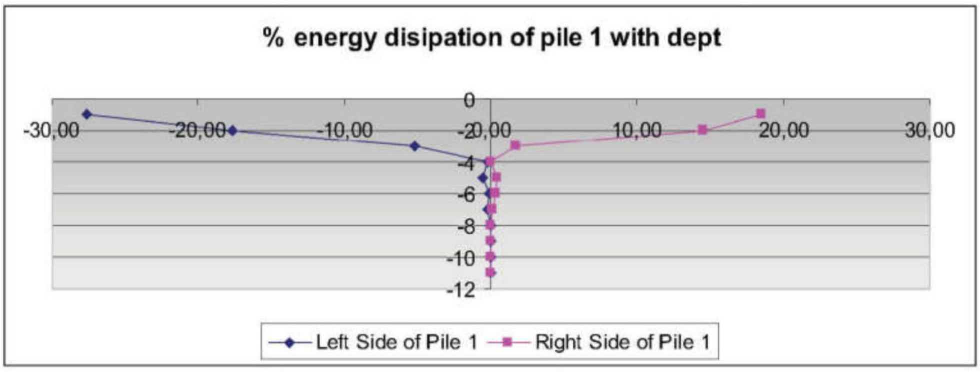

Figure 10. Percent (%) of seismic energy dissipation of link elements along the depth for pile 1 (left and right sides).

Slika 10. Procenat (%) disipacije seizmičke energije, za link elemente po dubini šipa 1 (za levu i desnu stranu).

Table 2. Link elements with depth, for left edge pile. Extreme displacements and forces, for El Centro, PGA 0.30 g.

Tabela 2. Link elementi po dubini, za levi krajnji šip. Ekstremna pomeranja i sile za El Centro, PGA 0.30 g

z (m)	Link	U extr (m)	F extr (kN)	(Fi*Ui) extr (kNm)	Σ (Fi*Ui) (kNm)	(Fsr*ΔUi)extr (kNm)	Σ ABS(A) (kNm)	A/ΣA %
1	1	0.00272	49.71	0.1352167	6.1454125	0.01424095	0.4188097	59.89
	2	0.00281	46.74	0.0939416	4.3699499	0.00716251	0.2804514	40.11
2	3	0.00138	85.81	0.1184187	6.5062411	0.01073076	0.4461167	66.98
	4	0.00145	62.63	0.0566888	2.8040334	0.00529569	0.2199727	33.02
3	5	0.0004518	44.10	0.0199249	1.2593537	0.00203323	0.0915624	77.69
	6	0.0005053	23.77	0.0057889	0.2804816	0.00062265	0.0262916	22.31
4	7	6.048E-05	15.99	0.0009670	0.0612844	0.00016362	0.0076096	94.26
	8	6.376E-05	5.46	0.0001129	0.0012892	2.4366E-05	0.0004630	5.74
5	9	0.000133	13.65	0.0011192	0.0590964	8.3331E-05	0.0045659	43.80
	10	9.831E-05	16.38	0.0016099	0.0642328	0.00015859	0.0058584	56.20
6	11	0.0001025	10.48	0.0005471	0.0289231	4.3299E-05	0.0025059	32.07
	12	7.628E-05	15.32	0.0011687	0.0609466	0.0001198	0.0053071	67.93
7	13	5.259E-05	4.93	0.0001033	0.0048663	1.8819E-05	0.0006463	24.67
	14	0.0000344	8.09	0.0002782	0.0153709	5.56E-05	0.0019731	75.33
8	15	2.197E-05	2.94	3204E-05	0.0007730	1.2754E-05	0.0002461	29.33
	16	0.0000164	4.41	7.238E-05	0.0021958	2.1798E-05	0.0005931	70.67
9	17	1.536E-05	3.88	4.967E-05	0.0010876	1.6543E-05	0.0003283	47.73
	18	1.496E-05	3.79	4.731E-05	0.0013961	1.0419E-05	0.0003595	52.27
10	19	1.051E-05	3.47	3.565E-05	0.0010162	1.2222E-05	0.0002711	55.46
	20	1.131E-05	3.13	2.896E-05	0.0008312	6.186E-06	0.0002177	44.54
11	21	4.76E-06	1.75	8.22E-06	2.34E-04	2.76E-06	6.98E-05	56.37
	22	4.95E-06	1.64	7.29E-06	1.75E-04	1.54E-06	5.40E-05	43.63

The table 3 presents variations of natural periods of the structure-pile-soil system with reference to the value of PGA of accelerogram El Centro: 0.20, 0.25 and 0.30g. The variation of the first natural period with a leap of PGA from 0.25 to 0.30g, appears insignificant, however, it is necessary to completely consider all the phenomena in the structure, piles and soil (link elements), to avoid a misinterpretation of the results.

Table 3. Natural periods due to different values of PGA of El Centro
Tabela 3. Periodi svojstvenih tonova za različite vrednosti PGA za El Centro

PGA (g)	T_1 (sec)	T_2 (sec)	T_1 %	T_2 %
Start	1.37255	0.44269	0	0
0.20	1.73011	0.86837	26.05	96.16
0.25	2.36767	1.00557	72.50	127.15
0.30	2.39338	1.03398	74.37	133.57

CONCLUSION

This paper presents changes of seismic performances of structures depending on the applied accelerograms and values of PGA. The method of calculation and implementation of *p-y* curves is also presented. It was demonstrated that a quick check of seismic properties of a structure is possible by observing the states of plastic hinges, variations of values of natural periods and displacements of a joint at the top of the structure during earthquakes (global, but also local drifts). All the listed parameters must be simultaneously considered for a complete understanding of non-linear behavior of the structure-foundation-soil system. It is also necessary to choose the accelerograms sets in accordance with EC8. It was shown that the pile-structure interaction (presented by a 2D frame) – can be sufficiently reliably assessed using the *p-y* curves for a specific type of soil.

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