KOMPARATIVNA NELINEARNA ANALIZA INTERAKCIJE ŠIP-TLO AB 2D RAMA*

COMPARATIVE NONLINEAR ANALYSIS OF A RC 2D FRAME SOIL-PILE INTERACTION*

Boris FOLIĆ
Radomir FOLIĆ

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1 UVOD

Tokom seizmičkih analiza obično se pretpostavlja uklještenje u osnovi, a zanemaruje se fleksibilnost tla i temelja. Ipak, za tačnije seizmičke analize potrebno je uvesti u proračun pored konstrukcije zgrade temelje i tlo, što uslovljava unošenje celokupnog sistema kao ulaznih podataka. Pri tome se posebne teškoće javljaju pri unošenju podataka o karakteristikama tla. U nekim radovima koriste se specijalne histerezisne zavisnosti i nelinearni odgovor sistema sa jednim stepenom slobode (SDOF) kao reprezent konstrukcije zgrade, pri čemu je lakša analiza uz uvođenje fleksibilnosti temelj-tlo i njihovog uticaja na odgovor konstrukcije. Uglavnom, smatra se da uvođenje interakcije redukuje odgovor konstrukcije, a time i oštećenja. Međutim, u pojedinim slučajevima može doći i do negativnih efekata, što je razmatrano u radu [7]. Neka istraživanja [7] su pokazala da se u seizmičkoj analizi mogu uvesti pojednostavljeni modeli tla i znatno olakšati proračun sistema, naročito regularnih zgrada [4] i [9]. Upoređenjem rezultata driftova, na 2D i 3D ramu, dobijenih pušover analizom sa rezultatima dobijenih primenom analize vremenske istorije u [8] je pokazano da se uvođenjem faktora modifikacije mogu dobiti konzervativni rezultati primenljivi u projektantskoj praksi. I u radu [22] je prikazan približni proračun krutih ramova uz uvođenje interakcije tlo-temelj-konstrukcija, primenljiv u praksi projektovanja. Analitička rešenja su znatno ređa, iako je bilo pokušaja [20].

Dr Boris Folić, Univerzitet u Beogradu, Inovativni centar Mašinskog fakulteta Kraljice Marije 16, Beograd
boris.folic@gmail.com
Radomir Folić, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Trg Dositeja Obradovića 6, Novi Sad
folic@uns.ac.rs

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1 INTRODUCTION

During seismic analysis of a structure, it is assumed that the building is clamped at the base and the soil and foundation flexibility is ignored. Yet, for more accurate seismic analyses, in addition to the building structure it is necessary to introduce foundations and soil, which requires entering of the entire system as input data. In the process, special difficulties arise when entering data of the soil characteristics. In some papers, special hysteresis dependencies and non linear response of the system with one degree of freedom (SDOF system) are used for representing of the building structure, whereby an analysis which introduces the foundation-soil flexibility and their impact on the structural response is easier to perform. It is generally considered that introduction of interaction reduces the structural response, and thus damage. However, in some cases, negative effects may occur, which was discussed in the paper [7]. Some research, e.g. [7], showed that in this seismic analysis, simplified soil models could be introduced thus making system design considerably easier, especially design of regular buildings, see [4] and [9]. By comparing results of drifts of 2D and 3D frames, obtained by a pushover analysis, with results obtained using the time history analysis, see [8], it is showed that by introducing the modification factors, one can obtain conservative results applicable in designing practice. In the paper [22], an approximate design of rigid frames, applicable in designing practice, with interaction of soil-

Dr. Boris Folic, University of Belgrade, Innovation Center of Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, boris.folic@gmail.com
Radomir Folic, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovica 6, Novi Sad, folic@uns.ac.rs

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Evropska regulativa za seizmičko projektovanje EN 1998, Part 1 i Part 5, ne razmatra detaljno problem uvođenja interakcije tlo-temelj-konstrukcija (SFI) u numeričkim seizmičkim analizama. U EN 1998-5 to se zahteva gde P-Δ efekti imaju veliku ulogu; konstrukcije sa masivnim i dubokim temeljima, i konstrukcije na veoma mekom tlu u kojima je prosečna brzina smičućih talasa manja od 100 m/s [5] i [10]. Razlike seizmičkog ponašanja objekata plitko fundiranih i na šipovima detaljno je opisana u [4] i [5]. U njima je detaljno opisan način analize kinematičke i inercijalne interakcije pri fundiranju na šipovima. Kinematička interakcija potiče od razlike pokreta tla i temelja ili šipova, tokom zemljotresa, pri čemu se masa zanemaruje. Kod inercijalne interakcije, pručava se uticaj inercijalnih sila od konstrukcije na temelje.

U ovom radu je sprovedena komparativna nelinearna statička (NSA), često nazvana pushover analiza, i dinamička analiza NDA, detaljno opisane u [3], na 2D rama AB skeletne zgrade fundirane na šipovima. U modelu je uključena i linearno-nelinearna interakcije šip-tlo korišćenjem link elemenata. Tlo je modelovano sa više(linijskim) plastičnim veznim elementima, kao anvelopama u obliku *p-y* krivih, sa obe strane šipa. P-y krive prenose (primaju) samo pritisak. Krive *p-y* su modelovane prema Koksu, Risu i Matloku [4] i [12] i [19] za potopljen pesak, i šipove prečnika 60 cm. Analizirane su seizmičke performanse sistema konstrukcija-temelj-tlo jednog 2D rama fundiranog na šipovima. Prikazano je delimično linearno i nešto detaljnije nelinearno ponašanje krovne grede, dok se ostale grede rama ponašaju nelinearno. Linearna krovna greda je ona kod koje nisu uvedeni plastični zglobovi u čvorovima na preseku sa unutrašnjim stubovima, ali ni u polju krovne grede.

foundation-structure, was presented. Analytical solutions are rare, even though there were attempts, [20].

European regulation for seismic design, EN 1998, Part 1 and Part 5, does not consider in detail the problem of introducing the soil-foundation-structure interaction (SFI) in the numerical seismic analyses. In EN 1998-5 it is required where P-Δ effects have an important role: the structures with massive and deep foundations, and structures in a very soft soil where the average velocity of shear waves is less than 100 m/s, see [5] and [10]. The difference of seismic behaviour of the structures founded on shallow foundations and on the piles was described in detail in [4] and [5]. In them, the method of analysis of kinematic and inertial interaction of pile foundations was described in detail.

A comparative non-linear static analysis (NSA), often called a pushover analysis, as well as the dynamic non-linear analysis (NDA), described in detail in [3], and applied on 2D frames of RC skeletal buildings founded on piles are presented in this paper. The model involves a linear-non-linear pile-soil interaction, using link elements. The soil is modelled using multiple (linear) plastic link elements, as envelopes in the form of the p-y curves, on both sides of the pile. P-y curves are transferring only compression and are modelled according to Cox, Reese and Matlock [4], [12] and [19] for submerged sand, and piles with a diameter 60 cm. The seismic performances of the structure-foundation-soil system of a 2D frame founded on piles are analyzed. Detailed analysis of hierarchy of formation of plastic hinges in the frame and piles is presented. A partial linear and a more detailed non-linear behaviour of a roof beam are presented, while the remaining beams of the frame behave non-linearly. Linear roof beam is the beam without plastic hinges at intersections with inner columns or along the beam. Kinematic interaction arises from different motions of the soil and foundation, or piles, during earthquake, while the mass is neglected. In inertial interaction, the effect of inertial forces from the structure upon the foundation is considered.

2 OPIS KONSTRUKCIJE, TEMELJA I METODA ANALIZE

2.1 Analizirana konstrukcija

Analiziran je fasadni ram koji ima četiri stuba, kao i unutrašnji ram. Na fasadnom ramu su ugaoni stub i ivični stubovi. Ugaoni stubovi fasadnog rama su fundirani na grupi od 3 šipa, a unutrašnji na grupi od po četiri šipa. Fasadni ram je "kondenzovan", tako što su svi elementi šipova ubačeni putem projekcije upravno na srednju ravan rama. Na taj način se model rama može prikazati u samo jednoj ravni. Grupa od 3 kružna šipa ima deo koji se sastoji od jednog šipa (1D60), i deo koji se sastoji od dva kondenzovana šipa (2D60) slika 1. Dakle u „kondenzovanom" modelu od tri šipa unose se samo dva šipa, 1 je samostalan šip, a drugi je dvostruki šip (tj. u ravanskom modelu je unet jedan šip kod koga su poprečni preseci FRAME elementa, u programu SAP2000, u delu Set Modifiers, krutost i masa pomnoženi sa 2). Shodno tome p-y krive „dvostrukog" šipa imaju dvostruko veću krutost. Objekat ima dve relativno vitke donje etaže. Visina prve dve etaže je po 5 metara, ali su zato poprečni preseci stubova na ove dve

2 DESCRIPTION OF THE STRUCTURE, FOUNDATIONS AND METHODS OF ANALYSIS

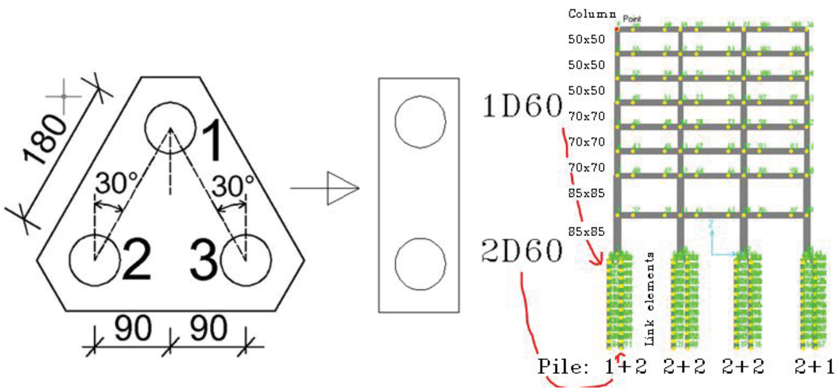
2.1 Analyzed structure

A façade frame with four columns and an inner frame are analyzed. On the façade frame, there are corner columns and peripheral columns. The corner columns of the facade frame are founded using a group of 3 piles, whereas the inner columns are founded on a group of four piles. The façade frame is "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 only two dimensions. The group of 3 circular piles consists of a part made of one pile (1D60), and another part made of two condensed piles (2D60), figure 1. 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 (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. In accordance with this, the p-y curves of the "double" pile etaže 85/85cm.

U seizmičkoj analizi su primenjene nelinearna statička (NSA), često nazvana pushover, i nelinearna dinamička analiza (NDA), u vremenskom domenu (Time History). S obzirom da se tokom NSA i NDA [3] praktično ne pojavljuju plastični zglobovi u šipovima kod krućih vrsta tla (osim u specijalnim slučajevima), analizirani su i uticaji u tlu, preko link elemenata po dubini, pod seizmičkim dejstvom (TH El Centro 0,30g). Oni na takav način nisu dovoljno obrađeni u dostupnoj literaturi. Analizirana su ekstremna pomeranja, sile, ukupan rad, "trenutni rad", i raspodela istih po dubini link elemenata šipa. Analiziran je samo jedan šip iz grupe i to samostalni šip (1D60) iz grupe od tri šipa (1+2, na slici 1). To je krajnji šip na obe strane simetričnog rama (vidi sliku 1 desno). Konkretno je, u ovom radu, istraživan samo levi krajnji šip. Takođe je analizirana promena ukupne smičuće sile u osnovi sa porastom vršnog ubrzanja (PGA), i promena stanja plastičnih zglobova u konstrukciji i šipovima i u skladu s tom promenom konstruktivnog sistema, promena prvog i drugog svojstvenog tona nakon završetka seizmičkog dejstva (Time History).

also have the double value of stiffness. The building has two relatively slender lower stories. The height of the first two storeys is 5 meters each, but the cross-sections of columns in these two floors are 85/85 cm.

Seismic analysis is performed using the non-linear static analysis (NSA), often called the pushover analysis, and the non-linear dynamic analysis (NDA) in the time domain (time history). Regarding that during NSA and NDA [3] there is practically no occurrence of plastic hinges in the piles for stiffer types of soil (except in special cases) the effects in the soil are analyzed too, via link elements along the depth, under a seismic action (TH El Centro 0.30g). They are not sufficiently discussed in the available literature in this way. Extreme displacements, forces, total work, "instantaneous work" in link elements and their distribution along depth of the pile are analyzed. Only one pile from the group is analyzed, namely, a single pile (1D60) from the group of three piles (1+2, in figure1). These are the end piles on both sides of the symmetrical frame (see figure 1 right). In this paper specifically, only the left endmost pile is studied. Also, the variation of the total seismic base-shear force, with the increase of peak acceleration (PGA) is analyzed, and also the variation of condition of plastic hinges in the structure and the piles, and variation of the first and second natural tones after seismic excitation (Time History)



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

Prostorni (3D) ram je dimenzionisan na zemljotresno dejstvo u programu SAP 2000 v14. sa uvođenjem upravnog pravca i torzije (sa 5% ekscentriciteta), za faktor ponašanja 5.85. Nakon toga je iz tako dimenzionisanog modela izdvojen, napred opisani, fasadni 2D ram sa pripadajućim opterećenjem. Raspon ramova je 8m, a to je i osno rastojanje stubova, u oba pravca. Objekat je dvoosno simetričan. Visina prve dve etaže je po 5m, a ostalih 6 etaža je 3.1 m. Model je sličan modelima datom u [2] i [4]. Razlika je u p-y krivama koje su u navedenom radu [4] date za šipove prečnika 1,2m. Takođe, u navedenom radu je dato više različitih modela, sa i bez interakcije šip-tlo. Izgled ovde usvojenog, samo jednog modela rama, je dat u nastavku rada, kod analize stanja plastičnih zglobova. Kod [2], za izveden objekat, stubovi su svi preseka 60/60cm, a opterećenje je nešto manje.

Izdvajanje 2D rama iz trodimenzionalnog (3D) rama prati specifična problematika [4] i [8]. Prvi parametar je

The spatial (3D) frame is dimensioned with reference to earthquake action, using SAP 2000 v14 software, including the effects in the perpendicular direction and torsion (with 5% eccentricity), for a behaviour factor of 5.85. The previously described façade 2D frame with its corresponding loads is then taken out of a 3D model dimensioned in this way. The span between frames is 8m, which is also the distance between the pile axes, in both directions, since the structure in question is symmetrical along two orthogonal axes. The height of the first two stories is 5m, while for the remaining 6 storeys, it is 3.1 m. The model is similar to models shown in [2] and [4]. However, the difference is in p-y curves, which are, in [4], given for piles of diameter 1.2m. Also, more different models with and without pile-soil interaction are given in [4]. The geometry of the single frame considered here is presented later in the section where the state of plastic hinges is analysed. Paper [2] is related to built structure, where all columns pripadajuće opterećenje, drugi je geometrija poprečnih preseka (pre svega) greda, a za dinamičku analizu, neophodno je proveriti i razliku svojstvenih perioda izdvojenog 2D rama u odnosu na 3D model. Poželjno je, proveriti i deformaciju („ugib“) vrha 3D objekta u odnosu na vrh 2D rama. Realnije ponašanje ravanskih modela (kod kojih je izdvojen samo jedan 2D ram), u odnosu na prostorni ram, daju modeli kod kojih je link elementima ili prostim štapovima spregnuto više ramova u 2D modelu [11]. Kao npr. spregnuti fasadni i unutrašnji 2D ram ili 2 unutrašnja i 2 fasadna, uz uslov da se spregnuti ramovi u 3D modelu moraju pružati u istom pravcu.

Kod izdvajanja 2D rama, neophodno je proveriti prihvatljivo poklapanje vrednosti normalnih sila u stubovima, i reakcija oslonaca za oba modela. Takođe, kod čvorova gde se sučeljavanju grede iz drugog pravca, može se primeniti komanda *Set Modifiers*, za uvećanje krutosti poprečnih preseka napregnutih na savijanje, zbog učešća torzione krutosti drugog pravca. Kod (malih) poprečnih preseka greda i tanjih ploča, kod kojih torziona krutost, brzo opada/degradira se tokom zemljotresa, bolje je uvesti nelinearnu rotacionu oprugu, kojom se simulira ova krutost, ali i pad iste tokom zemljotresa. Često se u seizmičkoj (dinamičkoj i kvazi statičkoj) analizi, zbog smanjenja broja nepoznatih isključuju ploče, i koriste bruto preseci greda, čak i bez pripadajućih aktivnih širina ploča, i bez komande *Modifiers*. Kako je to na strani sigurnosti, primenjeno je i u ovom radu, za fasadne grede. Uticaj spratnih ploča, na ujednačavanje horizontalnih pomeranja spratova, kod 2D i kod 3D rama, može se poboljšati komandom *Joint - Constraints (Equal)*.

Gornji čvorovi (u krovnoj ravni) unutrašnjih stubova ne zadovoljavaju uslove odnosa krutosti greda i stubova, te je u prvom delu rada, taj deo grede linearizovan, odnosno na tom delu nisu uneti plastični zglobovi. To će se sagledati, kasnije, u delu analize rezultata. (premestiti zarez)

Ukoliko se ne upotrebi preporučena opcija SAPa, automatske podele plastičnih zglobova u linijskim elementima od 0,02, lom greda se događa i na drugom spratu dosta rano, a kasnije i na drugim lokacijama, pa se produžava vreme proračuna. Ovaj primer nije prikazan, iako je i ovakav način loma moguć, ali manje verovatan, ako je konstrukcija dobro izvedena. Zato je u svim ovde prikazanim modelima, ova opcija primenjena.

Odnos ukupne seizmičke sile u osnovi i ukupne sile težine objekta, kod (regularnog, kvadratnog u osnovi) 3D modela, je: 5316 kN/71093 kN= 7,48%. Svojstveni periodi 3D modela su: T_1=T_2=2,04 sec, T_3=1,47 sec. Prva dva tona su horizontalna-lateralna, a treći je torzioni-obrtni [4].

are 60/60cm, and the loading is slightly lower.

Extraction of a 2D frame from a three-dimensional (3D) frame is accompanied by specific problems, [4] and [8]. The first parameter is the corresponding load; the second is the geometry of cross sections (primarily) of the beams, while for a dynamic analysis, it is necessary to check the difference between the natural periods of the extracted 2D frame and the 3D model. It is desirable to check and compare the deformation (horizontal deflection) of the top of a 3D object in comparison to the top of the 2D frame. A more realistic behaviour of the planar models (where only one 2D frame is extracted from 3D model), when compared with the spatial frame, is obtained by 2D models where more 2D frames are combined in one model, using link or truss elements, [11]. For instance, coupled façade and the interior 2D frame, or 2 interior and 2 façade frames, are examples of that. Of course, it is assumed that frames are aligned along the same direction.

When extracting a 2D frame, it is necessary to check the acceptable agreement of values of normal forces in the columns, and the support reactions of both models. Also, in a case of nodes where the beams from another direction are connected, one might use the command *Set Modifiers*, in order to increase the bending stiffness of sections, due to influence of the torsional stiffness in another direction. In the case of (relatively small) cross-sections of beams and thin slabs, where the torsional stiffness quickly decreases/degrades during earthquakes, it is better to introduce a non-linear rotational spring which simulates this stiffness and its decline during earthquakes. Very often, in the seismic (dynamic and quasi static) analysis, due to reduction of a number of unknowns, the slabs are excluded, and gross cross-sections of beams are used, even without the belonging active widths of the slabs, and without the *Modifiers* command. Since it is on the safety side, it is implemented in this paper, too, for the façade beams. The effects of the floor slabs to unify the horizontal storey displacements, in 2D and 3D frames, may be improved by using the command *Joint – Constraints (Equal)*.

Upper nodes (in the roof) of the inner columns do not meet the conditions of stiffness ratio of beams and columns, so in the first part of the paper this upper beam is linearized, i.e. no plastic hinges are introduced in this beam. It will be considered later, in the section of the result analysis.

Unless the recommended option of SAP, *Assign/Frame/Frame Signed Overwrights/Auto Subdivide Line Objects at Hinge* of 0,02 is used, the failure of the beams occurs on the second storey quite early, and later in other locations as well, so the time of calculation is prolonged. This example is not presented, even though such failure mode is quite possible, but unlikely, if the structure is well constructed. For this reason in all the presented models, this option is implemented.

The ratio of the total base-shear force and the total force of the building weight (of a regular, square layout) 3D model, is: 5316kN/71093kN= 7.48%. Natural periods of the 3D model are: T1=T2=2.04 sec, T3=1.47 sec. The first two tones are horizontal-lateral, and the third one is torsional-rotational [4].

2.2 Ponašanje i modeliranje tla u zemljotresu

Odgovor na pitanje šta se događa u tlu tokom zemljotresa, zavisi, pre svega, od načina modelovanja tla u sistemu konstrukcija temelj tlo, zatim koji zemljotres i kakav uticaj se konkretno istražuje. Verovatno najbolji odgovor, na ovo pitanje, pruža talasna mehanika, i njena primena na numeričke analize korišćenjem Solid elemenata tla. To je posebna problematika, jer u procesu modelovanja zahteva iznalaženje optimuma tokom zadovoljenja često suprotstavljenih uslova. Parametri koje u procesu definisanja modela treba odrediti su: dimenzije modela konstrukcije, zatim veličine modela sistema, veličine mreže KE, oblast frekvencije i vrste talasa koji se prostiru, granični problemi, itd. [17]. Kod ove metode, važno je u odnosu na veličinu konstrukcije proceniti minimalnu veličinu modela za sistem konstrukcija-temelj-tlo, kako bi vreme proračuna bilo što kraće, a da se pri tom adekvatno obuhvate svi potrebni talasni fenomeni. Takođe treba odrediti i maksimalnu veličinu konačnih elemenata tla, koja se ne sme prekoračiti kako ne bi došlo do neželjenih talasnih efekata u samim konačnim elementima tla i sl. Ovde ćemo se zadržati na korišćenju link elemenata tla (LES), kao Takedina anvelopa eksperimentalno određenih *p-y* krivih (ATPY), jer je to jednostavniji model za primenu, te će i odgovor biti zasnovan na istom.

2.3 *P-Y* krive za šipove u pesku

Tlo se u analizi dinamičke interakcije sistema konstrukcija-temelj-tlo može predstaviti upotrebom modela različitog stepena složenosti (sofisticiranosti). Uobičajene metode seizmičke analize nelinearnog ponašanja konstrukcija su kvazi-statička pušover NSA i nelinearna dinamička analiza u vremenskom domenu NDA, kao numerička integracija akcelerograma, tzv. metoda korak po korak (time history, step by step). Pri tome su za seizmička dejstva korišćeni akcelerogrami El Centro, za PGA 0,20; 0,25 i 0,30 *g*.

Tlo može biti modelovano preko različitih uslova oslanjanja, konstrukcije ili šipova, kao što je:

- linearnih opruga sa jednom čvornom tačkom (spring), koje trpe podjednako i zatezanja i pritisak,
- linearnih link elemenata
- više-linearnih plastičnih link elemenata, koje se mogu zadati tako, da prenose samo pritisak.

Tlo je modelovano preko elemenata veze, tzv. link elemenata, prema p-y modelu za pesak koji je razvio Ris i dr. Reese, Cox, Koop, 1974, i Reese , Sullivan, 1980, citirano prema [15].

Prema [13] verovatno prvi model p-y krivih uveli su McClelland and Focht (1958), preporučujući proceduru za korelaciju podataka triaksijalnog naponsko-deformacijskog opita sa krivama sila-pomeranje šipa za određene dubine, preko očekivanog modula reakcije tla, za svaki sloj tla, po dubini. Riz je prvi prikazao svoj koncept sloma tla oblika klina, koji se javlja blizu površine tla [19]. Uticaj variranja ulaznih parametara p-y krivih na odgovor šipa može se sagledati u [12].

2.2 Soil behaviour and its modelling during earthquakes

The answer to the question what occurs in the soil during earthquakes depends, primarily on the method of soil modelling in the structure-foundation-soil system, and then what earthquake and what effect are specifically investigated. The best answer to this question is probably provided by the wave mechanics, and its implementation in the numerical analyses using Solid elements of soil. It is a specific problem, because in the process of modelling, it requires finding an optimum for satisfying often confronted conditions. The parameters which need to be determined in the model definition process are: dimensions of the structural model, system model size, FE mesh size, frequency domain and types of propagating waves, boundary issues, etc. [17]. In this method, it is important to assess a minimum size of the model for the structure-foundation-soil system, in order to keep the calculation time as short as possible, but still to include all the necessary wave phenomena. Also, the maximum size of finite elements of soil must be determined, which must not be exceeded so as to avoid the undesirable wave effects in the actual finite elements of the soil, etc. We are discussing here the use of link elements in soil (LES), as Takeda envelopes of experimentally determined *p-y* curves (ATPY), because it is a simpler model for practical use, so the response will be based on it.

2.3 *P-Y* curves for piles in sand

Models of different levels of sophistication can be used for presentation of soil in an analysis of the dynamic interaction of a structure-foundation-soil system. The usual methods of seismic analysis of non-linear behaviour of structures are the quasi-static pushover NSA analysis and the non-linear dynamic NDA analysis in the time domain, as a numerical integration of accelerogram, a so-called step-by-step time history method. For the seismic action, accelerogram of El Centro, for PGA of 0.20; 0.25 and 0.30 *g* are used.

Soil can be modelled using various conditions of support, structure or piles, such as:

- Linear single-node springs, which equally resist tension and compression,
- Linear link elements
- Multi-linear plastic link elements which can be set so that only transfer compression.

Soil is modelled using the connection elements, so called link elements, according to the p-y sand model developed by Reese et al, Reese, Cox, Koop, 1974, and Reese, Sullivan, 1980, cited according to [15] .

According to [13] probably the first model of p-y curves was introduced by [10], which recommends the procedure for correlation of data of triaxial stress-strain test with the force-displacement curves of the piles for certain depths, via the expected soil reaction modulus, for every layer of soil, along the depth. Reese was the first to present his concept of wedge-like soil failure which occurs close to the soil surface [19]. The influence of variation of input parameters of p-y curves on the pile response can be observed in [12].

2.4 Pushover NSA – nelinearna statička analiza

U radu [3] detaljno su analizirane savremene metode za nelinearnu seizmičku analizu konstrukcija i način uvođenja prigušenja pri korišćenju neke od metoda. Ovde je ukratko prikazana pušover (PO) analiza u kojoj se određuju krive zavisnosti pomeranja kontrolnog čvora u_{max} (obično na vrhu rama) u odnosu na seizmičke smičuće sile u osnovi (BS-Base Shear), a za usvojen oblik raspodele opterećenja po visini objekta. Pretpostavlja se da usvojeni oblik opterećenja ostaje nepromenjen za sve stepene intenziteta, a time i deformisani oblik konstrukcije. Postepeno povećanje intenziteta opterećenja vrši se u koracima uz otvaranje plastičnih zglobova sve dok konstrukcije ne pređe u mehanizam. Kod konstrukcije pušover krivih, osim onih obaveznih po propisima, datih u EC8, poželjno je primeniti više različitih oblika raspodele opterećenja. Ovde su primenjeni sledeći oblici raspodele opterećenja po visini rama (odn. 2D modela zgrade):

- Konstantna raspodela (const).
- Linearno promenjiva (lin).
- Proporcionalno obliku prvog svojstvenog tona (1 mode) i
- Proporcionalno raspodeli (pripadajućih) masa (acc).

Takođe se mogu primeniti različiti tipovi prikaza PO krivih, a u SAP2000 su, za to, na raspolaganju:

1. Rezultantna sila u osnovi (BS) prema posmatranom pomeranju (MD),
2. ATC 40 metoda spektra kapaciteta,
3. FEMA 356 metoda koeficijenata,
4. FEMA 440 metoda ekvivalentne linearizacije, i
5. FEMA 440 metoda Modifikacije pomeranja.

3 REZULTATI PRORAČUNA I NJIHOVA ANALIZA

3.1 Rezultati NSA

Ovde su PO krive određene u programu SAP2000 v14, ali ne preko opcije *Display/Show Static Pushover Curve*, jer tada dijagram nije dovoljno pregledan, očitavanja vrednosti su nedovoljno precizna i ne mogu se vršiti odgovarajuće manipulacije, već je zbog toga to učinjeno preko putanje *Display/Show Plot Function*, dakle preko dijagrama funkcije *Umax/BS*. Takođe je PO kriva određena i prema proceduri FEMA356.

Na zbirnom dijagramu, za ovako određenje PO krive vidljiva je značajna razlika maksimalnih pomeranja kontrolnog čvora, u zavisnosti od oblika opterećenja, kao i razlike u početnoj inicijalnoj krutosti. Detaljnija analiza data je u tabeli 1.

2.4 Pushover NSA - non-linear static analysis

The paper [3] is analyzing the contemporary methods for non-linear seismic analysis of structures, and the ways how damping is introduced when using some of the methods. The pushover (PO) analysis is here briefly presented, which involves determination of curves which show the dependence of control node displacement u_{max} (typically at the top of the frame) with the seismic base shear (BS) force, for assumed shape of lateral 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 is 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 natural mode (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:

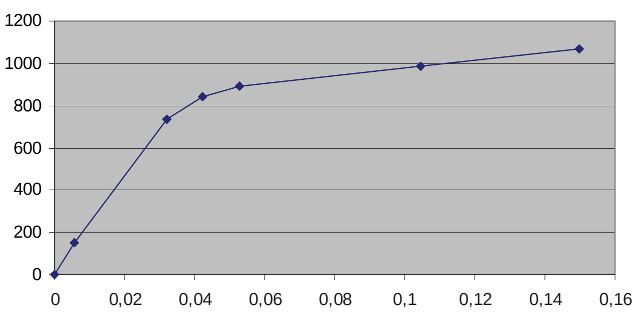
1. Resulting base shear force (BS) according to the observed displacement (MD),
2. ATC 40 spectrum capacity method,
3. FEMA 356 coefficients method,
4. FEMA 440 equivalent linearization method, and
5. FEMA 440 displacement modification method.

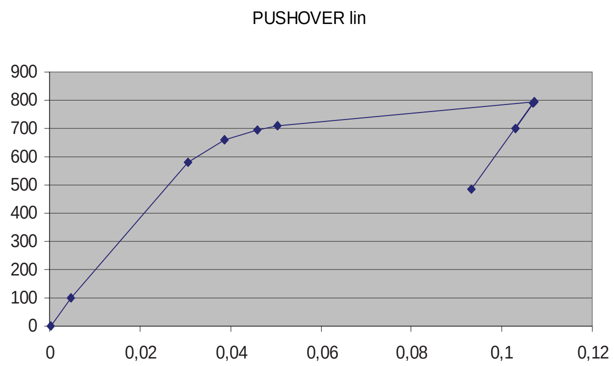
3 CALCULATION RESULTS AND THEIR ANALYSIS

3.1 NSA results

Here, the PO curves are determined using SAP 2000 v14 software, 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 is performed using the path Display/Show Plot Function, i.e. by using the function diagram U_{max}/*BS*. In addition, the PO curve is also determined according to the FEMA 356 procedure.

In the summary 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.



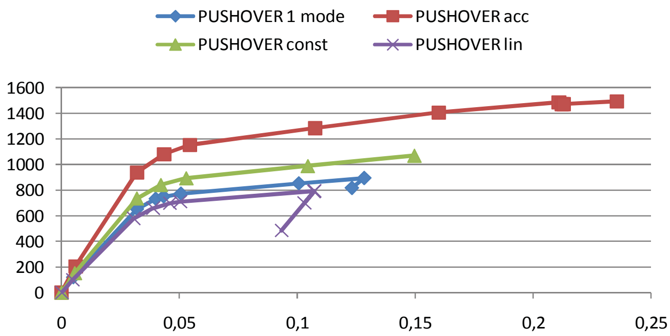


Slika 2a. Pušover kriva. Konstantna raspodela opterećenja po visini. Sila u osnovi BS=1069 kN, maksimalno pomeranje umax=14,97 cm.

Figure 2a. Pushover curve. Constant load shape along height BS=1069 kN, umax=14.97 cm.

Slika 2b. Pušover kriva. Linearna raspodela opterećenja po visini BS=793,1 kN, umax=10,73 cm.

Figure 2b. Pushover curve. Linear distributed load shape along height BS=793.1 kN, umax =10.73 cm.



Slika 3. Zbirni dijagram Pušover krivih za 4 oblika Raspodele opterećenja: linearna, 1 mode, konstantno (const) i proporcionalno masama acc.

Figure 3. Summary diagram Pushover curves, for 4 shapes load distribution: linear, 1 mode, const. and acc.

Tabela 1. Komparativni prikaz maksimalnih pomeranja čvora u vrhu i sila u osnovi u zavisnosti od oblika opterećenja. Kod vremenske analize u zavisnosti od PGA. Linearizovana krovna greda [6].

Table 1. Comparative analysis of max top node displacements and Base Shear, with respect to load shape. In TH with respect to PGA. Linear roof beam. [6].

	PGA (*g*) El Centro			Način distribucije vertikalnog opterećenja. *Distribution of vertical load*			
	0.20*g*	0.25*g*	0.30*g**	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

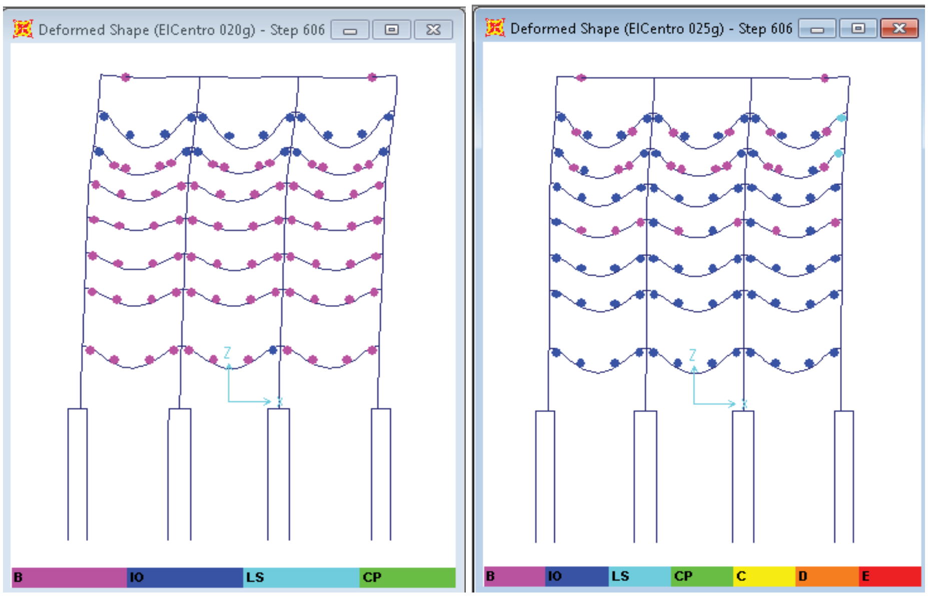
Razmatrani ram je svestrano tretiran, a s obzirom da je pre TH (NDA) analize preuzeto naponsko stanje konstrukcije od sopstvene težine, linearizovane krovne grede razmatranog rama [6] ostaju prave (slika 4). Kod nelinearnih se, nasuprot tome, jasno uočavaju ugibi što će biti prikazano u delu analiza rezultata na slikama 27, 28 i 29. Kod analize link elemenata, nelinearni su i ovi čvorovi, ali ni ovde plastični zglobovi nisu uneti na sredinama greda. Model rama sa plastičnim zglobovima i u sredinama greda, prikazan je na kraju rada, samo na

The considered frame is comprehensively treated, and since before the TH (NDA) analysis, the stress state of the structure under its self weight is taken, the linearized roof beams of the observed frame [6] remain straight (figure 4). In the non-linear ones, on the contrary, there are clearly observable deflections which will be presented in the section analysis of results in figures 27, 28 and 29. In the analysis of link elements, the nodes are non-linear, but the plastic hinges in the middle of the beams are not assumed. The model of the slici 31, uz kratak osvrt na problematiku istog.

Nelinearna dinamička analiza, urađena je za akcelerogram El Centro za vršne vrednosti PGA od 0.20, 0.25 i 0.30 *g*. Razmatrano je pomeranje čvora u vrhu i ukupne seizmicke sile u osnovi. Proveravana su stanja plastičnih zglobova (loma) na kraju svakog zemljotresa.

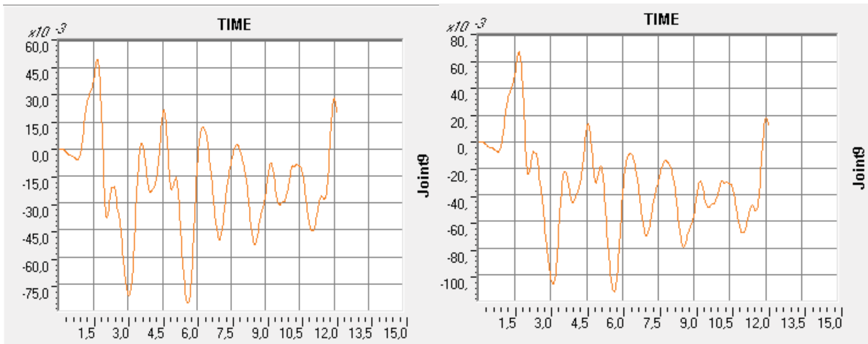
frame with plastic hinges in the middle of beams as well, is presented at the end of the paper, in figure 31 only, with a short comment on the issue.

Non-linear dynamic analysis is performed for the El Centro ground motion record, for peak PGA values 0.20, 0.25 and 0.30 *g*. Node displacements at the top and the seismic base shear are considered. The states of plastic hinges (failure) are checked at the end of each earthquake.



Slika 4. 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

Figure 4. State of plastic hinges (PHS) at the end earthquake ElCentro, left PGA 0.20g PHS: 79Y, 19 IO, right PGA 0.25g PHS: 71Y, 25 IO and 2 LS. Linear roof beams



Slika 5. 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. Displacement plot of the joint at the top of the building, due earthquake acc. El Centro: left PGA 0.20g, Umax =8.56cm, right PGA 0.25g, Umax =11.29 cm Linear roof beams.

Koeficijent proporcionalnosti i za sile i za pomeranja, kod prelaska sistema sa više stepeni slobode kretanja, (MDOF) na sistem sa jednim stepenom slobode (SDOF), je:

The proportionality coefficient, both for the forces and for displacements, during transition from a mullti degree of freedom system (MDOF) to a single degree of freedom system (SDOF) is:

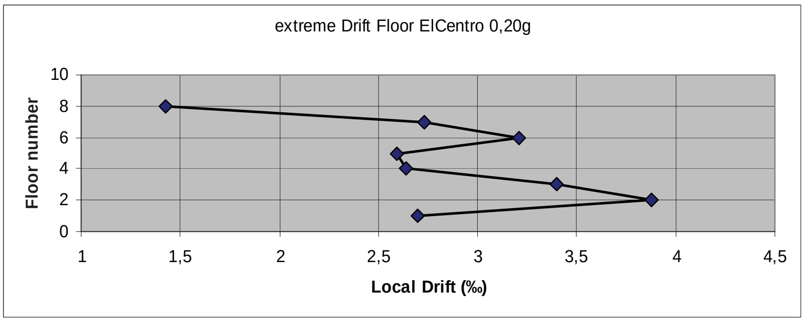
$$\Gamma = \frac{\Phi^T m 1}{\Phi^T m \Phi} = \frac{\sum m_i \Phi_i}{\sum m_i \Phi_i^{\ 2}} = \frac{m^*}{\sum m_i \Phi_i^{\ 2}} \qquad (1)$$

3.2 Driftovi stubova za različite vrednosti PGA

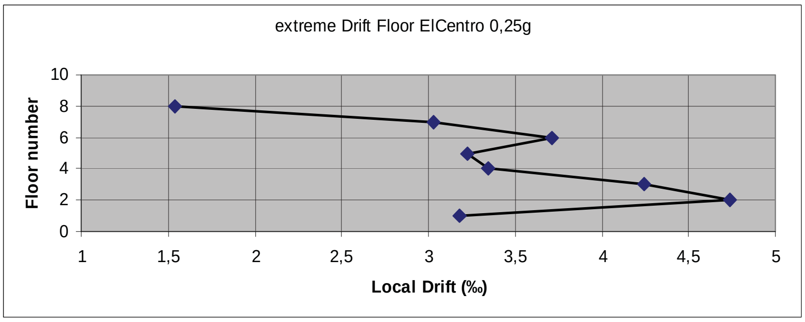
Sa nelinearnom (NL) krovnom gredom i celim NL 2D ramom, sračunate su ekstremne vrednosti drifta stubova i njihova promena tokom dejstva akcelerograma El Centro, za PGA 0,20; 0,25 i 0,30 *g*.

3.2 Column drifts for different values of PGA

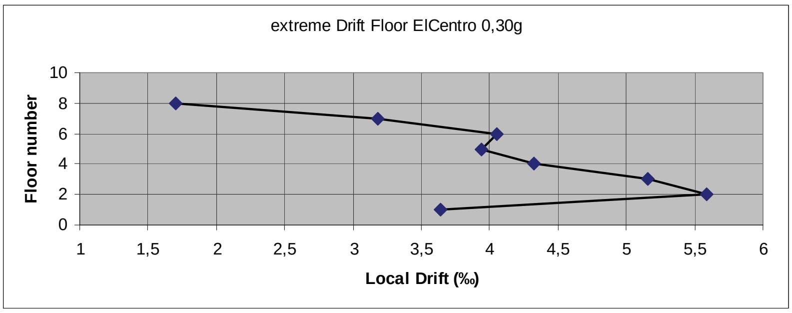
For the non-linear roof beam, and entire 2D frame, the extreme values of column drift and their variation during action of accelerogram of El Centro, for PGA of 0.20; 0.25 and 0.30 g, are calculated.



Slika 6a. Ekstremni spratni drift (stuba) El Centro 0,20g. Prekoračuje dozvoljene vrednosti
Figure 6a. El Centro 0.20g. Extreme Local Drift (column) exceeds permissible values



Slika 6b Ekstremni spratni drift (stuba) El Centro 0,25g. Prekoračuje dozvoljene vrednosti
Figure 6b El Centro 0.25g. Extreme Local Drift (column) exceeds permissible values



Slika 6c. Ekstremni spratni drift (stuba) El Centro 0,30g Prekoračuje dozvoljene vrednosti
Figure 6c. El Centro 0.30g. Extreme Local Drift (column) exceeds permissible values

Slika 6c se razlikuje po obliku u odnosu na 6a i 6b, za PGA 0,20 i 0,25*g*.

Figure 6c, is different in shape from Figs. 6a and 6b, which are given for PGA 0.20 and 0.25*g*.

3.3 *P-y* krive

P-y kriva (slika 7) se sastoji iz 4 dela, prvi linearni od koordinatnog početka do tačke *k*, drugi eksponencijalni deo od *k* do *m*, i treći deo je druga linearna funkcija od *m* do *u*, a posle tačke *u*, *p-y* kriva je konstantna prava.

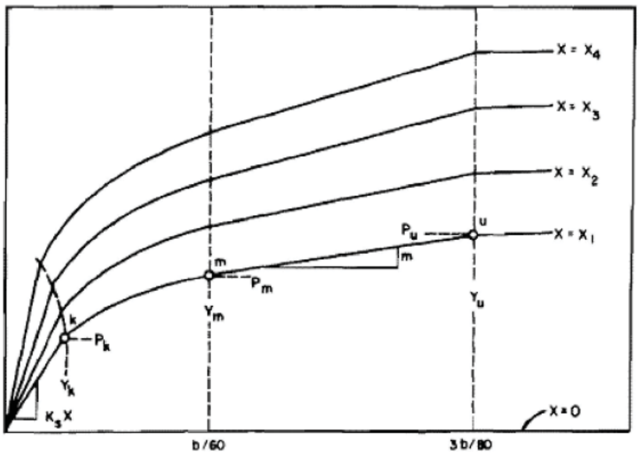
Koeficijenti redukcije (slika 8) A i B zavise od vrste opterećenja, a za dinamičku analizu koriste se krive cikličnog opterećenja. Koeficijenti A i B su dati na

3.3 *P-y* curves

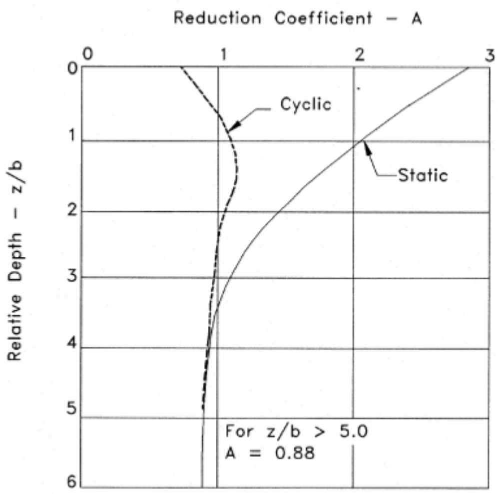
P-y curve (Fig. 7) consists of 4 parts: the first is linear from the coordinate beginning till the point u, the second is exponential part from k to m, the third is the second linear function from m to u, while after the point u, p-y line remains constant.

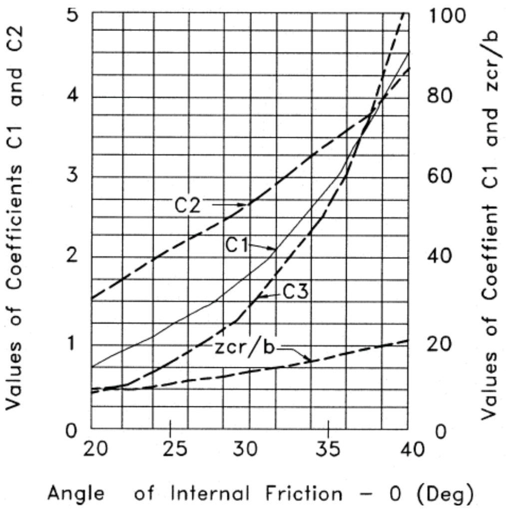
Reduction coefficients A and B (Fig. 8) depend on the type of the load, and for dynamic analysis, the dijagramu u intervalu od 0 do 6 z/b. Posle 5 dijametara šipa koeficijenti A i B imaju konstantnu vrednost. z_{cr} je dubina posle koje se oblik loma klinom menja u oblik loma blokom.

curves of cyclic load are used. The coefficients A and B are given in the graph in the interval 0 to z/b. After 5 pile diameters, coefficients A and B have a constant value. z_{cr} is the depth after which the wedge-like failure transforms into the block-like failure.



Slika 7. Konstrukcija karakterističnih oblika p-y krivih, Ris, Koks, Kup i dr. 1974, citirano prema [4]
Figure 7. Construction of characteristic shapes of p-y curves Reese, Cox, Coop at all. 1974, after [4]





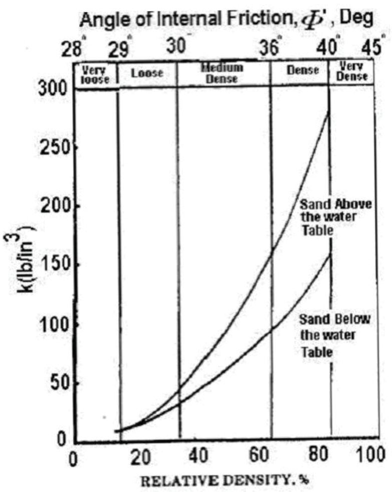
Slika 8. levo Koeficijenti redukcije A i B; Slika desno Faktori za sračunavanje granične otpornosti tla za horizontalno opterećen šip u pesku C_1,C_2,C_3 i z_{cr}, u odnosu na ugao unutrašnjeg trenja [15].

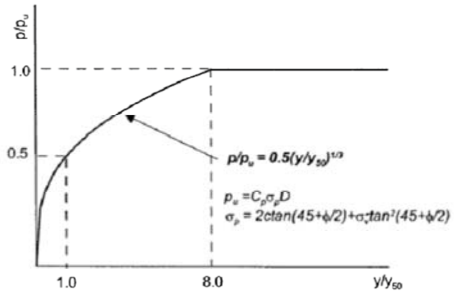
Figure 8. left Reduction coefficient A and B; right Factor for calculation of ultimate soil resistance for horizontal loaded pile in section C_1,C_2,C_3 and z_{cr}, related to the friction angle, after [15].

Tabela 2. Koeficijent horizontalne reakcije tla za pesak. Početni nagib p-y krive, u funkciji relativne krutosti i nivoa podzemne vode, potopljen i suv pesak.

Table 2. Coefficient of horizontal reaction for sand. Initial inclination p-y curve vs. relative density and level below ground water (submerged and dry sand).

Soil modulus k	parametar k za relativni stepen zbijenosti peska		
Realtivna zbijenost: *Relative density:*	Rastresit *Loose*	Srednje zbijen *Medium dense*	Krut *Dense*
Potopljen pesak *Submerged sand*	5.430 kPa/m	16.300 kPa/m	33.900 kPa/m
Suv, iznad NPV *Dry sand, above water level*	6.790 kPa/m	24.430 kPa/m	61.000 kPa/m





Slika 9. Početni modul horizontalne reakcije tla u zavisnosti od zbijenosti i ugla unutrašnjeg trenja, API (American Petroleum Institute), prema [4]

Figure 9. Initial modul of lateral reaction of soil in function of compaction and internal angle of friction, API (American Petroleum Institute), after [4]

Slika 10. Karakteristične krive za pesak sa uticajem kohezivnog dela, Rees i dr. [4]

Slika 10. Caracteristic curve for sand with influences of cohesive part, Rees at all [4]

Marchinson and Oneill, 1984 [15], pojednostavili su gornju proceduru i tri dela prave zamenili sa jednom jednačinom, kao što sledi:

Marchinson and Oneill, 1984 [15] simplified the above process, and replaced the three part *p-y* curve with a single analytical equation, as follows:

$$\frac{p}{p_u} = n \cdot A \cdot \tanh\left(\frac{k_H}{n \cdot A \cdot p_u} y\right) \tag{2}$$

p_u – granična horizontalna otpornost na dubini H od površine tla,

k_H – krutost tla, početni modul horizontalne reakcije (prema tabeli 2, za pesak),

y – horizontalno pomeranje šipa,

n – geometrijski faktor, =1,0 za prizmatične šipove,

A = 0,9 za ciklično opterećenje, (3-0,8(z/b)) ≥ 0,90 za statičko opt., z dubina za koju se p/y kriva određuje.

p-y krive su eksperimentalno izvedene za statičko i ciklično opterećenje, tako da kada koristimo ciklične krive za dinamičko opterećenje, ipak još uvek koristimo relativno mirno opterećenje, gde se mogu uhvatiti samo efekti ponavljanja opterećenja, ali ne i u potpunosti dinamički uticaji.

Where:

p_u – ultimate lateral soil resistance at a depth H below ground surface,

k_H – soil stiffness, initial modulus of lateral reaction (according to table 2, for sand)

y – lateral displacement of pile

n – geometric factor, =1.0 for prismatic piles

A = 0.9 for cyclic load (3-0.8(*z/b*)) ≥ 0.90; for the static load, for the depth z applies the *p-y* curve.

p-y curves are experimentally derived for static and cyclic load, so when the cyclic curves are used for dynamic loading, it is still a relatively calm loading, so only the effects of loading repetition can be assessed, but not the complete dynamic effects.

Tabela 3. p-y kriva: φ= 35°; D=0,60 m; γ= 10 kN/m³; k= 33900 kPa/m.
Table 3. p-y curve: φ= 35°; D=0.60 m; γ= 10 kN/m³; k= 33900 kPa/m.

i	z	k_o	y_a	$p_a=p_k$	$p_b=p_m$	$p_c=p_u$
1	1	33900	8.15E-04	27-64	42.86	52.23
2	2	67800	7.00E-04	47.47	105.34	144.80
3	3	101700	3.53E-04	35.90	178.72	285.95
4	4	135600	5.63E-04	76.29	303.64	485.82
5	5	169500	8.18E-04	138.73	461.23	737.98
6	6	203400	1.12E-03	227.78	651.51	1042.41
7	7	237300	1.47E-03	347.96	874.45	1399.13
8	8	271200	1.86E-03	503.70	1130.07	1808.12
9	9	305100	2.29E-03	699.40	1418.37	2269.39
10	10	339000	2.77E-03	939.43	1739.34	2782.95
11	11	372900	2.88E-03	1074.71	1952.70	3124.33

Tabela 4. p-y kriva za φ= 35°; D=0,60 m; γ= 10 kN/m3; k= 33900 kPa/m
Table 4. p-y curves for φ= 35°; D=0.60 m; γ= 10 kN/m3; k= 33900 kPa/m

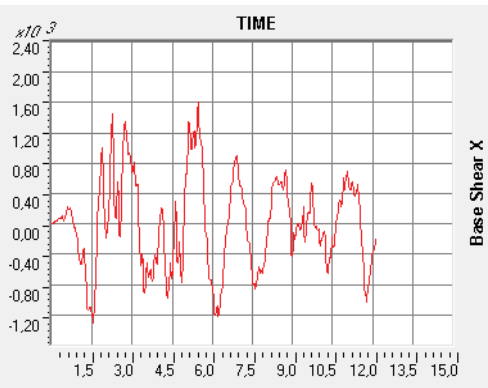
k_o=	33900	k_o=	67800	k_o=	101700	k_o=	135600
z=	**1**	*z*=	**2**	*z*=	**3**	*z*=	**4**
p_c=	52.23	p_c=	144.80	p_c=	285.95	p_c=	485.82
y (m)	*p* (kPa/m)	*y* (m)	*p*(kPa/m)	*y* (m)	*p*(kPa/m)	*y* (m)	*p*(kPa/m)
0.000001	0.00001	0.000001	0.00001	0.000001	0.00001	0.000001	0.00001
0	0	0	0	0	0	0	0
-0.001	-29.82	-0.001	-63.24	-0.001	-97.62	-0.001	-132.19
-0.002	-44.98	-0.002	-106.22	-0.002	-174.86	-0.002	-246.15
-0.003	-50.15	-0.003	-128.35	-0.003	-225.42	-0.003	-332.50
-0.0045	-51.93	-0.0045	-140.58	-0.0045	-263.57	-0.0045	-412.93
-0.005	-52.07	-0.005	-142.14	-0.005	-270.08	-0.005	-429.66
-0.007	-52.22	-0.007	-144.39	-0.007	-282.04	-0.007	-466.69
-0.009	-52.23	-0.009	-144.74	-0.009	-285.00	-0.009	-479.47
-0.01	-52.23	-0.01	-144.78	-0.01	-285.48	-0.01	-482.18
-0.015	-52.23	-0.015	-144.80	-0.015	-285.94	-0.015	-485.60
-0.02	-52.23	-0.02	-144.80	-0.02	-285.95	-0.02	-485.81
-0.0229	-52.23	-0.0229	-144.80	-0.0229	-285.95	-0.0229	-485.82
-0.025	-52.23	-0.025	-144.80	-0.025	-285.95	-0.025	-485.82
-0.03	-52.23	-0.03	-144.80	-0.03	-285.95	-0.03	-485.82
-0.035	-52.23	-0.035	-144.80	-0.035	-285.95	-0.035	-485.82
-0.18	-52.23	-0.18	-144.80	-0.18	-285.95	-0.18	-485.82

U pokušaju da se što bolje obuhvate i dinamički uticaji, link elementi su modelovani preko više linearnih plastičnih elemenata histerezisnog tipa, gde je ciklična p-y kriva poslužila kao svojevrsna anvelopa. Krive su sračunate kombinacijom obe metode, za prvu je korišćen program koji sračunava parametre krive za svaki metar dubine, rezultati su dati u tabeli 3, a uvedene su u SAP2000 kao što sledi u tabeli 4.

In order to include dynamic effects as much as possible, the link elements are modelled using multiple linear plastic elements of hysteretic type, where the cyclic p-y curve is used as kind of an envelope. The curves are calculated by combining both methods, and for the former the software is used which calculates the curve parameters for each meter of depth, the results being provided in table 3. Also, they are introduced in SAP2000 as given in table 4.

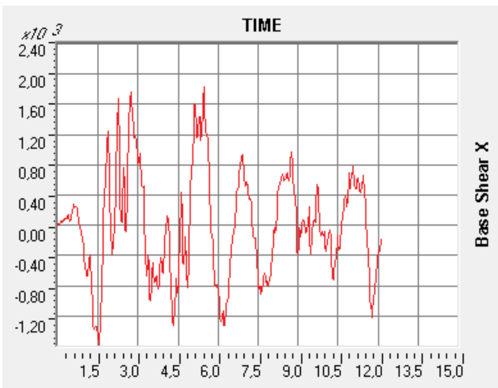
3.4 Sile u osnovi usled razmatranog seizmičkog dejstva

3.4 Base shear force due to the considered seismic action



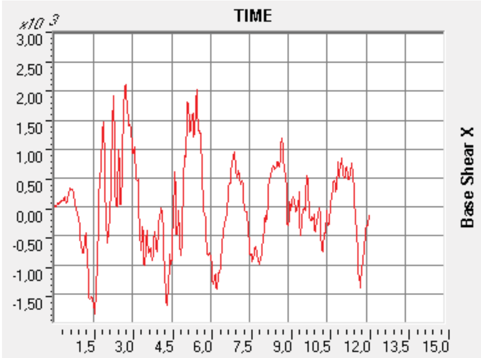
Slika 11a. Sila u osnovi X. ElCentro PGA 0,20 g. BS max 1608 kN (5,460 sec). BS min 1304 kN (1,540 sec).

Figure 11a. Base Shear X. ElCentro PGA 0.20 g. BS max 1608 kN (5.460 sec). BS min 1304 kN (1.540 sec).



Slika 11b. Sila u osnovi X. ElCentro PGA 0,25 g. BS max 1834 kN (5,460 sec). BS min 1582 kN (1,540 sec).

Figure 11b. Base Shear X. ElCentro PGA 0.25 g. BS max 1834 kN (5.460 sec). BS min 1582 kN (1.540 sec).



Slika 11c. Sila u osnovi X. ElCentro PGA 0,30 g. BS max 2114 kN (2,720 sec). BS min 1854 kN (1,540 sec)
Figure11c. Base Shear X. ElCentro PGA 0.30 g. BS max 2114 kN (2.720 sec). BS min 1854 kN (1.540 sec)

Sva tri grafika sila u osnovi su vrlo slična. Međutim primećuje se da je vršna vrednost maksimuma za 0,30g, pomerena sa 5,46 sec na 2,72 sec. Prema istraživanjima [18], kod analize uticaja akcelerograma, nije bitno samo vršno ubrzanje tla PGA, već je neophodno posmatrati i neposrednu okolinu, i uočiti na koji način je maksimum spregnut sa susednim ekstremima. To se ovde primenjuje i kod sile u osnovi.

All three graphs of the BS forces are basically very similar. However it can be observed that the peak value for 0,30g, changes from 5.46 sec to 2.72 sec. According to the research [18], during the accelerogram (i.e. time history) analysis, not only peak ground acceleration (PGA) is important, but it is necessary to observe the immediate surroundings of the peak, and find out in which way the peak is related to the adjacent peaks. It is implemented here for the Base Shear force.

Tabela 5. Zavisnost sile u osnovi i PGA(g). Trenutak max i min.
Table 5. Variation of base shear force with respect to PGA (g). Instances of max and min

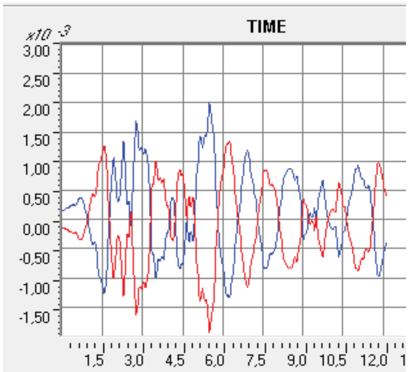
ElCentro PGA (*g*)	Base Shear max (kN)	Base Shear min (kN)	t max (sec)	t min (sec)
0.20	1608	1304	5.460	1.540
0.25	1834	1582	5.460	1.540
0.30	2114	1854	2.720	1.540

3.5 Uticaji u link elementima iz NDA (TH) za dejstvo „El Centro“ i preko rada

Kao rezultat ove analize na sl. 12 prikazani su dijagrami pomeranja i sila spregnutih parova link elemenata 1 i 2 (dubina 1 m), za PGA 0.20*g*. Ovi upareni elementi su spregnuti u istom čvoru šipa.

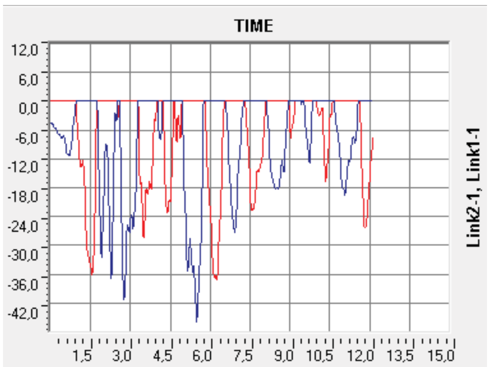
3.5 Effects in the link elements from NDA (TH) action of „El Centro“ and via the work

As a result of this analysis Fig. 12 presents displacement and force diagrams of coupled link elements 1 and 2 (depth 1 m), for PGA 0,20*g*. Coupled link elements are related to the same node.



Slika 12a. Link 1 i 2, nivo -1,0 m. PGA 0,20g El Centro NDA. Pomeranje: max 0,201cm. min 0,194 cm

Figure 12a. Link1 and 2, level -1,0 m. PGA 0,20g El Centro NDA. Displacement: max 0.201cm. Min 0.194 cm 0.201cm. min 0.194 cm.

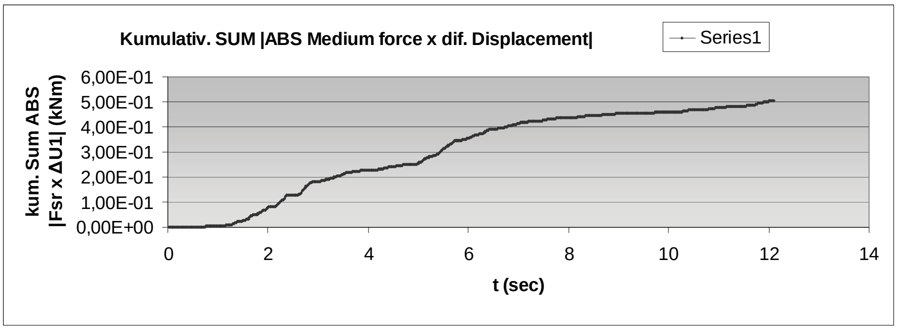


Slika 12b. Link 1 i 2, nivo -1,0 m. PGA 0,20g El Centro NDA. Sila. max 45,88 kN

Figure 12b. Link 1 and 2, level -1.0 m. PGA 0.20g El Centro NDA. Force. max 45.88 kN

Pored nelinearne analize razmatran je apsolutni rad, uparenih link elemenata, kao pozitivna vrednost dejstva sile duž puta. Dijagram kumulativnog Apsolutnog rada, uparenih link elemenata prikazan je na sl. 13. Apsolutni rad je neophodan kako ne bi došlo do poništavanja pozitivnog i negativnog rada tokom sumiranja. Negativni rad je posledica množenja sile u link elementu sa negativnim predznakom, sa pozitivnim predznakom pomeranja istog. Na slici 13 uočljivi su strmiji delovi kumulativne krive, koji predstavljaju mesta na kojima se “gomila” intenzitet akcelerograma koji utiče na rad link elemenata. Tu se zapravo radi o disipaciji seizmičke energije u tlu, na oko 1 m dubine od površine tla.

In addition to the non-linear analysis, the Absolute work of coupled link elements is determined as a positive value of force action along the path. The diagram of cumulative Absolute work of the coupled link elements is presented in Fig. 13. The absolute work is necessary to avoid cancelation of the positive and negative works during addition. The negative work is a consequence of multiplication of a force in the link element with a negative sign, with positive displacement. In Figure 13 steep sections of the cumulative curve are noticeable, which represent the locations where the intensity of the accelerogram which affects the work of link elements is “piling up”. It is actually the case of dissipation of seismic energy in soil, at around 1 m bellow the surface.



Slika 13. Kumulativni Apsolutni rad link elemenata tokom dejstva El Centro. Link 1 i 2, nivo -1,0 m dubina tla. PGA 0,20g ELCentro NDA.

Figure 13. Cumulative Absolute work of link elements under action of El Centro. Link 1 and 2, level 1,0 m depth below ground surface. PGA 0.20g ELCentro NDA.

Nadalje, u tabelama su navedene karakteristične vrednosti pojedinih uticaja u link elementima.

Further, the tables 6 to 9 show the characteristic values of individual parameters of the link elements.

*Tabela 6. Link 1 i 2 Trenutni rad= Sila * Pomeranje F_i x U_{1i} (kNm) El Centro 0,20g.*
*Table 6. Link 1 and 2 “ Instantenous work“ = Force * Displacement F_i x U_{1i} (kNm) El Centro 0.20g.*

	Link 2	Link 1	ElCe 0.20*g*
min	4.98E-02	8.90E-02	
max	-7.04E-08	-4.79E-07	
extr	0.04982	0.089016	
Suma	2.945	4.522	7.467
%	39.44	60.56	

Ovde se kao trenutni rad ne posmatra čist rad, kao dejstvo sile duž puta, već samo trenutna vrednosti sile (F_i), kao reakcije link elementa u trenutku (t_i) pomnožene sa trenutnom (ekstremnom) vrednošću odgovarajućeg pomeranja čvora (U_{1i}) u kome se sustiču link elemenat i konačni elementi šipa, u datom trenutku dejstva akcelerograma. Zato je i napisan proizvod sile i pomeranja, tj. sila x pomeranje. Obe ove veličine su linearne funkcije, u posmatranim vremenskim intervalima, te se u opštem smislu (kao integral) množi trougao sa trapezom (ovde trapez zamenjen pravougaonikom) čija je ordinata srednja vrednost sile. Strogo uzevši trebalo bi, dakle, posmatrati srednju vrednost sile (F_{sr}) i razliku pomeranja (Δ_{U1}), u svakom pojedinačnom intervalu vremena, kao čisti rad. Čisti rad link elemenata dat je u tabeli 7, i to su vrednosti manjeg reda veličine od prethodno navedenog trenutnog rada. S

Here, instantaneous work is not considered as an effective work, as an action of the force along the path, but only as the instantaneous value of the force (F_i), as a reaction of the link element at a time (t_i) multiplied by the instantaneous (extreme) value of the corresponding node displacement (U_{1i}) at which the link element and the finite elements of the pile join together, at a given moment of ground motion action. That is why it is written as a product of the force and displacement, i.e. Force x Displacement. Both parameters are linear functions, at the observed time intervals, so in the general sense (as an integral) a triangle is multiplied by a trapezoid (here a trapezoid is replaced by a rectangle) whose ordinate is a mean force value. Strictly speaking, one should observe the mean force value (F_{sr}) and displacement difference (Δ_{U1}), at each individual interval of time, as effective work. Effective work of elements is provided in table 7, obzirom da su izlazni podaci, za razliku od ulaznih, dati u jednakim vremenskim intervalima od 0,02sec, iz vrednosti čistog rada se direktno može dobiti i snaga po link elementu množenjem sa 1/0.02=50 Hz (J/sec=Watt).

and those are the values of a lower order of magnitude than the previously mentioned instantaneous work. Regarding that the output data, as opposed to the input data, are given at equal time intervals of 0.02sec, from the value of the effective work one can directly calculate the power by a link element, by multiplying with 1/0,02=50 Hz (J/sec=Wat).

Tabela 7. Link 1 i 2. Apsolutni rad, ABS |A = F_{sr} x Δ_{U1}| (kNm); El Centro 0,20g
Table 7. Link 1 i 2. Abs. work, ABS |A = F_{sr} x Δ_{U1}| (kNm); El Centro 0.20g

	Link 2	Link 1	
min	3.96E-03	6.77E-03	
max	0.00E+00	0.00E+00	
extr	0.00396	0.006773	Suma
Suma	0.197484	0.308631	0.506115
	39.02	60.98	%

Ekstremne vrednosti suma Abs rada sila u uparenim link elementima su različite. Za gornji slučaj je to odnos 39/61=0.64. To je posledica uvedenog nelinearnog ponašanja link elemenata i nesimetrije akcelerograma.

The extreme values of sums of Absolute work of the forces in the coupled link elements are different. In this case, it is the ratio 39/61=0.64. It is a consequence of the introduced non-linear behaviour of link elements and asymmetry of accelerogram.

Tabela 8. Link 1 i 2 Pomernje (m); Sila – reakcije (kN); ElCentro 0,20 g
Table 8. Link 1 and 2 Displacement (m); Force – reaction (kN); ElCentro 0.20 g.

Extr	Link 2	Link 1
Displac.(m)	0.00201	0.00194
Force (kN)	37.18	45.88

Ekstremne vrednosti sila i pomeranja u uparenim link elementima su različite. Za gornji slučaj je to odnos za sile 37/46=0,81 što nije zanemarljivo, a za pomeranja 201/194=1,036 što su bliske vrednosti.

The extreme values of forces and displacements in the coupled link elements are different. In this case, the force ratio is 37/46=0.81, which is not negligible, but obtained displacement ratio is 201/194=1.036 which are close values.

Table 9. Promena ekstremnog pomeranja (cm) i sila (kN) u link elementima sa porastom PGA El Centro.
Table 9. Variation of extreme displacement in (cm) and force in (kN) in link elements under PGA El Centro

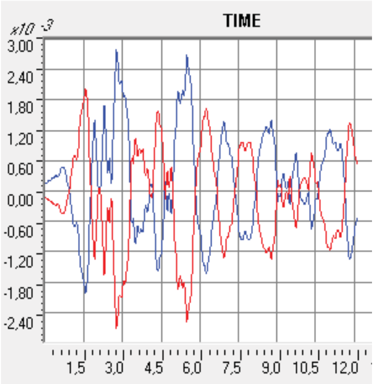
	pomeranja	pomeranja	sile	Sile
PGA (*g*)	Link 1 i 2	Link 3 i 4	Link 1 i 2	Link 3 i 4
0.20	0.201	0.100	45.88	65.26
0.25	0.231	0.114	47.65	72.71
0.30	0.281	0.145	49.71	85.81

Postoji jaka linearna zavisnost između vršnog ubrzanja PGA i pomeranja Link elementa. Približno za Link 1 i 2: U1≈0.95 · PGA(*g*); a za Link 3 i 4: U1≈0,48 · PGA(*g*). Što se tiče sila Link elementa (*y*), linearna zavisnost između PGA ($x=a_h/g$) i istih, određena je preciznije tehnikom najmanjih kvadrata, i za Link 1 i 2: y = 38.3·x + 38.172, (R^2 = 0,9981); a za Link 3 i 4: *y* = 205,5·*x* + 23.218, (R^2 = 0,9754). Kod Link elemenata 1 i 2, usled porasta PGA od 0,20g do 0,30 *g*, pomeranja rastu za oko 40%, dok kod Link 3 i 4, za istu promenu PGA ekstremno pomeranje raste za 45%.

Nadalje su, na slikama 14 do 24, prikazani dijagrami sila i pomeranja Link elemenata za El Centro PGA 0,3g.

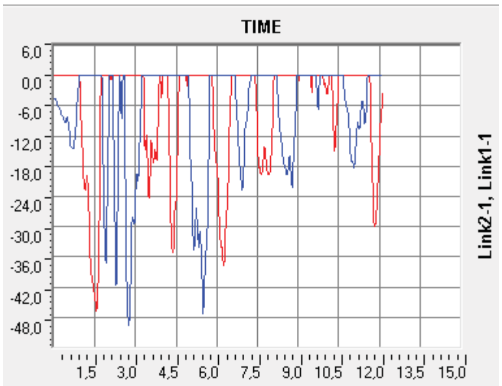
There is a strong linear dependence between the peak ground acceleration PGA and Link element displacement. Approximately, for the Links 1 and 2 it is: U1≈0.95 * PGA (*g*); and for the Links 3 and 4: U1≈0.48*PGA (*g*). As for the forces of the Link element (y), the linear dependence between PGA ($x=a_h/g$) and forces is more accurately determined using the least square technique. For the Links 1 and 2 it is: *y* = 38.3·*x* + 38.172, (R^2 = 0.9981), while for the Links 3 and 4 it is: y = 205.5·x + 23.218, (R^2 = 0.9754). In the case of Link elements 1 and 2, due to the increase of PGA from 0.20*g* to 0.30 *g*, the displacements increase for around 40%, while for the Links 3 and 4, for the same change of PGA the extreme displacement increases for 45%.

Further in the text, Figures 14 to 24 are presenting the force and displacement diagrams of the Link elements for El Centro PGA 0.30 g.



Slika 14a. Link 1 i 2, nivo -1,0 m. PGA 0,30g ElCentro NDA. Pomeranje: max 0,281cm. min 0,272 cm

Figure 14a. Link 1 and 2, level -1.0 m. PGA 0.30g El Centro NDA. Displacement. max 0.281cm. min 0.272 cm

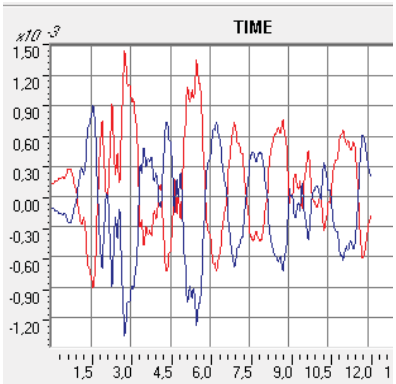


Slika 14b. Link 1 i 2, nivo -1,0 m. PGA 0,30g ElCentro NDA. Sila max 49,71 kN

Figure 14b. Link 1 and 2, level -1.0 m. PGA 0.30g El Centro NDA. Force. max 49.71 kN

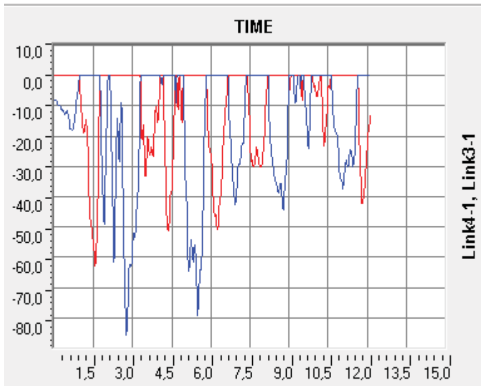
Primetne su praznine u silama reakcija Link elemenata 1 i 2. Na oko 3,9 sec, zatim 4,6sec, a na 9 sec je najveća pauza u reakcijama sila Link elementa 1 i 2. To bi mogao biti znak da je došlo do odvajanja (gap) na kontaktu šipa i tla.

There are noticeable gaps in the reaction forces of Link elements 1 and 2. They are at around 3.9 sec, then at 4.6sec, and at 9 sec there is the largest gap in the force reactions of Link elements 1 and 2. It could be a sign that there is a gap between the pile and the soil.



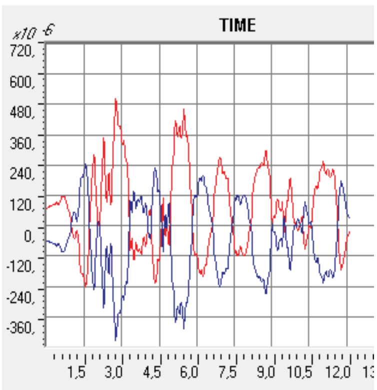
Slika 15a. Link 3 i 4, nivo -2 m. PGA 0,30g El Centro NDA. Pomeranje: max 0,281cm, min 0,272 cm.

Figure 15a. Link 3 and 4, level -2 m. PGA 0.30g EL Centro NDA. Displacement: max 0.281cm, min 0.272 cm.



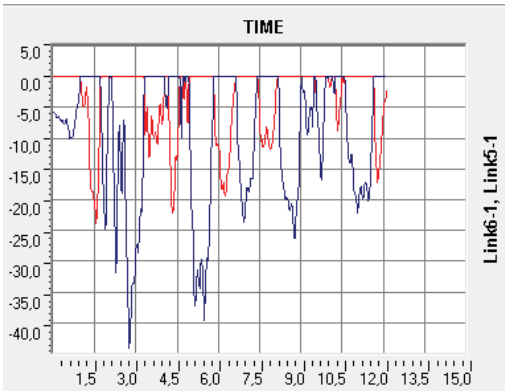
Slika 15b. Link 3 i 4, nivo -2,0 m. PGA 0,30g El Centro. NDA. Sila max 85,81 kN.

Figure 15b. Links 3 and 4, level -2.0 m. PGA 0.30g El Centro. NDA. Force max 85.81 kN



Slika 16a. Link 5 i 6, nivo -3,0 m. PGA 0,30g El Centro NDA. Pomeranje: max 0,0505 cm, min 0,0452 cm.

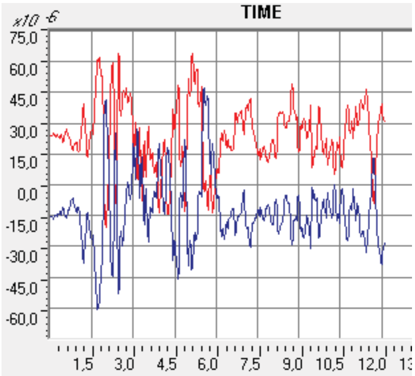
Figure 16a. Link 5 and 6, level -3.0 m. PGA 0.30g El Centro NDA. Displacem.: max 0.0505 cm, min 0.045 cm.



Slika 16b. Link 5 i 6, nivo -3,0 m. PGA 0,30g El Centro. NDA. Sila max 44,10 kN.

Figure 16b. Links 5 and 6, level -3.0 m. PGA 0.30g El Centro. NDA. Force max 44.10 kN

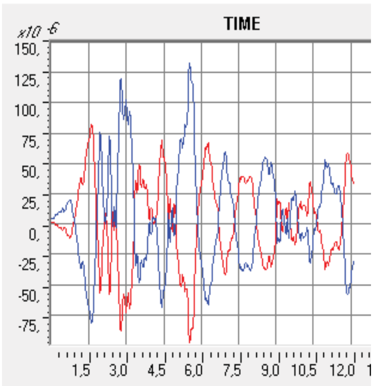
Iako je po vremenu trajanja raspodela sila gotovo ujednačena Link 5 / Link 6 ≈ 60% / 40%, Link elemenat 5 ima veće sile reakcija (skoro duplo veće od L6). Precizniji podaci su prikazani u sumarnoj tabeli Link elemenata.



*Slika 17a. Link 7 i 8, nivo -4,0 m. PGA 0,30g El Centro NDA. Pomeranje: max 6,376*10-5 m, min 6,048*10-5m.*

*Figure 17a. Link 7 and 8, level -4 m. PGA 0.30g El Centro NDA. Displace. max 6.376*10-5m, min 6.048*10-5m.*

Primetna je znatna nesimetrija sila reakcija šipa na dubini 4m od površine terena. Praktično samo link element 7 reaguje i u odnosu na link element 8, to je preko 90% reaktivne sile tokom ukupnog trajanja seizmičkog odgovora na El Centro od 0,30*g*. Pretpostavlja se da je ovakvo ponašanje u sprezi sa prazninom reakcija u link elementima 1 i 2, i asimetrijama intenziteta sila Link elemenata od 3 do 6.



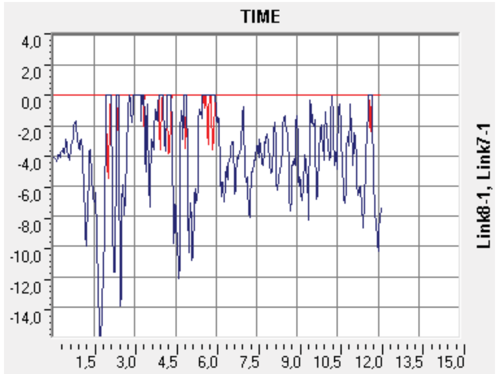
*Slika 18a. Link 9 i 10, nivo -5,0 m. PGA 0,30g El Centro NDA. Pomeranje: max 1,330*10-4m, min. 9,831*10-5m.*

*Figure 18a. Displacement Link 9 and 10, level -5.0 m. PGA 0.30g El Centro NDA. max 1.330*10-4m, min. 9.831*10-5m.*

Raspodela sila reakcija postaje ponovo ujednačena kod Linka 9 i 10 (5 m od nivoa terena). To bi moglo biti mesto uklještenja šipa, kod modela zamenjujuće konzole, (5/0,6=8,3 *D*), s tim da uklještenje može biti i elastično.

Na slici 21b primećuje se prelazni oblik dijagrama sila, u odnosu na više (i niže) nivoe tla od nivoa -7m. Još uvek se uočavaju duži intervali sila reakcija pojedinog link elementa, ali linije nisu više tako glatke kao za gornje slojeve tla, i manje podsećaju na anvelope, a više

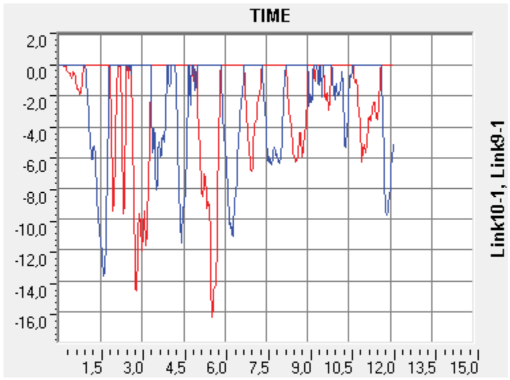
Even though in terms of time, the force distribution is almost uniform: Link 5 / Link 6 ≈ 60% / 40%, the Link element 5 exhibits higher reaction forces (almost twice as that of L6). More accurate data are presented in the summary table of the Link elements.



Slika 17b. Link 7 i 8, nivo -4,0 m. PGA 0,30g El Centro. NDA. Sila max 15,99 kN.

Figure 17b. Links 7 and 8, level -4.0 m. PGA 0.30g El Centro. NDA. Force max 15.99 kN

There is a considerable asymmetry of reaction forces of the pile at a depth of 4m below the surface. Practically, only the link element 7 is reacting, and in relation to the link element 8, it is over 90% of the reactive force during the total duration of the seismic response to El Centro of 0,30*g*. It is assumed that such behaviour is related to the absence of reaction of the link elements 1 and 2, and to force intensity asymmetry of the Link elements 3 to 6.



Slika 18b. Link 9 i 10, nivo -5,0 m. PGA 0,30g El Centro. NDA. Sila max 16,38 kN.

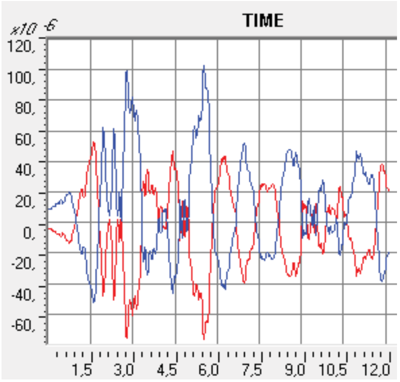
Figure 18b. Links 9 and 10, level -5.0 m. PGA 0.30g El Centro. NDA. Force max 16.38 kN

Distribution of reaction forces becomes even again in the Links 9 and 10 (5 m below the ground level). It could be location where the pile is clamped, in the substitute cantilever model (5/0.6=8.3 *D*), provided that the restraint may be elastic as well.

In Fig. 21 one may notice a transition form of the force diagram with respect to higher (and lower) soil levels then the level -7m. The longer intervals of reaction forces of individual link elements can still be observed, but the lines are not as smooth as for the upper layers.

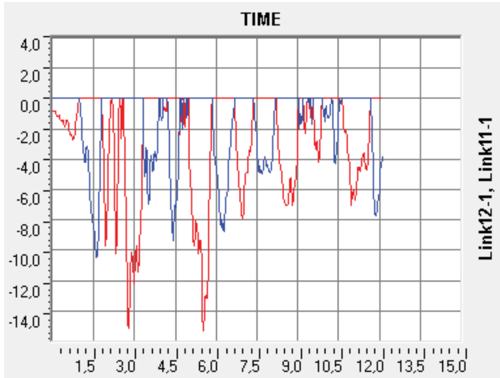
na impulsne strukture (igličastog oblika).

Also, the lines resemble envelopes less, but rather resemble the impulsive structures (having a pointed form).



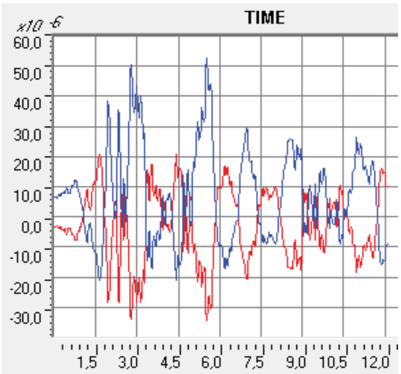
*Slika 19a. Link 11 i 12, nivo -6,0 m. PGA 0,30g El Centro NDA. Pomeranje: max 1,025*10-4 m, min. 7,628*10-5m.*

*Figure 19a. Displacement Link 11 and 12, level -6.0 m. PGA 0.30g ELCentro NDA. max 1.025*10-4m, min. 7.628*10-5m.*



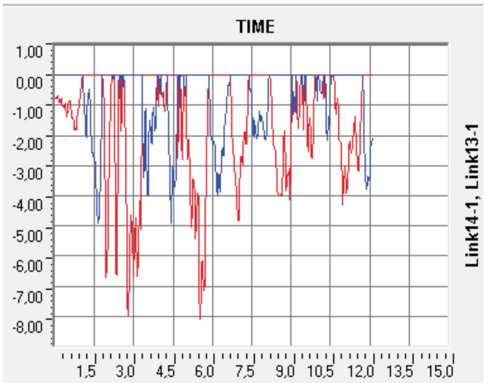
Slika 19b. Link 11 i 12, nivo -6,0 m. PGA 0,30g El Centro. NDA. Sila max 15,32 kN.

Figure 19b. Links 11 and 12, level -6.0 m. PGA 0.30g El Centro. NDA. Force max 15.32 kN



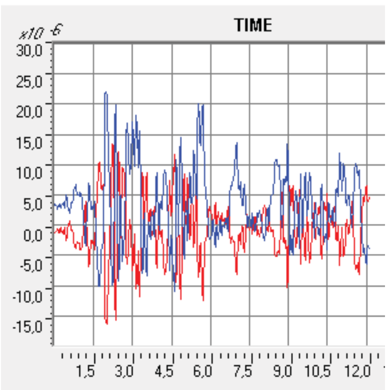
*Slika 20a. Link 13 i 14, nivo -7,0 m. PGA 0,30g El Centro NDA. Pomeranje: max 3,440*10-5 m, min. 5,259*10-5m.*

*Figure 20a. Displacement Link 13 and 14, level -7.0 m. PGA 0.30g El Centro NDA. max 3.440*10-5 m, min. 5.259*10-5m.*



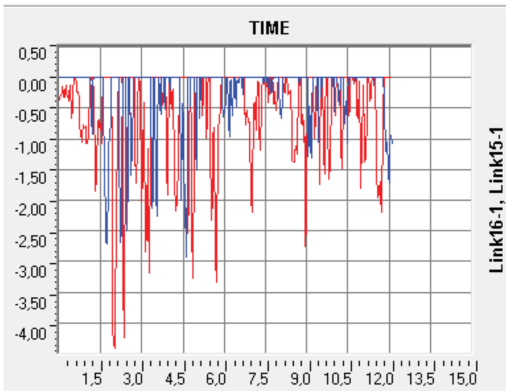
Slika 20b. Link 13 i 14, nivo -7,0 m. PGA 0,30g El Centro. NDA. Sila max 8,086 kN.

Figure 20b. Links 13 and 14, level -7.0 m. PGA 0.30g ELCentro. NDA. Force max 8.086 kN



Slika 21a. Link 15 i 16, nivo -8,0 m. PGA 0,30g El Centro NDA. Pomeranje: max 2,197x10-5 m, min. 1,640x10-5m.

*Figure 21a. Link 15 and 16, level -8.0 m. PGA 0.30g El Centro NDA. Displacement max 2.197*10-5 m, min 1.640*10-5m.*



Slika 21b. Link 15 i 16, nivo -8,0 m. PGA 0,30g El Centro. NDA. Sila max 4,413 kN.

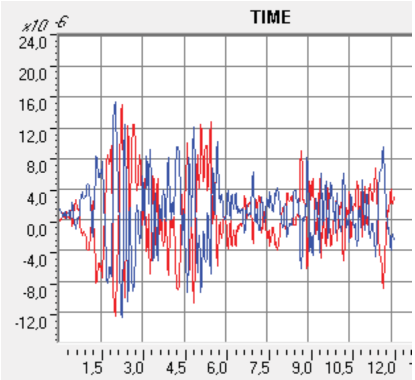
Figure 21b. Links 15 and 16, level -8.0 m. PGA 0.30g El Centro. NDA. Force max 4.413 kN

Dijagram sila reakcija postaje oštar sa naizmenično raspoređenim elementima Link 15 i 16, nivo 8.0 m od površine tla (8/0.6=13.3 *D*).

Dijagram pomeranja Link elemenata 21 i 22 se ne uočava, jer se radi o malim veličinama, ali se mogu jasno očitati numeričke vrednosti, koje su i date u opisu slike 24a. (11/0,6=18,3 *D*).

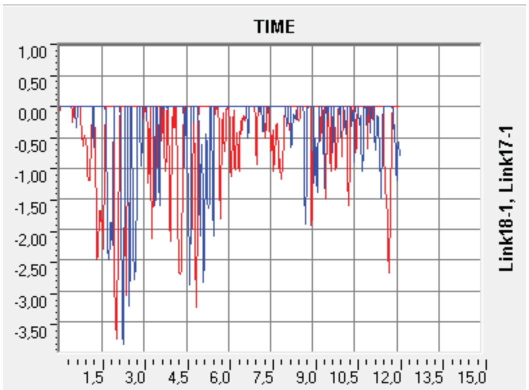
The reaction force diagram becomes pointed, with alternatively arranged elements Links 15 and 16, level 8.0 m below surface (8/0,6=13.3 *D*).

There is no noticeable displacement diagram of Link elements 21 and 22, because those are small values. However, the numerical values may be clearly seen, as they are provided in the description of Figure 24a. (11/0.6=18.3 *D*).



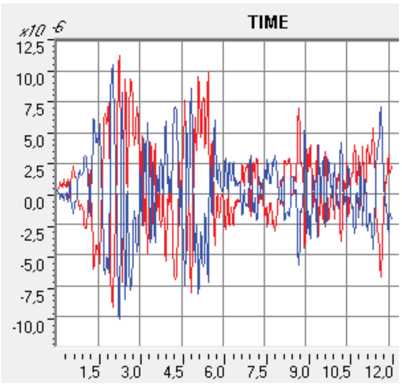
Slika 22a. Link 17 i 18, nivo -9,0 m. 0,30g El Centro. NDA. Pomeranje max 1,536x10-5 m.

Figure 22a. Link 17 and 18, level -9.0 m. 0.30g El Centro. NDA. Displacem. max 1.536x10-5 m



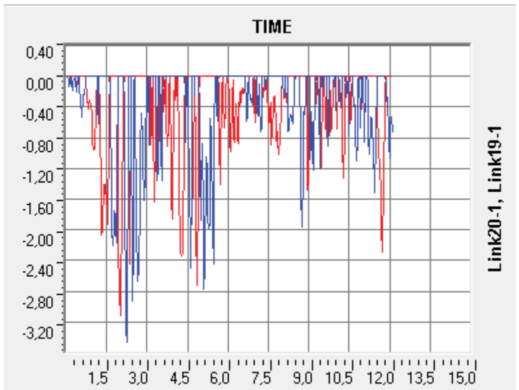
Slika 22b. Link 17 i 18, nivo -9,0 m; 0,30g El Centro. NDA. max Sila 3,881 kN.

Figure 22b. Links 17 and 18, level -9.0 m 0.30g El Centro. NDA. max Force 3.881 kN.



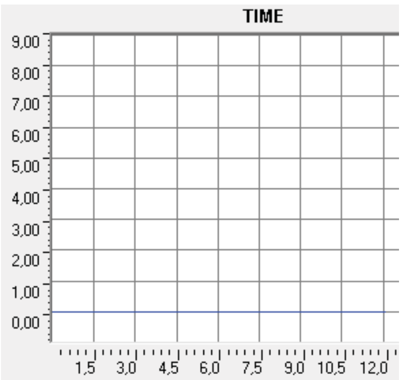
*Slika 23a. Link 19 i 20, nivo -10, m. 0,30g El Centro. NDA. Pomeranje max 1.131*10-5 m.*

*Figure 23a. Link 19 and 20, level -10. m. 0.30g El Centro. NDA. Displace. max 1.131*10-5 m.*



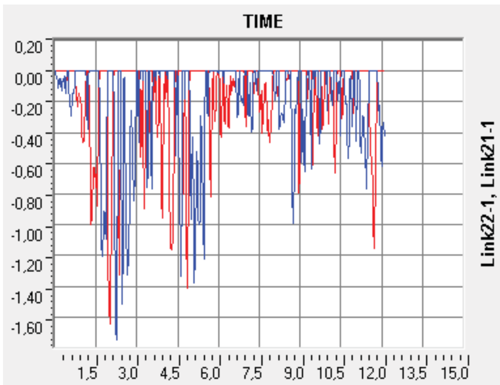
Slika. 23b. Link 19 i 20, nivo -10, m. 0,30g El Centro. NDA. max Sila 3,468 kN.

Figure 23b. Links 19 and 20, level -10.0 m 0.30g El Centro. NDA. max Force 3.468 kN.



*Slika 24a. Link 21 i 22, nivo -11,0 m. 0,30gEl Centro. NDA. Pomeranje max 4,949*10-6 m.*

*Figure 24a. Link 21 and 22, level -11.0 m. 0.30g El Centro. NDA. Displacem. max 4.949*10-6 m.*



Slika. 24b. Link 21 i 22, nivo -11,0 m. 0,30g El Centro. NDA. max Sila 1,747 kN

Figure 24b. Links 21 and 22, level -11.0 m 0.30g El Centro. NDA. max Force 1.747 kN.

Tabela 10. Link elementi po dubini, za levi krajnji šip. Ekstremno pomeranje, ekstremne sile za El Centro 0.30 g
Table 10. Link elements with depth, for left edge pile. Extreme displacement, extr. forces, for El Centro PGA 0.30 g.

Z	Link	U extr	F extr	(Fi*Ui) extr	Σ (Fi*Ui)	(Fsr*ΔUi)extr	Σ ABS(A)	A/ΣA
(m)		(m)	(kN)	(kNm)	(kNm)	(kNm)	(kNm)	%
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

Maksimalna pomeranja link elemenata u prvih tri metara dubine iznose od 2,8 mm do 0,4 mm. Uprkos ovako malim pomeranjima preko 95 % seizmičke energije link elemenata ovog šipa se potroši upravo na toj dubini. To je (3m/0,60m=5*D*) dubina od pet prečnika šipa. To je u skladu sa najvećim uticajima na koeficijente A i B (za granično opterećenje kod pomeranja i sile) kod teorije *p-y* krivih za statičko i ponovljeno opterećenje.

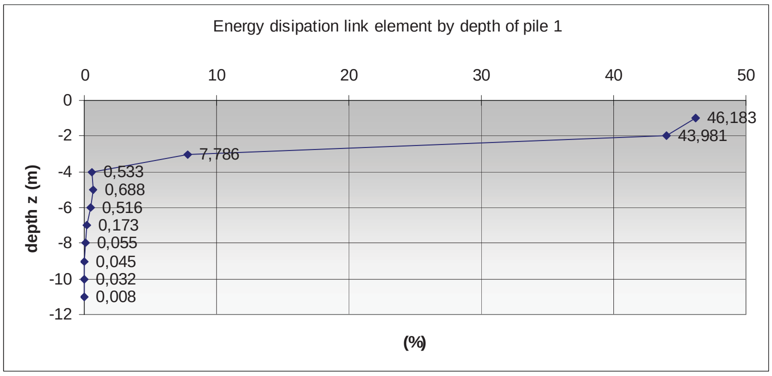
Tabela 11 odnosi se na levi krajnji stojeći šip prečnika D60cm, fundiranog na dubini od 12m, pri čemu su temeljni jastuci debljine 100cm, te je dužina šipa 11m, od donje ivice jastuka do uklještenja u bazi. Krive *p-y* urađene su za svaki metar po dubini šipa, s tim što je uticaj temeljnih jastuka zanemaren. (Napomena: kod izvođenja temelja mašina, neophodno je izvršiti dobro zbijanje tla oko temelja, jer time ovaj uticaj kontakta temelja i tla postaje značajan). Prema tabeli 11, za levi krajnji stojeći šip D60cm, 90% disipacije energije link elemenata tla se obavlja u gornja dva metra dubine (2m/0,60m=3.33), a 99% disipacije energije link elemenata tla, se obavlja u gornjih četiri-pet metara dubine (5m/0,60m=8,33*D*). Ukupan rad link elemenata ovog stojećeg šipa, tokom dejstva zemljotresa El Centro od PGA 0,30 *g*, je relativno mali i iznosi svega 1513 Nm. Iako naizgled mali, ovaj pritisak je dobro raspoređen po dubini tla i veoma značajan za seizmičku otpornost konstrukcije. Slikovito, to bi bio rad koji bi izvršio čovek koji bi čekrkom podigao teret mase 155kg, sa površine zemlje na 1 metar visine.

The maximum displacement of link elements at the first three meters of depth range between 2.8mm and 0.4 mm. In spite of such small displacements, over 95 % of seismic energy of link elements of this pile is dissipated exactly at that depth. It is (3m/0,60m=5*D*) a depth of five diameters of a pile. It is in agreement with the highest effect on coefficients A and B (for limit loads of displacements and forces) of the theory of *p-y* curves for the static and cyclic loads.

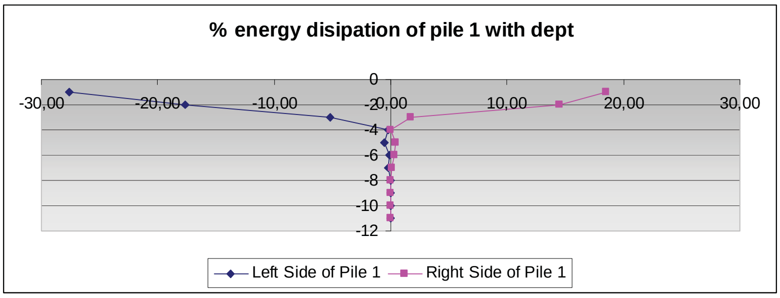
Table 11 refers to the left-end standing pile, with diameter D60cm, founded at a depth of 12m, whereby the foundation cap is 100cm thick, so the pile length is 11m, from the lower side of the cap to the base. The *p-y* curves are calculated for each meter of pile depth, while the influence of the foundation cap is ignored. (Note: when constructing foundations for machinery, it is necessary to compact the soil around the foundations well, because the effect of the foundation and soil contact becomes influential). According to table 11, in case of the left-end standing pile D60cm, 90% of energy dissipation of the link elements of the soil is performed in the top 2 meters of depth (2m/0,60m=3.33). And 99% of energy dissipation of link elements of soil is performed in the top four-five meters of depth (5m/0.60m=8,33*D*). The total work of the link elements of this standing pile, during the action of El Centro earthquake with PGA 0.30 *g*, is relatively small and amounts to mere 1513 Nm. Even though it is seemingly small, this pressure is well distributed along the soil depth, and very important for seismic resistance of the structure. In descriptive terms, it would be the work performed by a man who would lift a 155kg weight using a pulley to a height of 1 meter.

Table 11 Link elementi po dubini za levi krajnji šip. Kumulativni ABS rad uparenih link elemenata (na svaki metar dubine).
Table 11 Link elements with depth for left edge pile. Cumulative ABS work of coupled link elements.

z(m)	Link	cumulative ΣABS Ai (kNm)	%	Σ %
-1	L1+L2	0.6989213980	46.183	46.183
-2	L3+L4	0.6655929120	43.981	90.163
-3	L5+L6	0.1178280390	7.786	97.949
-4	L7+L8	0.0080650920	0.533	98.482
-5	L9+10	0.010409607	0.688	99.170
-6	L11+12	0.007806610	0.516	99.686
-7	L13+14	0.002618564	0.173	99.859
-8	L15+16	0.000839051	0.055	99.914
-9	L17+18	0.000687646	0.045	99.960
-10	L19+20	0.000488583	0.032	99.992
-11	L21+22	0.000123804	0.008	100.000
	Σ	1.513381300		



Slika 25. Procenat (%) disipacije energije za link elemente po dubini za šip 1
Figure 25. Percent (%) energy dissipation of link elements with depth from soil surface for pile 1



Slika 26. Procenat (%) disipacije seizmičke energije, za link elemente, po dubini šipa 1 (za levu i desnu stranu).
Figure 26. Percent (%) seismic energy dissipation, of link elements with depth for pile 1 (left and right sides)

Pretpostavlja se da se seizmički udar dešava u jednoj ravni, ravni 2*D* rama. Tako da se može posmatrati leva i desna strana rama. Ovo nije sasvim tačno, ali može se prihvatiti u postupku postepene analize uticaja u tlu i sistemu tlo-šip.

3.6 Razvoj plastičnih zglobova i prvi svojstveni ton (El Centro sa PGA 0,20; 0,25; 0,30g)

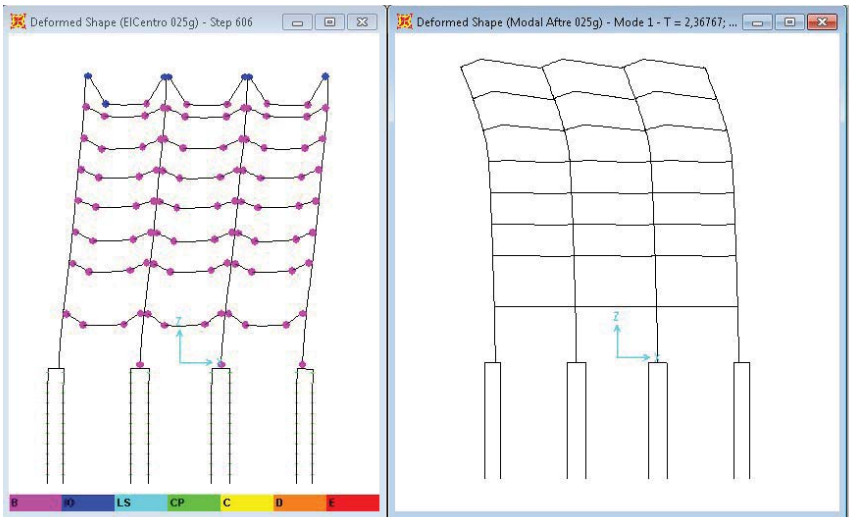
Proučena je i promena stanja plastičnih zglobova - state of plastic hinge (SPH) i usled promene statičkog sistema promenu prvog svojstvenog oblika, 2*D* rama fundiranog na šipovima, sa porastom PGA.

It is assumed that the seismic impact occurs in one plane, the 2*D* frame plane. Thus, the left and the right sides of the frame may be distinguished. This is not entirely true, but it can be accepted in the analysis procedure of the effects in the soil and the soil-pile system.

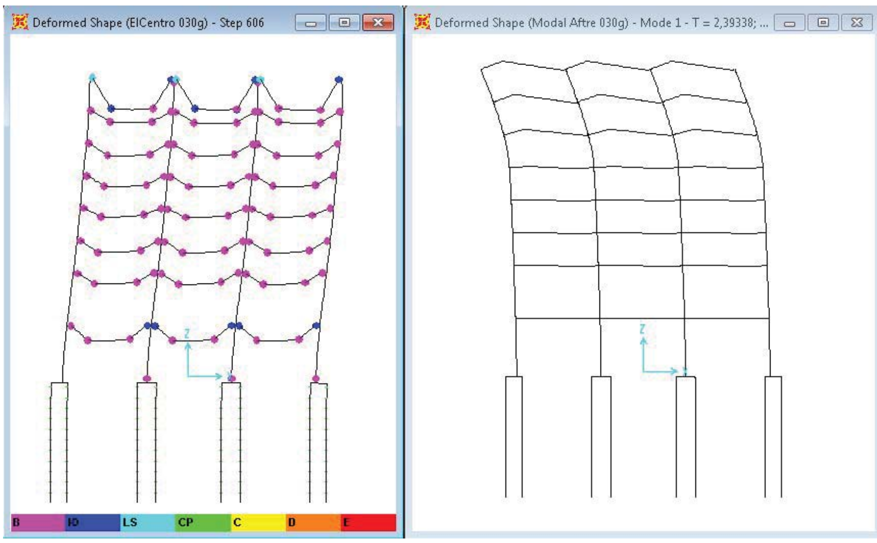
3.6 Development of plastic hinges and the first natural mode (El Centro of PGA 0.20; 0.25; 0.30*g*)

The variation and change of condition of plastic hinges and the first natural mode of a 2*D* frame founded on piles, with the increase of PGA is studied.

Slika 27. El Centor 0,20g stanje na kraju zemljotresa. Levo) plast. zglobovi: 90 Y + 6 IO; desno) oblik 1 vibracija
Figure 27. El Centro 0.20 g. State at the end of an earthqake. Left, Pl Hinge state: 90 Y + 6 IO. Right, Mode 1.



Slika 28. El Centor 0,25g stanje na kraju zemljotresa. Levo) plast. zglobovi: : 92 Y +7 IO; desno) oblik 1 vibracija
Figure 28. El Centro 0.25 g. State at the end of an earthqake. Pl Hinge state: 92 Y +7 IO. Right, Mode 1.



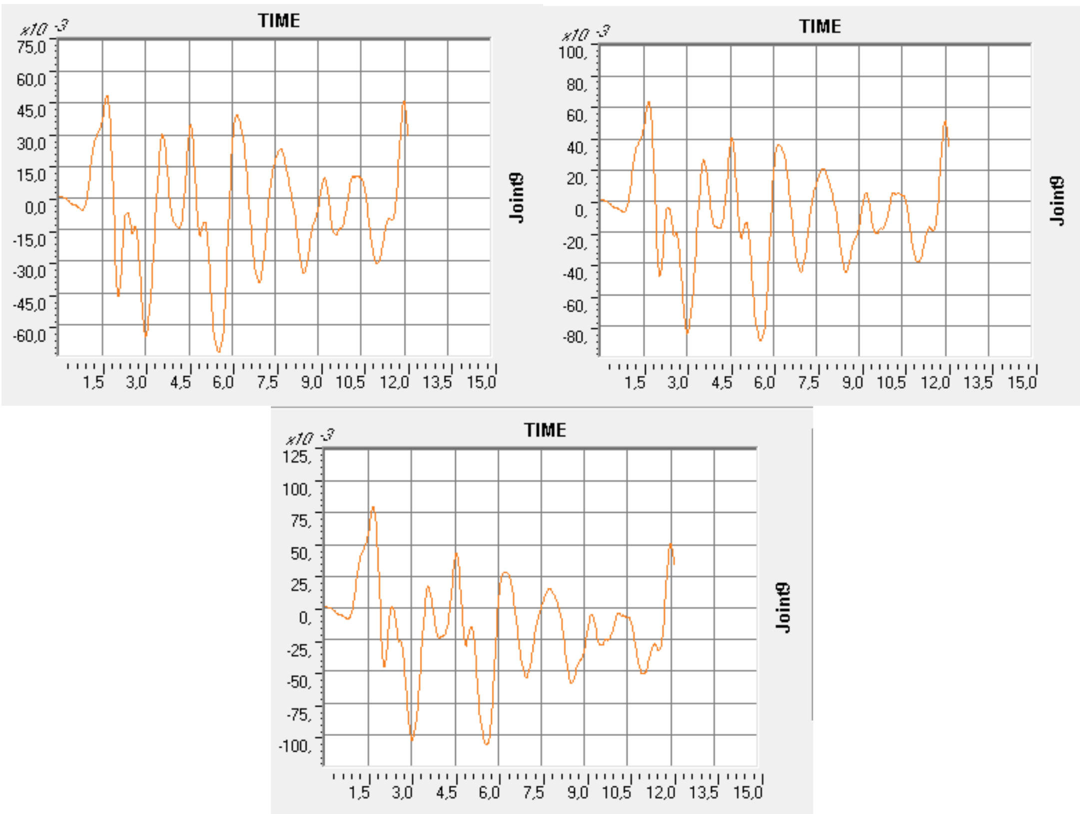
Slika 29. El Centor 0,30g stanje na kraju zemljotresa. Levo) plast. Zglobovi: 86 Y +10 IO+3 LS; desno) oblik 1 vibracija
Figure 29. El Centro 0.30 g. State at the end of an earthqake. Pl Hinge state: 86 Y +10 IO+3 LS. Right, Mode 1.

U tabeli 12 prikazana je promena prvog i drugog svojstvenog tona, nakon dejstva akcelerograma El Centro, od 0,20; 0,25 i 0,30 *g* i odgovarajuće promene statičkog sistema zbog pojave plastičnih zglobova.

Table 12 is presenting variation of the first and the second natural modes, after action of accelerogram El Centro, of 0.20; 0.25 and 0.30 g and the corresponding change of the statical system due to appearance of plastic hinges.

Tabela 12. Prva dva svojstvena perioda posle El Centra različitih PGA. 2D ram.
Table 12. The first two natural periods after El Centro with different PGA. 2D Frame.

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



Slika 30. Pomeranje čvora 9, u vrhu rama, tokom dejstva zemljotresa El Centro, za PGA 0.20; 0.25 i 0.30g. Gore levo za 0,20 g, gore desno 0,25 g i dole 0,30 g

Figure 30. Displacement of node 9, at the top of the frame, during action of earthquake El Centro, for PGA 0.20; 0.25 and 0.30g. Upper left for 0.20 g, upper right 0.25 g and down 0.30 g

Table. 13. Pomeranje čvora u vrhu stuba, za različito PGA, za nelinearnu i linearnu krovnu gredu.
Table. 13. Displacement of the node at the column top, for different PGA, for nonlinear and linear roof girder.

PGA (*g*)	min *U1* Joint 9	max *U1* Joint 9	extr *U1* Joint 9	Lin. Roof Beam	L/NL RB%
0.20	-0.0731	0.0485	0.0731	0.0856	117.10
0.25	-0.0894	0.0636	0.0894	0.1129	126.29
0.30	-0.1078	0.0802	0.1078	0.1447	134.23

Ekstremno pomeranje čvora u vrhu je kod linearizovane krovne grede veće kod PGA 0,20*g* za 17%, kod PGA 0,25*g* za 26%, i kod PGA 0,30*g*, za 34%.

Od interesa je i prikaz uticaja uvođenja plastičnih

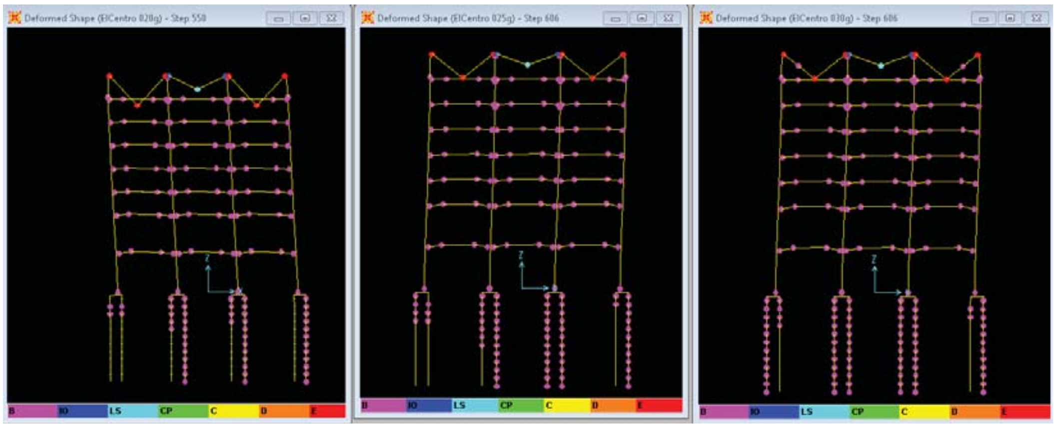
Extreme displacement of node at the top in the case of linearized roof beam is 17% higher for PGA 0,20*g*, 26% for PGA 0,25*g* and 34%for PGA 0,30*g*.

It is also of interest to present the effect of zglobova u sredinama raspona greda, za različito PGA i raspored ostalih plastičnih zglobova, uključivo i one koji se javljaju u šipovima.

Na slici 31, sistem postaje senzitivan na uvođenje plastičnih zglobova u sredinama raspona greda. Krovne grede doživljavaju kolaps, za sva 3 PGA (0.20; 0.25; 0.30*g*). Ostale grede i stubovi se povoljnije ponašaju, međutim, to je na račun šipova, jer se plastični zglobovi sele u šipove, već pri PGA 0.20*g*. Svi ostali plastični zglobovi osim krovnih ulaze u stanje B, tj. početak tečenja *Y(yield)*. Slična pojava se dešava [4] kod srednjeg rama mosta, ali to je logična pojava ispitivanja promene krutosti tla. Naime u [4], varirane su krutosti linearnih opruga tla na šipovima, kada je često uočena pojava seljenja plastičnih zglobova u šipove, tokom smanjenja krutosti tla. Ova pojava ne događa se uvek, a zavisi i od prvog (ponekad i drugog) sopstvenog tona konstrukcije, i spektra odgovora primenjenog akcelerograma. Dubinu pojave plastičnih zglobova, kod srednjeg rama mosta, za nekoliko vrsta tla, proučio je [21]. U [14] navodi se podatak, da se rezultati *p-y* krivih u nekim slučajevima mogu razlikovati i nekoliko puta.

introduction of plastic hinges at the mid-span of beams, for different PGA and the arrangement of other plastic hinges, including those occurring in the piles.

In Figure 31, the system becomes sensitive to introduction of plastic hinges at the mid-spans of the beams. The roof beams collapse, in case of all 3 PGA (0,20; 0,25; 0,30*g*). The other beams and columns behave in a more favourable way; however, this comes at the expanse of the piles, because the plastic hinges migrate to the piles, as early as at PGA 0,20*g*. All other plastic hinges, except the roof ones, acquire the B state, which is the onset of yield *Y(yield)*. A similar phenomenon took place in [4] at the middle frame of a bridge, but it is a logical consequence of testing the variation of soil rigidity. Namely in [4], the stiffness of linear springs of the soil on piles was varied, and the phenomenon of migration of plastic hinges into piles was often observed, during the reduction of soil density. This phenomenon does not occur always, and it depends on the first (and sometimes on the second) natural mode of the structure, and the response spectrum of the applied accelerogram. The depth of the onset of plastic hinges, for the middle frame of a bridge, for several types of soil was studied in [21]. In [14] it was mentioned, that the results of *p-y* curves in some cases can be different several times.



Slika 31. Raspodela plastičnih zglobova za različito PGA pri pojavi plastičnih zglobova u sredini raspona krovnih greda
Figure 31. Plasitic hinge in midle of beam span, for different PGA, and distribution of plastic hinges

Ovde kod zgrada, krutost tla nije varirana. Naime, korišćena je samo jedna vrsta tla (krut pesak, potopljen), uvek ista dužina šipa i uslovi uklještenja u bazi. Korišćena je samo jedna vrsta akcelerograma, a to je El Centro, samo horizontalna komponenta, za PGA 0.20; 0.25 i 0.30*g*. Ova pojava kod zgrada zahteva dalja istraživanja. Između ostalog, precizniju primenu modela datih u [2]. Za određene vrste tla, akcelerograme, vršna ubrzanja i karakteristike šipova, mogu se izvući rezultati, kojima se umesto p-y krivih modeluje sekantna krutost opruga tla [16].

For the buildings here, the soil stiffness is not varied. Namely, only one type of soil is used (dense sand, submerged), always the same length of piles and clamped conditions at the base. Only one type of accelerogram is used: it is El Centro, only the horizontal component, for PGA 0.20; 0.25 and 0,30*g*. This phenomenon related to buildings requires further research. Among other things, a more accurate use of models provided in [2]. For certain types of soils, accelerograms, peak accelerations and pile characteristics, results may be determined, where one could model the secant stiffness of the soil springs instead of using the *p-y* curves [16].

4 ZAKLJUČAK

Tlo ispod temelja često se u seizmičkim analizama apstrahuje, a konstrukcija smatra uklještenom u temelje. Međutim, kod visokih zgrada, mostova većih raspona i

4 CONCLUSIONS

Soil beneath the foundations is often ignored in seismic analyses, and structures are considered as clamped in the foundations. However, tall buildings, nekim inženjerskim konstrukcijama treba u seizmičkoj analizi uključiti i interakciju konstrukcija-temelj-tlo. Uvođenje analize na 3D modelima je veoma kompleksno, pa je u ovom radu pokazano da se zamenom prostorne skeletne konstrukcije zgrade 2D ramom problem znatno pojednostavljuje.

Kod određivanja seizmičkih performansi konstrukcije korišćenjem NSA (pušover analize) bitno je odrediti tačku kada konstrukcija prelazi u mehanizam. Promenu broja i stanja plastičnih zglobova sa porastom pomeranja, u koracima NSA kod određivanja PO krivih u programu SAP2000 v14, nije lako direktno utvrditi. Bolji prikaz PO krivih za zgrade ima program ETABS, mada se i kod programskog paketa SAP2000, mogu dobiti dobri prikazi naročito kod inženjerskih objekata, ali treba voditi računa o alternativnim procedurama. Analiza korišćenjem metode N2 PO se primenjuje za određivanje ciljnog pomeranje konstrukcije, kao tačka preseka seizmičkog zahteva (preko spektra odgovora) i seizmičkog kapaciteta konstrukcije. Prikazan postupak relativno pojednostavljene procedure za određivanje uticaja NSA i NDA dinamičke interakcije tlo-šip-konstrukcija. Radi dobijanja sveobuhvatnije slike performansi konstrukcije osim više različitih modela, sa i bez interakcije, neophodno je primeniti više različitih metoda, oblika opterećenja, više različitih vrsta i skaliranja akcelerograma, zatim procedura i programskih paketa.

Numeričkim istraživanjima uticaja u tlu, utvrđeno je da su sile reakcija link elementa male veličine u odnosu na ukupnu seizmičku silu u osnovi. Iako su intenziteti reakcija link elemenata, tokom dejstva zemljotresa, u odnosu na vrednost sila u osnovi, relativno male veličine, one su veoma značajne za ukupnu seizmičku otpornost objekta. Uočene su određene zakonitosti promene dijagrama sila po dubini link elemenata, ali je iste neophodno tumačiti na dijagramima, što je u ovom radu urađeno.

Analizom seizmičkog ponašanja pri ulaznim podacima (akcelerogrami za PGA 0.20; 0.25 i 0.30*g*) razmatrani sistem je veoma osetljiv na uvođenje plastičnih zglobova u sredinama raspona greda. U krovnim gredama došlo je do loma, za sva 3 PGA (0.20; 0.25; 0.30*g*), ostale grede i stubovi se povoljnije ponašaju jer se plastični zglobovi „sele“ u šipove, već pri PGA 0.20g. Zbog toga je veoma važno pri projektovanju AB ramovskih konstrukcija adekvatnim dimenzionisanjem i detaljima izbeći formiranje plastičnih zglobova u poljima greda.

Može se zaključiti da se uvođenjem SSI postiže pozitivan efekat naročito ako se radi o krućim konstrukcijama zgrada, da bi se izbegle veće deformacije tavanica i potencijalni sudar sa susednim objektima u gušćim urbanim sredinama, što je potvrđeno u [1] i [9].

Naredna istraživanja potrebno je proširiti, na sve šipove rama, i za *p-y* krive za različite relativne zbijenosti peska. Takođe je potrebno uvesti i vertikalnu interakciju sa tlom, koja je u ovom radu zanemarena. Takođe je, kod pušover krivih potrebno utvrditi da li postoji jaka zakonitost oblika vertikalnog opterećenja od gornje konstrukcije, sa oblikom odziva *p-y* krivih po dubini šipova (oblik odziva pomeranja čvorova i drift šipova). Ovaj odziv može se posmatrati i kod TH analize, a da li postoji jasna zakonitost to tek treba utvrditi.

large-span bridges and some engineering structures require inclusion of the structure-foundation-soil interaction. Introduction of the analysis based on 3D models is very complex, so in this paper it is shown that by replacing the spatial frame structure of a building, with a 2D frame, the problem is considerably simplified.

When determining the seismic performance of a structure using the NSA (pushover analysis), it is important to determine the point at which the structure becomes a mechanism. The change in the number and states of plastic hinges resulting from the increase in displacements, (in steps) of PO curves using SAP2000 v14 software cannot be easily determined. ETABS software has better displays of PO curves, although this can be achieved in SAP2000 as well (especially in the case of engineering structures) if alternative procedures are taken into account. A 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 of the seismic capacity of structures. The presented relatively simplified procedure for determining the effects of NSA and dynamic NDA soil-pile-structure interaction is provided 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.

Numerical research of effects in the soil, determined that reaction forces of link elements are small in relation to the total base force. Even though the intensities of link elements reactions during earthquakes are relatively small in comparison to the value of base forces, they are very important for the total seismic resistance of the structure. Certain regularities in the variation of the force diagram, along the depth of the link elements are observed, but they need to be interpreted on the diagrams, which has been done in this paper.

The analysis of the seismic behaviour using the input data (accelerograms with PGA 0.20; 0.25 and 0.30*g*) showed that the considered system is very sensitive at early formation (introduction) of plastic hinges at mid-spans of the beams. There was a failure of the roof beams, for all 3 PGA (0.20; 0.25; 0.30*g*), while the remaining beams and columns behave more favourably, because the plastic hinges migrate to piles, as early as at PGA 0,20*g*. For that reason, it is very important to avoid formation of plastic hinges in the beam spans using adequate design and details of RC frame structures.

It may be concluded that by introduction of SSI a positive effect could be achieved especially if stiff building structures are in question, in order to avoid severe ceiling deformations and potential collision with adjacent structures in densely populated urban environments, which is confirmed in [1] and [9] as well.

The following research must be extended to all the frame piles, and to *p-y* curves for different relative sand densities. It is also necessary to introduce a vertical interaction with the soil which is ignored in this paper. Also, in pushover curves, it is necessary to determine whether there is a strong regularity of the vertical load upon the superstructure, with the form of response of *p-y* curves, along the depth of the piles (shape of the nodal displacement response and the pile drift). This response may be analysed through the TH analysis as well, and it still needs to be determined if there is a clear regularity.

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REZIME

KOMPARATIVNA NELINEARNA ANALIZA INTERAKCIJE ŠIP-TLO AB 2D RAMA

Boris FOLIĆ
Radomir FOLIĆ

U radu je sprovedena komparativna nelinearna statička (NSA) i nelinearna dinamička analiza (NDA) seizmičkog ponašanja rama kao dela skeletne konstrukcije AB zgrade fundirane na šipovima. Da bi se dobila realnija slika ponašanja ramovske konstrukcije u analizu je uključena interakcija konstrukcija – temelj – tlo. Pri tome u proračunski model je uključena i linearno-nelinearna dinamička interakcija šip-tlo korišćenjem link elemenata.

Konstrukcija temelja sastoji se od bušenih šipove prečnika 60cm. Tlo je modelovano sa više (linijskih) plastičnih veznih elemenata, kao p-y krivama, sa obe strane šipa, za potopljen krut pesak, i uz pretpostavku da *p-y* krive (eksperimentalno određene nelinearne krive zavisnosti: pomeranje/pritisak, u tlu po dubini šipa) primaju samo pritisak. Analizom je ukazano na probleme, koje prate izdvajanje 2D ramova kao reprezenta regularne prostorne 3D konstrukcije. Proučen je uticaj pojave i lokacije pojedinih plastičnih zglobova na seizmičke performanse analiziranog konstruktivnog sistema, i analizirana relativna spratna pomeranja (driftovi). Zaključeno je da se analizom 2D rama u interakciji sa temeljom i tlom, mogu dobiti dovoljno tačni rezultati ponašanja i ocene seizmičkih performansi skeletne AB višespratne zgrade. To je značajno jer uvođenje prostorne konstrukcije u ovakve analize je veoma kompleksno i zahtevno.

Ključne reči: Dinamička interakcija tlo-šip, nelinearna dinamička analiza (NDA), nelinearna statička (pušover) analiza (NSA), Interakcija tlo-konstrukcija (SSI), višelinijski plastični link element MPLE, *p-y* krive, raspodela uticaja po dubini tla link elemenata

SUMMARY

COMPARATIVE NONLINEAR ANALYSIS OF A RC 2D FRAME SOIL-PILE INTERACTION

Boris FOLIC
Radomir FOLIC

Comparative non-linear static (NSA) and non-linear dynamic analyses (NDA) of 2D frames (as parts of skeletal 3D structures) of RC buildings founded on piles are presented in this paper. In order to produce a more realistic presentation of behaviour of a frame structure, the analysis involves a structure-foundation-soil interaction. Also, the model involves a linear-non-linear dynamic pile-soil interaction, using link elements. The foundation consists of drilled piles having 60 cm in diameter. The soil is modelled using Multi-linear plastic link elements, as well as with p-y curves, on both sides of the pile, assuming that *p-y* curves transfer only compression (p-y curves are experimentally determined non-linear relationships of displacement/pressure in soil, along the depth of a pile). The analysis shows the problems which accompany extraction of a 2D frame, as a representative of a regular 3D space frame. The impact of onset and location of individual plastic hinges on seismic performances of the analyzed structural system are investigated, and relative floor drifts are analyzed. It was concluded that the analysis of 2D frame, in the interaction with the foundation and soil, may provide sufficiently accurate results of behaviour and assessments of seismic performances of skeletal RC multi-storey building. It is important, because introduction of a spatial structure in such analyses is very complex and challenging.

Key words: Dynamic soil-pile interaction (DSPI), non-linear dynamic analysis (NDA), non-linear static (pushover) analysis (NSA), soil-structure interaction (SSI), multiline plastic link elements (MPLE), *p-y* curves, after-shock, distribution of influence with depth of soil