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Evaluating Soil Liquefaction Susceptibility Using CPT Data: A Case Study from Brest Pokupski

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Abstract

This paper presents a method for assessing the probability of liquefaction based on results from the Cone Penetration Test (CPT). The procedure is based on comparing the cyclic shear stress induced by an earthquake with the soil's resistance to liquefaction. All required steps and corrections are described in detail, and an example is provided for evaluating liquefaction potential in the village of Brest Pokupski following the 2020 earthquake near the town of Petrinja.

Key words: liquefaction, CPT, cone penetration test, cyclic shear stress, CRR, CSR, factor of safety

Korištenje CPT metode za procjenu podložnosti tla na likvefakciju: primjer Bresta Pokupskog

Sažetak

U radu je prikazana metoda procjene vjerojatnosti pojave likvefakcije temeljem rezultata statičkog penetracijskog pokusa (CPT). Postupak se temelji na usporedbi cikličkog posmičnog naprezanja uzrokovanog potresom i otpornosti tla na likvefakciju. Detaljno su opisani svi potrebni koraci i korekcije, a prikazan je i primjer određivanja potencijala likvefakcije u naselju Brest Pokupski nakon potresa koji je 2020. godine pogodio područje Petrinje.

Ključne riječi: likvefakcija, CPT, statički penetracijski pokus, cikličko posmično naprezanje, CRR, CSR, faktor sigurnosti

1 Introduction

Liquefaction is a phenomenon involving the loss of bearing capacity in saturated, loose soils due to cyclic loading, most commonly caused by earthquakes. It results in a significant reduction in the soil's shear strength, which can lead to severe damage to building foundations, roads, and other infrastructure. The assessment of liquefaction potential is based on comparing the seismic demand, expressed as cyclic shear stress, with the soil's resistance to such loading. Various methods are used for this purpose, the most common being the Standard Penetration Test (SPT), Cone Penetration Test (CPT), geophysical shear wave - based techniques, and the Becker Penetration Test (BPT).
As noted by Bačić et al. [1], although laboratory testing methods provide the most accurate assessments, in practice in-situ tests are more commonly employed due to their efficiency, lower cost, and repeatability. Among them, the Cone Penetration Test (CPT) stands out for its ability to provide continuous profiling without disturbing the soil structure and for its strong empirical correlations with liquefaction occurrence. During a CPT, an instrumented cone is pushed into the ground at a constant rate, while measurements are taken of the cone tip resistance q_c, sleeve friction f_s, and pore water pressure u_2. From these measurements, additional parameters are derived, such as the soil behavior type index *SBT* and the normalized clean sand equivalent resistance q_{c1Ncs}, which are then used to calculate the factor of safety and the probability of liquefaction triggering.
For a comprehensive assessment, it is also necessary to determine the soil stratigraphy, bulk unit weight, and fines content, as these parameters significantly influence the soil's resistance to cyclic loading. In this study, all of these parameters are estimated based on correlations with CPT data. The soil layering is identified using an algorithm for vertical profiling [2], the bulk unit weight is estimated using regression models tailored for northern Croatia [3] and the fines content is evaluated using artificial neural networks and analytical expressions developed to correlate CPT measurements with fines content [4].
In the following sections, the application of a CPT-based liquefaction evaluation method is presented using a case study from Brest Pokupski, a village located near the epicenter of the 2020 Petrinja earthquake (Mw = 6.4). The area experienced intense ground shaking, with recorded peak ground acceleration (PGA) values reaching up to 0.77 g, which contributed to widespread ground damage and manifestations of liquefaction. The analysis follows the procedure developed by Boulanger and Idriss [5].

2 Methodology for Evaluating Liquefaction Potential

To evaluate the probability of soil liquefaction under seismic loading conditions, this study employs a method based on Cone Penetration Test (CPT) data [5]. The seismic demand is quantified using the Cyclic Stress Ratio *CSR*, while the soil resistance to liquefaction is expressed as the Cyclic Resistance Ratio *CRR*. The assessment is based on comparing these two parameters, with additional empirical correction factors applied to account for site-specific conditions and earthquake characteristics.

At the beginning of the analysis, CPT measurements are collected: cone tip resistance q_c, sleeve friction f_s and pore water pressure u_2. These are supplemented by seismic input parameters, including the peak ground acceleration *PGA* expressed in units of gravity (a_{max}/g) and the moment magnitude *M* of the earthquake. The groundwater level *GWL* must also be defined to distinguish between saturated and unsaturated soil layers.

The bulk unit weight of soil γ is estimated using empirical correlations [3], allowing the calculation of the total vertical stress σ_v. The pore water pressure u_0 is computed assuming hydrostatic conditions, depending on the depth below the groundwater level *GWL*. Above the groundwater table, the pore water pressure is assumed to be zero; in saturated zones, it increases linearly with depth. The effective vertical stress σ'_v is then obtained by subtracting the in-situ pore water pressure: $\sigma'_v = \sigma_v - u_0$. These stress values enable the calculation of the Cyclic Stress Ratio (*CSR*), which represents the seismic demand in the soil:

$$CSR = 0.65 \frac{\sigma_v}{\sigma_v'} \frac{a_{\max}}{g} r_d \tag{1}$$

where r_d is the depth reduction factor, which varies with depth and earthquake magnitude.

Further, a correction of the cone tip resistance for overburden stress is applied using the expression:

$$q_{c1N} = C_N \cdot \frac{q_c}{P_a} \tag{2}$$

where C_N is the correction factor calculated as a function of the effective vertical stress σ'_v, and P_a is the reference atmospheric pressure. This yields the normalized cone resistance, allowing for comparison between soil layers at different depths.

The vertical soil profile is derived based on the Soil Behavior Type Index *SBT*, which is computed from CPT data. This index enables soil classification and identification of layers susceptible to liquefaction. The profiling procedure follows the methodology presented in [2], which allows for automated vertical stratification using continuous CPT records.

The normalized resistance is then further corrected to a clean sand equivalent to eliminate the influence of fines content, resulting in the clean sand adjusted cone resistance q_{c1Ncs}. In this study, the fines content is estimated using empirical correlations with CPT parameters developed specifically for soils in Croatia [4]. This correction is essential for evaluating liquefaction resistance using empirical charts developed for clean sands or sands with low fines content.

Finally, based on the corrected resistance $q_{c1N,cs}$, the cyclic resistance ratio under standard reference conditions ($CRR_{M=7.5,\ \sigma'v=1\ atm}$) is determined using the empirical correlations proposed in [5]:

$$CRR = \exp\left(\frac{q_{C1Ncs}}{113} + \left(\frac{q_{C1Ncs}}{1000}\right)^2 - \left(\frac{q_{C1Ncs}}{140}\right)^3 + \left(\frac{q_{C1Ncs}}{137}\right)^4 - 2.80\right) \tag{3}$$

The obtained cyclic resistance ratio (CRR) is then corrected for magnitude effects using the Magnitude Scaling Factor (*MSF*) and for effective stress effects using the K_σ factor, according to the following expression:

$$\mathrm{CRR} = \mathrm{CRR}_{M=7{,}5\sigma/v=1atm} \cdot \mathrm{MSF} \cdot \mathrm{K}_\sigma \tag{4}$$

The *MSF* is used to adjust the liquefaction resistance of the soil for earthquakes of different magnitudes. Since the empirical *CRR* correlations are derived for a reference magnitude of M = 7.5, scaling is required for other magnitudes. Larger earthquakes involve a greater number of loading cycles and therefore pose a higher risk of liquefaction, which results in $MSF < 1$ for $M > 7.5$, and $MSF > 1$ for $M < 7.5$. The K_σ factor accounts for the influence of effective vertical stress on the liquefaction resistance. This factor typically ranges between 0.8 and 1.2, and is also determined using empirical correlations.

By comparing the corrected values of *CRR* and *CSR*, the factor of safety *FS* against liquefaction is calculated:

$$FS = \frac{CRR}{CSR} \tag{5}$$

A factor of safety FS less than 1.0 indicates a potential for liquefaction, while values greater than 1.0 suggest that the soil's resistance exceeds the imposed seismic demand. For the purpose of quantitative risk assessment, a probabilistic model proposed by Juang et al. [6] is used, in which the probability of liquefaction occurrence with depth (PL) is calculated as:

$$PL = \frac{1}{\left(1+FS\right)^{3.3}} \tag{6}$$

3 Evaluation of Liquefaction Potential in Brest Pokupski After the 2020 Earthquake

On 29 December 2020, a destructive earthquake with a moment magnitude M_w of 6.4 struck central Croatia. The epicenter was located approximately 3 km southwest of the town of Petrinja, at a depth of about 10 km. The earthquake caused widespread material damage, including severe structural failures and building collapses in Petrinja, Glina, Sisak, and nearby settlements. Tragically, the event resulted in 7 fatalities and more than 20 people injured, while thousands were displaced from their homes.

One of the most severely affected locations was the village of Brest Pokupski, situated approximately 3.2 km southwest of central Petrinja, while the epicenter was just 3.3 km from the village. According to the United States Geological Survey (USGS), the mainshock generated a peak ground acceleration *PGA* of 0.77 g, indicating extremely strong ground shaking in the affected area.

This unusually high PGA value helps explain the extent and severity of structural damage, as well as the occurrence of multiple geotechnical failures in Brest Pokupski, including widespread ground deformations, sand boils, and lateral spreading - all of which are characteristic indicators of soil liquefaction. An example of sand ejecta with visible surface cracks is shown in Figure 1a, while saturated sand deposits, sampled during investigation work campaign, are shown in Figure 1b.

Figure 1. Evidence of soil liquefaction in the village of Brest Pokupski: a) sand ejecta and surface cracks, b) saturated sand deposits

For the purpose of assessing liquefaction potential, extensive geotechnical investigations were carried out, including borehole drilling with continuous coring and Standard Penetration Tests (SPT), Cone Penetration Tests (CPT), laboratory testing of soil samples, and geophysical surveys using seismic refraction and Multichannel Analysis of Surface Waves (MASW). The locations of the CPT soundings are shown in Figure 2.

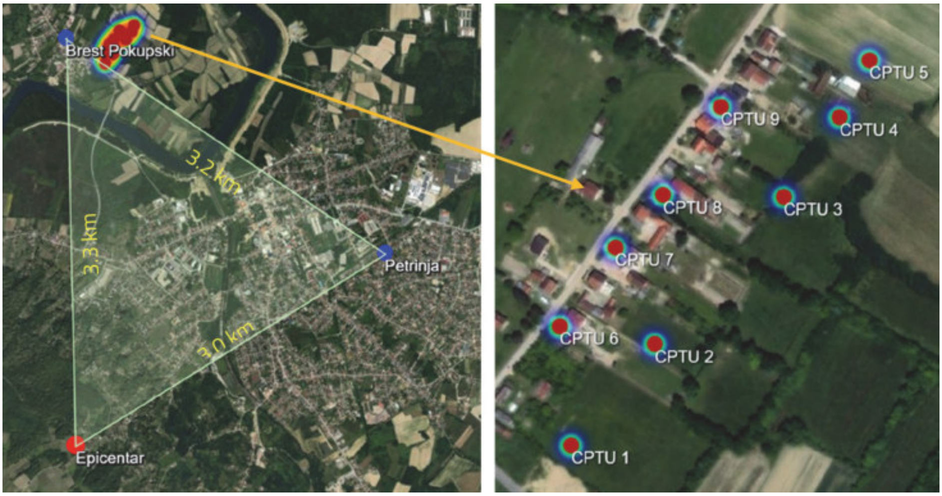

Figure 2. Spatial distribution of CPT investigation points in Brest Pokupski

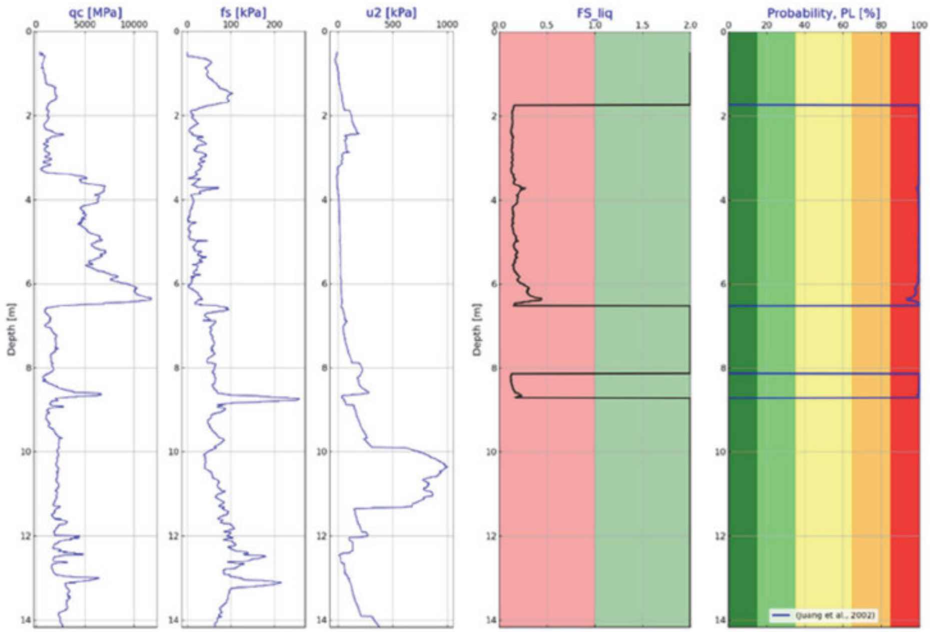

Figure 3. CPT results and liquefaction probability assessment at sounding location CPT 5

As an example, Figure 3 presents the results from one of the CPTs (CPT5), including measured values of cone tip resistance q_c, sleeve friction f_s, and pore water pressure u_2, as well as the computed factor of safety *FS* against liquefaction and the probability of liquefaction *PL* with depth. Depth intervals with an increased risk of liquefaction are highlighted, with the most critical layer identified between 1.8 and 6.5 meters, where a very low safety factor (FS ≈ 0.21) and a high liquefaction probability (PL ≈ 98.95 %) were observed. Figure 4 shows the liquefaction triggering chart with data from Brest Pokupski included (a_{max} = 0.77 g, M = 6.4).

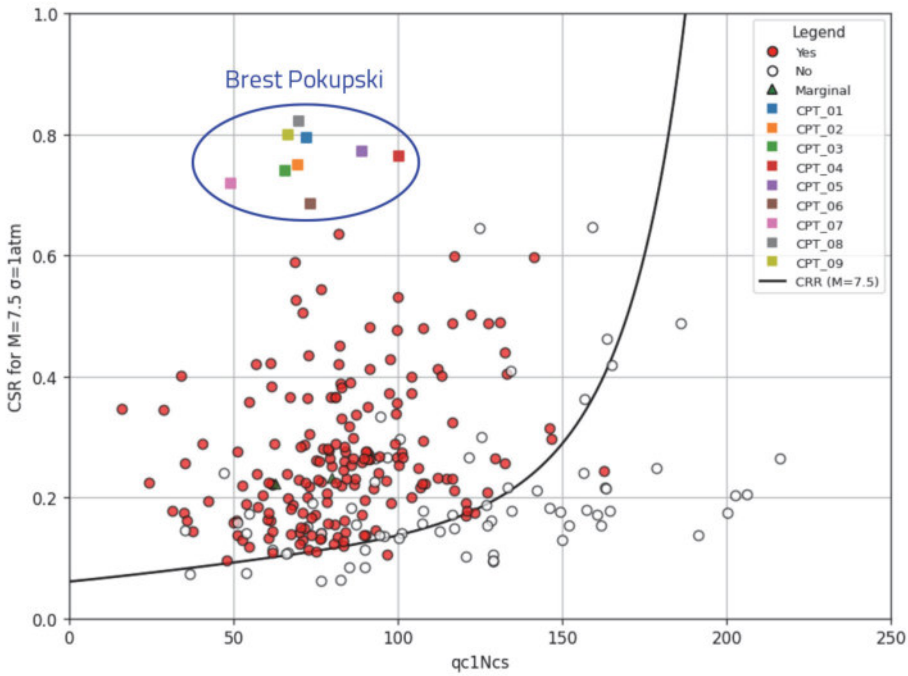

Figure 4. Liquefaction triggering chart with data from Brest Pokupski

The chart in Figure 4 shows the critical soil layers identified from nine CPT profiles, defined as the shallowest saturated layers thicker than 1 meter, in which the factor of safety *FS* remains consistently below 1.0. These layers were selected as the most representative in terms of liquefaction risk. The data points are color-coded, corresponding to different CPT locations, and represent zones with a high potential for liquefaction triggering under seismic loading.

In the background of the chart, the deterministic liquefaction resistance boundary (CRR line) is shown, as defined by Equation (3). This curve was developed based on the extensive empirical database compiled by Boulanger and Idriss [5], which includes more than 210 well-documented CPT case histories from 30 sites worldwide, covering a range of soil types, seismic intensities, and ground conditions. Each case was carefully evaluated to confirm whether liquefaction had occurred or not, and all data were normalized to reference conditions of *M* = 7.5 and σ'_v = 1 atm, ensuring consistency and comparability across sites.

In the *CSR*–q_{c1Ncs} space, points plotted above the *CRR* line correspond to conditions under which liquefaction was observed, while those below the line are associated with non-liquefied cases. The data from Brest Pokupski are positioned entirely above the *CRR* line, and in many cases well beyond the upper boundary of the reference database, occupying a domain that suggests extreme seismic loading. This is primarily attributed to the peak ground acceleration *PGA* of 0.77 g, recorded very close to the epicenter, despite the moderate moment magnitude *M* = 6.4.

The concentration of data in this extreme region confirms both the exceptionally high seismic demand imposed on the site and the pronounced liquefaction susceptibility of the local soils. It also supports the robustness and sensitivity of the applied CPT-based evaluation method in identifying critical conditions. Furthermore, the consistency between observed surface manifestations (e.g., sand boils and lateral spreading) and calculated triggering conditions reinforces the validity of the methodology for use in post-earthquake forensic analysis and forward-looking hazard assessments.

4 Conclusion

This study presents the application of a CPT-based method for evaluating liquefaction potential, following the approach proposed by Boulanger and Idriss (2014), using the example of soils in the village of Brest Pokupski affected by the 2020 Petrinja earthquake. Analysis of nine CPT profiles revealed saturated soil layers thicker than 1 meter with consistently low factors of safety (FS < 1.0), where the probability of liquefaction reached up to 99%.

In the *CSR*–q_{c1Ncs} chart, all data points from Brest Pokupski lie above the empirical *CRR* line, within the region of the reference database corresponding to confirmed liquefaction cases. This positioning is a consequence of the exceptionally high peak ground acceleration (PGA = 0.77 g) recorded near the epicenter, despite the earthquake's moderate magnitude (M = 6.4).

The method has proven to be reliable, effective, and applicable in practice, especially at sites where laboratory data are limited. Its application enables rapid and quantitatively grounded assessment of seismic soil vulnerability, although it remains sensitive to the accuracy of local groundwater depth estimations and to correlations used for fines content evaluation.

Acknowledgment

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IZVJEŠĆA O PROVEDENOM DODATNOM OBRAZOVANJU I USAVRŠAVANJU ZAPOSLENIKA

rujan 2024. - srpanj 2025.

Usavršavanje "Using Project Excellence Baseline (PEB) and Individual Competence Baseline (ICB) for the assessment of the project management excellence" u Cape Town-u

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Sažetak

Cilj dodatnog usavršavanja „Using Project Excellence Baseline (PEB) and Individual Competence Baseline (ICB) for the assessment of the project management excellence" u Cape Town-u je pružanje uvida u PEB i ICB model i način kako koristiti ove modele za ocjenu kvalitete projekata odnosno kvalitete upravljanja projektom. Model PEB često se koristi za ocjenjivanje velikih građevinskih infrastrukturnih projekata, a temelji se na tri stupa: ljudi i svrha, procesi i resursi te rezultati projekta. Svako od temeljnih područja koja se ocjenjuju sadrže niz indikatora, a sam pristup vrednovanju osigurava relativno veliku objektivnosti (detaljni sustavi bodovanja). Model ICB jedan je od svjetski poznatijih modela za procjenu kompetencija voditelja projekta, a trenutno važeći ICB4 model naglasak stavlja na tri domene: kompetencije perspektive (kontekst), prakse (tehničke kompetencije) te kompetencije ljudi (bihevioristične kompetencije). Kompetentan voditelj (građevinskog) projekta je onaj koji sustavno primjenjuje razne kompetencije (iz svake od domena) odnosno onaj koji može prikazati znanje, vještine i sposobnost u ključnim trenutcima u projektu i time aktivno utjecati na postizanje njegovog uspjeha.

Ključne riječi: modeli za ocjenjivanje, upravljanje projektima, procesi, kompetencije, voditelji projekata

Training "Using Project Excellence Baseline (PEB) and Individual Competence Baseline (ICB) for the assessment of the project management excellence" in Cape Town

Abstract

The goal of the additional training "Using Project Excellence Baseline (PEB) and Individual Competence Baseline (ICB) for the assessment of the project management excellence" in Cape Town is to provide insight into the PEB and ICB model and how to use these models to assess the quality of projects and the quality of project management. The PEB model is often used to evaluate large construction infrastructure projects, and is based on three pillars: people and purpose, processes and resources, and project results. Each of the fundamental areas that are evaluated contain a number of indicators, and the evaluation approach itself ensures relatively high objectivity (detailed scoring systems). The ICB model is one of the world's most well-known models for assessing project manager competences, and the currently valid ICB4 model emphasizes three domains: perspective competences (context), practice (technical competences), and people competencies (behavioral competences). A competent manager of a (construction) project is one who systematically applies various competences (from each of the domains), that is, one who can demonstrate knowledge, skills and abilities at key moments in the project and thus actively influence its success.

Key words: assessment models, project management, projects, processes, competencies, project managers

Usavršavanje u SUSTAIN laboratoriju na Rosenstiel School of Marine, Atmospheric, and Earth Science u Miamiu, Floridi

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Sažetak

Stručno usavršavanje provedeno na Rosenstiel School of Marine, Atmospheric, and Earth Science na Sveučilištu u Miamiju omogućilo je neposredan uvid u rad jednog od najnaprednijih laboratorija za simulaciju ekstremnih morskih uvjeta – SUSTAIN laboratorija. Tijekom boravka sudjelovalo se u istraživačkim aktivnostima vezanima uz ponašanje valne energije pri prolasku preko obalnih prepreka u uvjetima visokih brzina vjetra, koje se u ovom laboratoriju mogu generirati do 250 km/h. Uz praktičan rad i razmjenu znanja s lokalnim istraživačkim timom, ostvarena je i prilika za predstavljanje teme doktorskog istraživanja kroz stručno izlaganje. Usavršavanje je pridonijelo razvoju stručnih kompetencija i uspostavi međunarodne znanstvene suradnje, s naglaskom na povezivanje metodoloških pristupa i zajednički rad na budućim istraživačkim publikacijama.

Ključne riječi: valna energija, SUSTAIN laboratorij, ekstremni valni uvjeti, vjetrovni valovi

Training at the SUSTAIN Laboratory, Rosenstiel School of Marine, Atmospheric, and Earth Science, Miami, Florida

Abstract

Professional training conducted at the Rosenstiel School of Marine, Atmospheric, and Earth Science at the University of Miami provided direct insight into the work of one of the most advanced laboratories for simulating extreme ocean conditions – the SUSTAIN laboratory. During the stay, participation in research activities focused on the behavior of wave energy as it interacts with coastal barriers under high wind speeds, which can be simulated in this laboratory up to 250 km/h. In addition to hands-on work and knowledge exchange with the local research team, the training also included the opportunity to present the topic of the doctoral research through a professional seminar. This experience contributed to the development of professional competencies and the establishment of international scientific cooperation, with an emphasis on methodological integration and collaborative work on future research publications.

Key words: wave energy, SUSTAIN laboratory, extreme wave conditions, wind-generated waves

Usavršavanje "9th International Course on Seismic Analysis of Structures using OpenSees: Finite Element-based Framework and Civil Engineering Applications" na Švicarskom saveznom tehnološkom institutu u Lausannei (EPFL)

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Sažetak

Proljetna škola "9th International Course on Seismic Analysis of Structures using OpenSees" održana je od 5. do 7. ožujka 2025. na EPFL-u u Lausannei. Tečaj je fokusiran na korištenje softvera otvorenog koda OpenSees za seizmičku analizu konstrukcija, s naglaskom na nelinearne analize. Polaznici su kroz uvodne lekcije upoznati s osnovama OpenSees-a, njegovom Python implementacijom (OpenSeesPy) te osnovama programiranja u Pythonu i TCL-u. Praktični dio uključivao je modeliranje linearnih i složenijih konstrukcija, statičku i dinamičku analizu te metode koncentrirane i raspodijeljene plastičnosti. Predstavljena su dva grafička sučelja za modeliranje u OpenSees-u: STKO, napredni alat za profesionalnu primjenu, te SAMUEL, jednostavnije sučelje razvijeno za edukaciju i nelinearne analize. Tečaj je uključivao i radionice o naprednim materijalnim modelima, parametrizaciji i geotehničkom modeliranju. Sudjelovanje vodećih stručnjaka iz Švicarske, Italije i Kine dodatno je obogatilo edukaciju, pružajući korisne primjere prilagodbe OpenSees-a specifičnim inženjerskim potrebama.

Ključne riječi: OpenSees, nelinearne analize, programski jezici, modeliranje konstrukcija, grafička sučelja

"9th International Course on Seismic Analysis of Structures using OpenSees: Finite Element-based Framework and Civil Engineering Applications" at Swiss Federal Institute of Technology in Lausanne (EPFL)

Abstract

The Spring School "9th International Course on Seismic Analysis of Structures using OpenSees" was held from March 5 to 7, 2025, at EPFL in Lausanne. The course focused on using the open-source software OpenSees for seismic structural analysis, emphasizing nonlinear analyses. Participants were introduced to the basics of OpenSees, its Python implementation (OpenSeesPy), and programming fundamentals in Python and TCL. The practical part included modeling linear and more complex structures, static and dynamic analyses, and methods of concentrated and distributed plasticity. Two graphical user interfaces for modeling in OpenSees were presented: STKO, an advanced tool for professional use, and SAMUEL, a simpler interface developed for education and nonlinear analyses. The course also covered advanced material models, parameterization, and geotechnical modeling. Participation of leading experts from Switzerland, Italy, and China enriched the training by providing valuable examples of adapting OpenSees to specific engineering needs.

Key words: OpenSees, nonlinear analysis, programming languages, structural modeling, graphical interfaces

Usavršavanje „Railway Engineering: Track and Train Interaction" i „Railway Engineering: Performance over Time" na Tehničkom sveučilištu Delft

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Sažetak

Usavršavanje „Railway Engineering: Track and Train Interaction" i „Railway Engineering: Performance over Time" pod organizacijom Tehničkog sveučilišta u Delftu predstavlja ciklus online radionica posvećen proučavanju najnovijih saznanja u području željezničkog inženjerstva. Radionice nude pregled najnovijih postignuća u analizi interakcije vozila i kolosijeka, dinamičkih sila, buke, vibracija te utjecaja navedenih faktora na trajnost željezničke infrastrukture. Poseban naglasak stavljen je na sistematski pristup optimizaciji i održavanju, uključujući primjenu inovativnih metoda prediktivnog i preventivnog održavanja temeljenog na praćenju realnog stanja sustava. Sudionicima se kroz praktičan rad omogućuje analiza složenih studija slučaja i razvoj optimalnih rješenja održavanja, oslanjajući se na integraciju najvažnijih pokazatelja učinkovitosti sustava. Polaznici stječu stručna znanja i vještine primjenjive u znanstveno-istraživačkom radu i nastavi, s ciljem unapređenja razumijevanja i implementacije inovativnih rješenja u području održavanja i optimizacije željezničkih sustava.

Ključne riječi: željeznička infrastruktura, prediktivno održavanje, dinamičke sile, kontakt tračnica-kotač

Training "Railway Engineering: Track and Train Interaction" and "Railway Engineering: Performance over Time" at Delft University of Technology

Abstract

The training programs "Railway Engineering: Track and Train Interaction" and "Railway Engineering: Performance over Time", organized by the Delft University of Technology, constitute a series of online workshops dedicated to exploring the latest knowledge in the field of railway engineering. The workshops offer an overview of recent advancements in the analysis of vehicle-track interaction, dynamic forces, noise, vibrations, and the impact of these factors on the durability of railway infrastructure. Special emphasis is placed on a systematic approach to optimization and maintenance, including the application of innovative methods for predictive and preventive maintenance based on real-time condition monitoring. Through hands-on work, participants engage in the analysis of complex case studies and the development of optimal maintenance strategies, relying on the integration of key system performance indicators. Participants acquire expert knowledge and skills applicable in scientific research and teaching, with the goal of enhancing the understanding and implementation of innovative solutions in the maintenance and optimization of railway systems.

Key words: railway infrastructure, predictive maintenance, dynamic forces, wheel-rail contact

SAŽECI OBRANJENIH DOKTORSKIH RADOVA

rujan 2023. - srpanj 2024.