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USE OF THE NEW DYNAMIC CONE PENETROMETER FOR THE STUDY OF SOIL LIQUEFACTION ALONG THE KUPA RIVER, PETRINJA AREA (CROATIA)

KORIŠTENJE NOVOG DINAMIČKOG KONUSNOG PENETROMETRA (DCP) U ISTRAŽIVANJU LIKVEFAKCIJE UZ RIJEKU KUPU NA PETRINJSKOM PODRUČJU

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ABSTRACT

During the Petrinja earthquake sequence in December 2020, numerous liquefied sand ejections came to the surface along the Kupa, Sava and Glina rivers in Quaternary alluvial sediments. In October 2022, we performed field investigation in the epicentral area, involving geotechnical and geophysical techniques, at different sites with sand ejecta or lateral spreading along the Kupa river. Geotechnical soundings were carried out with variable energy dynamic cone penetrometer. We used both Light Dynamic Penetrometer (DPL - Panda) and its Super Heavy version (DPSH - Grizzly), to evaluate the soil characteristics and to specify the geometries of the various subsurface sedimentary layers. This paper presents one of the ground site models based on DPL and DPSH tests along with Electrical Resistivity Tomography (ERT) profiles. The resulting models will contribute to a better understanding of mechanical characteristics of soils and their potential to liquefy

Keywords: Liquefaction, Kupa river, Croatia, geotechnical investigations, dynamic penetration, geotechnical model, geophysical investigations.

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SAŽETAK

Tijekom potresne serije koja je započela Petrinjskim potresom u prosincu 2020., došlo je do likvefakcije na mnoštvu lokacija u kvartarnim aluvijalnim sedimentima rijeka Kupe, Save i Gline. U listopadu 2022. provedeni su terenski radovi koji su uključivali geotehnička i geofizička istraživanja na nekoliko lokaliteta s izbojima pijeska ili bočnim širenjem u epicentralnom području uz rijeku Kupu. Geotehnička sondiranja tla provedena su automatiziranim dinamičkim konusnim penetrometrima. Za procjenu karakteristika tla i određivanje prostornog rasporeda formacija u podzemlju korišteni su lagani dinamički penetrometar (DPL - Panda) i njegova robusnija verzija (DPSH - Grizzly). Ovaj rad donosi modele tla izrađene na temelju dinamičkog sondiranja tla (DPL i DPSH) zajedno s profilima električne tomografije (ERT). Dobiveni modeli doprinijet će boljem poznavanju mehaničkih karakteristika slojeva tla podložnih pojavi likvefakcije.

Ključne riječi: likvefakcija, rijeka Kupa, Hrvatska, geotehnička istraživanja, dinamičko sondiranje, geotehnički model, geofizička istraživanja

INTRODUCTION

The M_w 6.4 earthquake on the 29th December 2020 stroke Petrinja and the neighbouring cities of Sisak and Glina. It was preceded by one strong foreshock the previous day (Mw = 5.2) and followed by a series of M_w >4 aftershocks (Baize et al, 2022). This earthquake sequence caused a lot of ground failures including liquefaction features at the surface such as sand blows, lateral spreading and ground subsidence (Pollak and al, 2021).

Herak & Herak (2010) depicted liquefaction features related to the October 1909 earthquake (so-called "Kupa Valley earthquake", Ms ~5.75-6) which occurred along the same fault system. It seems that this historical event led to less extensive liquefaction than the 2020 one when more than 2100 features appeared within a 20 km radius around the epicentre. Most of liquefaction sand ejecta then came to the surface along and in the immediate vicinity of the Kupa, Sava and Glina rivers. They concerned the Quaternary formations, and most probably the Upper Pleistocene/Holocene fluvial sediments (Pollak et al, 2021).

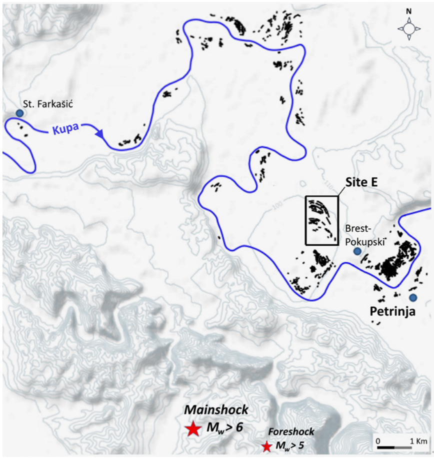

Figure 1. *Map of sand ejecta and fissures along the Kupa river between Stari Farkašić and Petrinja (Baize et al., 2022).*

This liquefaction phenomenon which generally occurs for earthquakes with Mw ≥ 5 (Green & Bommer, 2019) corresponds to a rapid drop in the soil strength with the build-up of water pressure within soils during ground shaking. It mainly occurs in shallow loose water-saturated sands or silty sands in the first fifteen meters of depth (Huang & Yu, 2013; Kavazanjian et al., 2016).

For subsequent modelling studies of the liquefaction conditions in the area, we started a series of cross investigations to specify the geotechnical model in the liquefied zones. In this regard, observations and fieldwork include geological, geotechnical and geophysical investigation that were led in April and October 2022, at different sites along the Kupa river.

This paper focuses on the geotechnical soundings carried out by means of instrumented dynamic cone penetrometers test (DPT) and present the relevance of their use with geophysical methods. A lightweight (DPL) and a super heavy (DPSH) devices were used, denominated respectively P.A.N.D.A. 3 and Grizzly 3. An application is then shown for an investigated paleo-meander of the Kupa river (site E in Figure 1). Indeed, the Kupa valley has been particularly affected and shows numerous sand ejecta (shown in Figure 1). It therefore represents an area of specific interest, both for the investigation of paleo-liquefaction related to older earthquakes and for the characterization of liquefied soils at depth. At the end, the perspectives of studies are drawn.

CONTRIBUTION OF THE INSTRUMENTED DYNAMIC CONE PENETROMETER

In soil investigation, the use of in-situ test and among these, dynamic penetrometers (SPT and DPT), are very common in the world. Dynamic cone penetration test (DCPT) is a widely used, easy handling and low cost technique for geotechnical soil characterization (Goldmann, 1699; Broms & Flodin, 1988). DCPT is also a reliable and interesting technique to study the dynamic behaviour of soils (Tokimatsu, 1988). However, DCPT provides only a single information about the soil: the dynamic cone resistance (q_d). Moreover, unlike static cone penetrometers (CPT) and their very sophisticated tools, DCPT remains associated with old and rudimentary technology.

It was only at the end of the 1980s that the first major improvements of DCPT took place. In France, Gourvès (1991) developed the first instrumented dynamic variable energy penetrometer: the P.A.N.D.A®. Here, driving energy can be adapted according to the soil stiffness variations, since for each blow the energy supplied is directly measured. Dynamic cone resistance (q_d) is obtained by means of the Dutch formula (ISO Standard 22476-2, 2005)).

One of the great advantages of P.A.N.D.A is that it allows fine prospection of soft to high resistance soils, since the measurements obtained (log of sounding) have a high vertical resolution. The large collection of data provided facilitates the implementation of statistical analysis in order to characterize soil spatial variability (Villavicencio et al., 2016; Sastre et al., 2020)

Furthermore, the use of dynamic penetrometers for liquefaction risk assessment is well-known through the SPT method (Seed & Idriss, 1971). In the case of DCPT, some work has been applied to assess the risk of liquefaction (Hashemi & Nikudel, 2016; Hubler & Hanley, 2021; Rollins & Roy, 2021). Concerning P.A.N.D.A®, several works have shown its relevance in liquefaction risk assessment and propose complementary methods to those existing today (Villavicencio et al., 2016; Hubler & Hanley, 2021; Retamales et al., 2021). These methods are mainly based on the q_d value (obtained according to the Dutch formula), its correlations with CPT or SPT and coupled with soil characteristics (fine content, index of density or the permeability).

Nevertheless, the use of the Dutch formula to determine the dynamic cone resistance q_d by means of DPT can be conservative, especially if the drive energy is not controlled. In fact, it has been shown that it is possible to obtain similar values to those measured with CPT in sands if the energy is controlled during DPT driving and if the wave equation is applied (Schnaid et al., 2017; Benz Navarrete and al., 2022).

Recently, a new version of P.A.N.D.A. was designed P.A.N.D.A. 3. It is based on the same functional principle of the device developed by Gourvès (1991) but incorporates new sensors and wave equation analysis (Benz Navarrete and al., 2022). In addition, the same principle was incorporated into the DPSH test to improve it, hereafter namely Grizzly 3 test.

SITE SETTING

All the sandy ejecta along the Kupa (shown in Figure 1) are mainly fine pure sands (Pollak et al, 2021). They were identified in the Holocene alluvial sediments in flat areas around 100 m in elevation (reference system based on HVRS71 geoid model) and located close to the riverbanks or within old meanders. Those materials mainly correspond to surface formations called “ap” and “am” formations on the geological map of Sisak (Pikija, 1987) and belong to the younger terrace (Kekus, 1984). From the ground surface, they correspond to 2 m thick clayey silts overlying different sands and then gravels and coarse sands (Pollack et al, 2021). Their overall thickness is considered generally less than 5 m but may reach up to 9 m upstream of Petrinja. Some Kupa valley’s profiles tend to indicate the bottom of the river to approximately 90 m a.s.l, which is confirmed at the Farkasic hydrometeorological station. As a result, the sedimentary column to investigate in those flat areas is likely less than 15 m thick.

Hydraulically, these sediments are water-saturated by the alluvial aquifer of the Kupa whose level depends directly on that of the river. It’s worth mentioning that during the earthquake sequence in 2020, the Kupa level was rising from 98.7 m to 100.6 m at the Farkasic station between December 27th and 31st, which corresponds to a level of water very close to the ground surface in the liquefied areas.

Several sites were selected according to an approach and choice of investigation methods described in Moiriat et al. (this issue). Each site was subject to an exhaustive geotechnical and geophysical investigation campaign. Due to space limitations in this document, we will focus on one site called E1. It is located perpendicularly on the eastern edge of a paleo-meander (site E on the Figure 1).

APPLICATION AT SITE E1

Site presentation and performed tests

Site E1 presents sands ejecta still observable in 2022. They generally lined up subparallel to the meander’s banks (doted orange line on the Figure 2). The investigation map is presented on the Figure 2, with 2 core-boreholes (E1-B01 and E1-B02); 3 resistivity profiles (E01, E02 and E03); two GPR areal surveys (with 400 and 200 MHz antennas) with several parallel profiles which can be combined into a 3D dataset, one trench of 2 m of depth (T1), and 9 geotechnical soundings (summarized on Table 1) disposed along a profile of 100 m with a 12.5 m between each. The Panda P04 was defective and substituted by the P04bis located in a sand blow (Figure 2).

Table 1. *List of DCPT tests on site E1*

Order	Symbol	DCPT type	Total depth
1	Y01	GRZ	11 m
2	P01	PDA	7 m
3	Y02	GRZ	10 m
4	P02	PDA	10 m
5	Y03	GRZ	14 m
6	P03	PDA	10 m
7	Y04	GRZ	11 m
8	P04bis	PDA	4 m
9	Y05	GRZ	10 m

Nature of soils and water conditions

Based on core samples from the E1-B01 and the trench, the encountered soils from the surface to the bottom (Figure 3) are 3 m of fine soils including two layers of silty clay and one clayey silt (Unit 1); a succession of more or less silty fine sands between around 3 and 6.6 m of depth (Unit 2) with rounded grains in some layers indicating presumably that they have been transported by fluvial flow; several levels of more and more coarse sands, then gravels found from 7.4 m of depth (Unit 3). This lithological succession in 3 units is consistent with the literature descriptions (Pollak et al., 2021) and the observations in the trench too.

In the trench, centimetric and vertical sand dykes intersect the silty layers; however, the observations were very limited by collapsing trench walls just the day after digging. These collapses happened after the rise of water level within the trench. This correlates with the water inflows during drilling of E1-B01 before encountering the water table at 3.5 m depth (Figure 3). Presumably, the water table is locally artesian here.

The sieve analysis from different sand ejecta at site E1 reveal fine and poor graded sands SP-SM in the classification (ASTM, 2010), with an uniformity coefficient (Cu) larger than 4. Their curves are very close to those of the sands drilled between 4 and 5 m depth (Figure 4). According to the grading range of liquefiable soils with a Cu > 3.5 (Iai et al., 1986), almost all the levels in the Unit 2 between 3 and 7 m are prone to liquefaction (Figure 4).

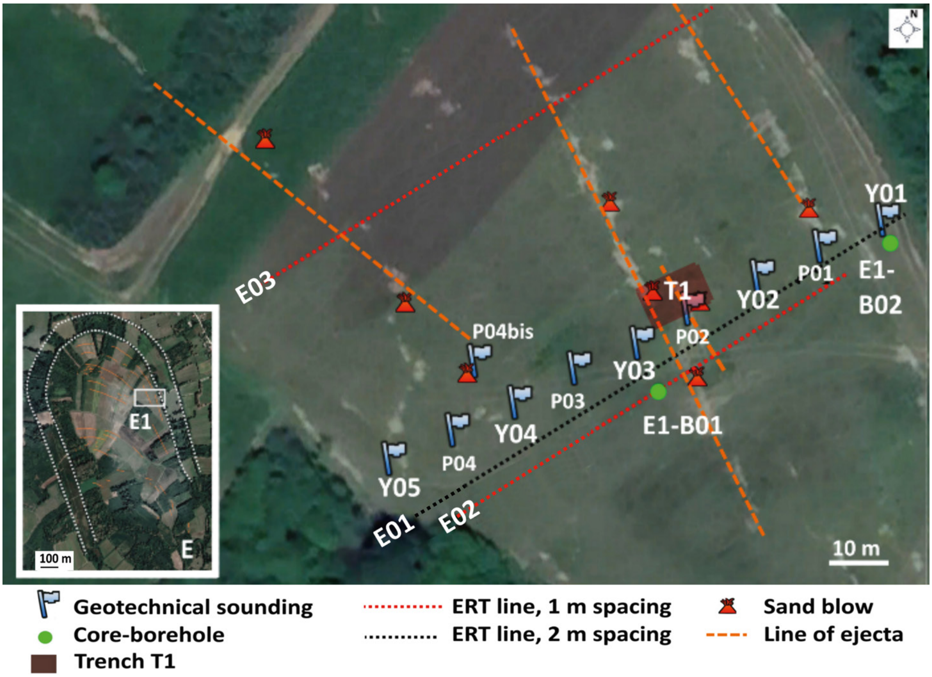

Figure 2. *Location of field investigations at E1 site*

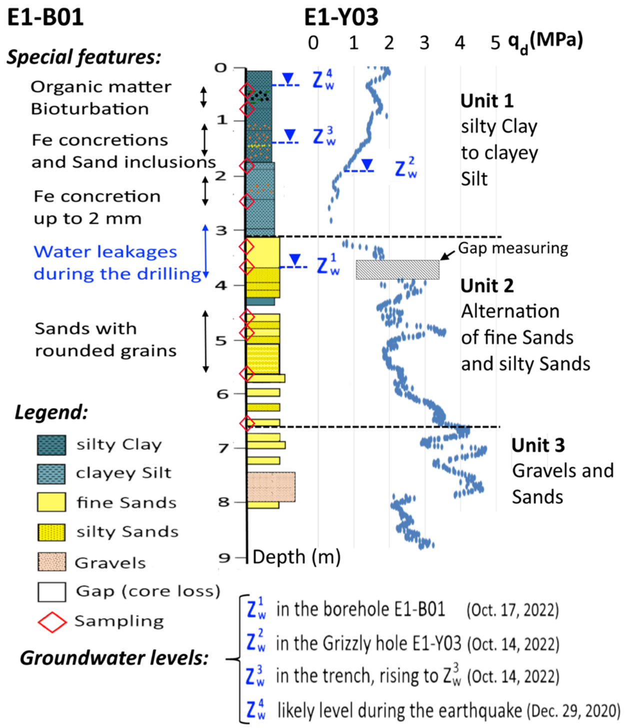

Figure 3: *Stratigraphy in the first 9 meters*

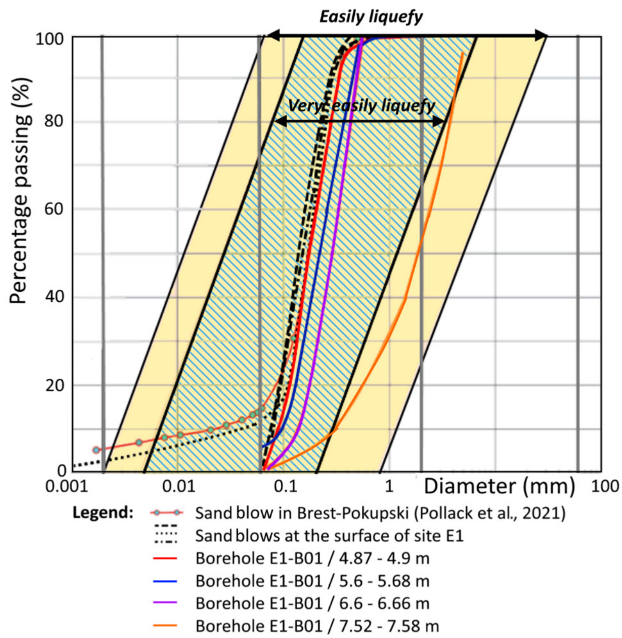

Figure 4. *Site E1 - Cumulative particle size - plots for sands*

Soil dynamic resistance (q_d) of different units and ground model

Figure 5 shows the different DCPT penetration resistance profiles along one ERT profile. All the DCPT present similar trend of variations of q_d with the depth. Unit 1 presents a decrease of soil dynamic resistance (q_d) with values ranging from 3.5 MPa and less than 1 MPa below the topsoil. The limit between the silty layers (Unit 1) and the sands (Unit 2) is always underlined by an increase of q_d and then values steadily continue to increase with the depth and could reach 5 and 8 MPa at the bottom of the Unit 2. In this Unit, some levels of low q_d (≤ 2 MPa) (loose sands) are found between 3 and 6 m of depth. Some low values $1 \leq q_d \leq 3$ MPa are also measured in the Unit 3 between depth ranges (8-9 m and 10-11 m). The layers of gravels have a high q_d exceeding around 5-6 MPa.

Figure 5 also allows highlights the variations of thicknesses of Units 1 and 2 along the profile and constitutes a first ground model perpendicularly to the banks of meander. The limits between each unit and especially the limit between Units 1 and 2 exhibit multi-metric undulations along the cross-section.

Contribution of geophysics and discussion

Figure 6 presents the results of ERT E02 with 1 m spacing. As the resistivity of porous sediment depends on the degree of water-saturation and clay content, the fine soils have lower resistivity values (colder colors) while high values of resistivity indicate coarse-grained material (warmer colors).

The superposition of the geotechnical boreholes and the resistivity profile underlines that the limit between Units 1 and 2 would be around 50 Ωm resistivity. Topographic variations of this limit along the profile are also highlighted between 2 and 6 m of depth (red areas in Figure 6) that may be connected to the evolution of the meander. These undulations observed on 2D geotechnical and geophysical profiles could be of sedimentary origin. However, post-depositional large and local transfer of sands, during 2020 liquefaction event, could be responsible for them, as suggested by the line of sand ejection at the surface (Figure 2) near the DCPT P02. This ejecta line is also clearly visible on the GPR images (not shown). Both ground models built from the regularly spaced penetration tests profiles and those obtained by geophysics seem to be quite coherent. However, to have a total convergence it would be necessary to carry out a data fusion. This work will be done shortly and in line with the work by Xu et al. (2022). We will apply a non-parametric data driven approach. An alternative based on empirical parametric function between geotechnical and geophysical data will be tested. If the latest is preferred, one of the focuses of this work will be to transform the original data to obtain correlatable information. Electrical resistivity is related to water content and porosity which is not directly related to mechanical resistance to penetration.

CONCLUSION AND PERSPECTIVES

This document presents an overview of the soil investigation campaign carried out during the autumn 2022 along the Kupa River, at one of selected sites. It has emphasized:

- the Panda and Grizzly ability to image/detect the different layers recognized by geological surveys and allow to correlate them to define a first geotechnical model,
- that sources of liquefaction are likely the Unit 2,
- that the stratigraphy of the alluvium with 3 units is in accordance with the expectations
- the pertinence of the ground model obtained by both methods.

To come out with the robust model, we will incorporate other parameters not yet analyzed that were provided by Panda and Grizzly (velocity of P-waves, energy measurements).

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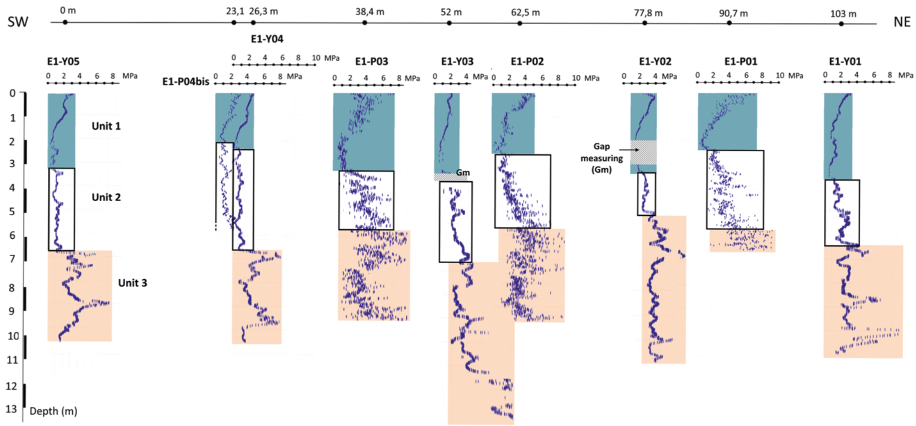

Figure 5: *Geotechnical cross-section of the eastern edge of paleomeander (site E1)*

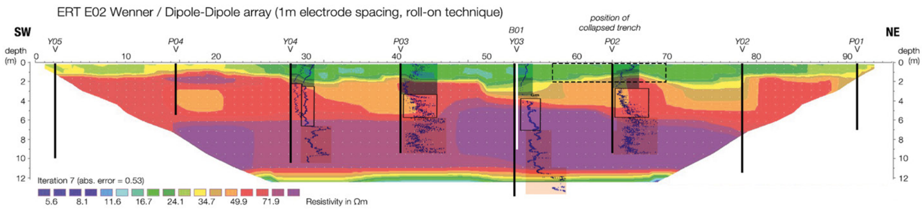

Figure 6: *Electrical Resistivity Tomography (ERT) profile (E02) with 1 meter spacing measured in a dipole-dipole and Wenner array (roll-on technique). Some data from the DCPT tests are included to show the correlation between geotechnical and geophysical data. Black solid lines: reached depth with the DCPT tests; white solid line: reached depth for core-borehole B01; dashed rectangle: extent of the collapsed trench.*

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