Post-liquefaction analysis and shear wave determination using instrumented dcp: application to cephalonia island (Greece) and petrinja area (Croatia)

Denis Moiriat[1], *Miguel Angel* Benz Navarrete[2], *Tuan Anh* Luong[2], *Philippe* Reiffsteck[3], *Bruno* Mravlja[4], *Nikola* Belić[5], *Pauline* Rischette[6], *Nikos* Theodoulidis[7], *Branko* Kordic[5] and *Snježana* Markušić[4]

[1]*Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-Roses, France*
[2]*Sol Solution, Riom, France*
[3]*SRO Laboratory, Gustave Eiffel University, Marne la Vallée, France*
[4]*University of Zagreb, Croatia*
[5] *HGI-CGS Croatian Geological Survey, 10000 Zagreb, Croatia*
[6]*CEA, France*
[7]*ITSAK Thessaloniki, Grèce*
[#]*Corresponding author: denis.moiriat@irsn.fr*

ABSTRACT

This work presents both a summary of its implementation at two post-seismic sites: the island of Cephalonia (Greece), and the Petrinja (Croatia) along the Kupa river. In the first case, the main objective was to characterize the surface formations of the Koutavos plio-quaternary sedimentary basin to propose a 1D model of the surface soil column and assess the influence of the variability of these surface formations on the amplification of seismic motion. The second experimental campaign in Croatia was aimed at identifying the soil layers that had been liquefied following the events of 2020, as well as highlighting the different soil models obtained by geophysics or constructed from instrumented variable-energy DCP. For each investigated site, additional geophysical and geotechnical tests were carried out. The data collected with this new technology were compared with those obtained previously with other geophysical methods (MASW), in order to assess the shear wave velocity obtained in particular.

Keywords: Liquefaction, paleo-liquefaction, soil characterization, dynamic probing, instrumented DCP, Panda test

1. Introduction

Soil liquefaction causes damage to soil and structures, which can result in a significant risk to people, as well as material damage and major economic impacts. Consequently, and due to the difficulty of obtaining representative soil samples in the field, the assessment of liquefaction potential based on in-situ tests becomes an important issue in the study of a seismic site susceptibility. Moreover, seismic events often take place in areas that are difficult to access, especially once the earthquake has occurred. It is therefore necessary to develop new techniques, alternatives to conventional geotechnical tests (CPT, SPT), based on light, quick, sophisticated, and cost-effective equipment.

An alternative is the cone dynamic penetration test, DPT (ISO 22476-2). Although some studies have shown the interest of DPT to shallow soil characterization or liquefaction triggering (Espinace et al., 2013; López Retamales, 2022; Rollins et al., 2018; Schnaid et al., 2007, 2009), most of these devices do not allow continuous soil resistance measurement, control of the drive energy and even less, the measurement the energy really transmitted to the rods. In addition, they are based on empirical methods and remain a rudimentary technique and technology. In most cases, DPTs are heavy and cumbersome, which limits access to the study sites.

In addition, the ongoing need to carry out work on sites after seismic disasters, which are often inaccessible by car, in overseas, archipelagos or remote locations, requires measurement equipment that can meet not only soil characterisation tasks, but also collect data in large numbers of points, accurately and as quickly as possible.

Instrumented variable-energy DCP (Panda® and Grizzly®) are a modern alternative to conventional techniques mentioned above (Gourvès, 1991; Benz Navarrete et al., 2019; Benz Navarrete et al., 2021). They provide easy access to restricted sites with a minimum of equipment and enable very high vertical resolution measurements. Moreover, the latest version of these devices allows an estimation of soil stress-strain properties almost continuously with depth.

In this work we are interested and the characterisation of different sites that have been affected by liquefaction or earthquake events. The main goal is to be able to provide easily, vertical, and spatial mapping of the surface layers and their spatial variability. This is necessary to understand post liquefaction phenomena, but also characterize shallow geological models in terms of ground amplification. In this context, the purpose of this study is to evaluate the capabilities of the variable energy dynamic penetrometer as an alternative means of characterizing soil layers that have undergone liquefaction. We were also interested in their application in a more specific context, that of characterizing the surface layers of the Plio-Quaternary Koutavos basin, on the island of Cephalonia (Greece). The possibility offered by these devices, enabling their in-situ transport, has already been highlighted. In addition, we used the latest version, which allow to obtain, based on wave equation analysis, the shear wave velocity.

2. Site description

Two sites were studied: area of Petrinja along the Kupa river (Croatia) and Koutavos lagoon, Cephalonia Island (Grece). At Petrinja, the objective is twofold: build and propose a surface terrain model to identify the layers of sand that have liquefied, and to couple, compare and correlate geophysical and geotechnical measurements (shear wave velocity) carried out at different locations. In Koutavos Lagoon site, the main goal is to apply the instrumented DCP to characterize the shallow formations of the Koutavos plio-quaternary sedimentary basin in order to evaluate the effects of the variability of these surface formations on the amplification of seismic motion.

2.1. Petrinja area along the Kupa river, Croatia

Croatia is located in a highly seismically active region in the northeast edge of the Adria-Eurasia collision zone (compressional area). The Mw 6.4 Petrinja earthquake on the 29th December 2020 occurred in the junction between the southwest part of the Pannonian basin and the north of the Internal Dinarides. It occurred only nine months after the destructive Zagreb earthquake (Mw = 5.4) and stroke Petrinja and the neighboring cities of Sisak and Glina. It was preceded by one strong foreshock the previous day (Mw = 5.2) and followed by a series of Mw > 4 aftershocks. This earthquake sequence caused a lot of ground failures including liquefaction features such as sand blows, lateral spreading, and ground subsidence. During the Petrinja, numerous liquefied sand ejecta came to the surface along the Kupa, Sava and Glina rivers in Quaternary alluvial sediments (**Fig. 1**).

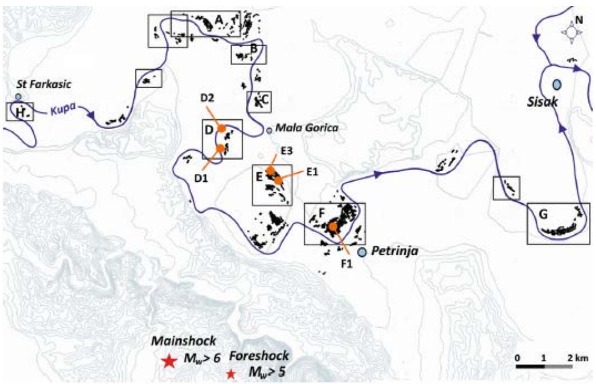

Figure 1. Petrinja (Croatia), Kupa river, studied sites (E1, E3, D1, D2) that have shown liquefaction and sand ejections

In this study, different geophysical and geotechnical campaign were performed; and main attention will be focused on E1, D1 and D2 sites (**Fig. 1**). In the **Fig. 3**, a geological profile as well as cone resistance and shear wave velocity measured on site E1 are presented.

2.2. Koutavos, Cephalonia Island, Greece

The island of Cephalonia, located in western Greece and bordering the active transform fault known as the Cephalonia Transform Fault Zone (CTFZ), is the site of recurrent earthquakes, including the 1953 earthquake of magnitude Mw = 7.2, which uplifted the southern half of the island by up to 1 m in places (Cushing et., 2020). Because of high seismic activity, this region is a major site of interest for the study of strong ground motion and the effects of sites induced by favourable geological configurations such as sedimentary basins.

In this context, Koutavos sedimentary basin near the town of Argostoli has been extensively during the last decade. Filled with Quaternary and detrital sediments from the Neogene, this plio-Quaternary basin has been the subject of several investigation campaigns to characterise the different formations at basin scale. While previous investigations have made it possible to characterise and represent the main formations of the basin using 3D modelling, the shallow profile of the Koutavos basin, around ten metres thick, remains relatively unclear. This superficial layer is composed mainly of Holocene muddy sediments over which debris resulting from the devastating earthquake of 1953 was deposited It is also interbedded with coarser deposits attributed to former paleo-tsunamis, which overall a high degree of vertical and lateral heterogeneity at the scale of the basin. These loose superficial formations are also saturated under the embankments by a superficial aquifer connected to the Ionian Sea and might include liquefiable formations, as evidenced by the ejections that occurred during the earthquakes in early 2014 on the coastal periphery of the Koutavos basin (**Fig. 2**). As these surface formations can exhibit non-linear behaviour and play a role in coupling studies between building foundations and soils, a new geotechnical campaign was carried out to better characterise these shallow layers.

Figure 2. Cephalonia Island, Koutavos Lagoon, test performed at Ionaniet, Krani plain and Koutavos park

A considerable number of tests have been carried out (**Fig. 2**) and **Fig. 4** shows one of the tests carried out in Koutavos as well as the geological, cone resistance and shear wave velocity profiles.

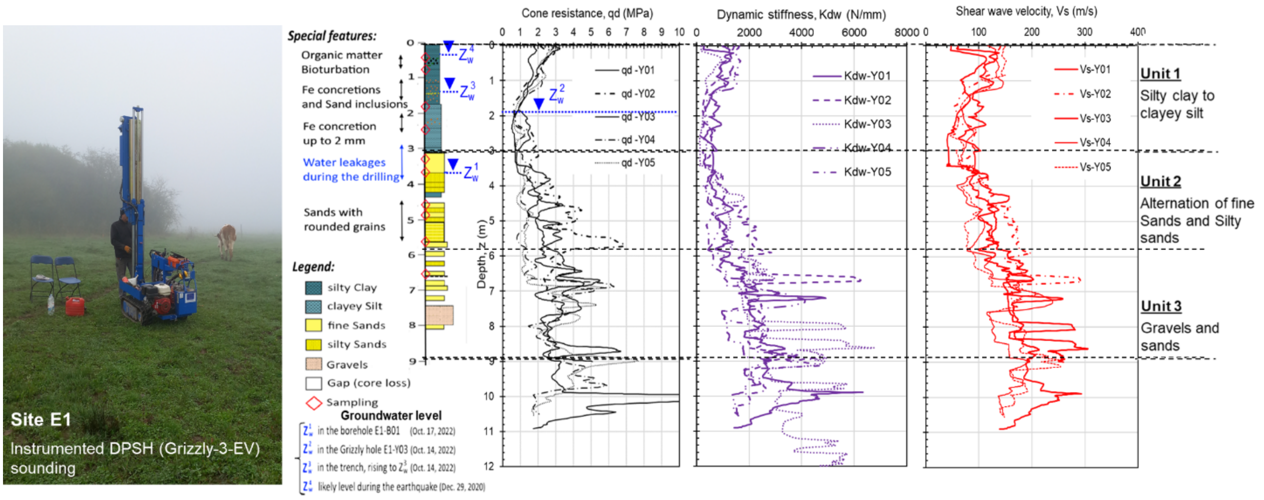

Figure 3. Geotechnical tests carried out at Petrinja (Croatia), site E1. Instrumented automatic DPSH (Grizzly-3-EV), geological profile and typical result : cone resistance, dynamic stifness and shear wave velocity profiles.

3. Instrumented variable energy DCP and shear wave velocity assessment

The French instrumented variable energy DCP, the Panda®, was created in 1989 (Gourvès, 1991). It is the first instrumented DCP to include digital analysis in its test routine. The principle of the Panda is the same as that of dynamic penetrometers. However, for each blow, as recommended by (ISO 22476-2), the drive energy (E) is measured at the anvil using strain gauges. Other sensors simultaneously measure the penetration (e) of the cone into the soil. The HMI (Human Machine Interface), called TDD, receives these measurements and the dynamic cone resistance (*qd*) is automatically computed using the Dutch formula (as recommended by ISO 22476-2). The system consists of 6 main components: manual hammer, instrumented anvil, rods, cones, central acquisition unit (UCA) and dialogue terminal (TDD). The rod used has a diameter of 14 mm and the cone has a cross-section of 4 cm^2. The total weight of the equipment is less than 20 kg, making it easy to transport. The whole IT routine has been fully compiled, making it easier to carry out surveys. However, variable-energy driving is the main originality and major interest of this equipment, as it allows the penetration power (Pp) to be adapted (by accelerating or slowing down the hammer) according to the hardness of the soil.

In addition, the latest version of the device (the Panda 3®, see **Fig. 4**) includes other sensors enabling the wave equation to be applied in the analyze of each recorded blow. Moreover, the same measurement principle, as well as the test procedure (by varying the drive energy automatically and according to the soil hardness) has been applied to the heavier penetrometers (DPSH). while maintaining the machine's simplicity, operability, compactness, and transportability (the Grizzly-3-EV, see **Fig. 3**).

3.1. Panda 3 and Grizzly-3-EV penetrometers

The principle of the test remains the same that of Panda. However, the theoretical basis, instrumentation and measurement analysis are more sophisticated. In this case, the analysis of the measurement is based on the wave equation. To do this, the device is equipped with sensors to record the deformation and acceleration caused by the compression wave generated by the blow. From these recordings and for each blow provided during driving, the descending and ascending waves are automatically decoupled, enabling to compute, by reconstruction methods, the stress, velocity, and displacement at cone/soil interface. For each impact, we can obtain a dynamic cone load curve, named DCLT curve. From these curves and all the data recorded; various parameters are determined, including dynamic and pseudo-static resistance, dynamic stiffness, penetrometric shear modulus, shear wave velocity…
Inspired by the Panda penetrometer, the Grizzly®-3-EV is an instrumented computer-assisted, tracked DPSH penetrometer for dynamic variable energy test. Here, the measurement principle is the same of Panda 3 and the instrumentation is that incorporated in the SPT or Becker penetrometer; the main difference is that here everything is automated, even the energy variation. The main characteristics of these devices, compared with those of other penetrometers used in other studies, are summarised in **Table 1**.
In the context of our study, that of post-liquefaction and the characterisation of surface formations induced by seismic events, these tools represent a major interest, facilitating access to the sites, the performance and interpretation of the tests, the precision and high vertical resolution of the measurements as well as the ability to measure shear waves velocity at each blow. A typical result obtained with these devices (i.e.: profiles of cone resistance, dynamic stiffness) is presented in the **Fig. 3** and **4**. Shear wave velocity profiles are presented below.

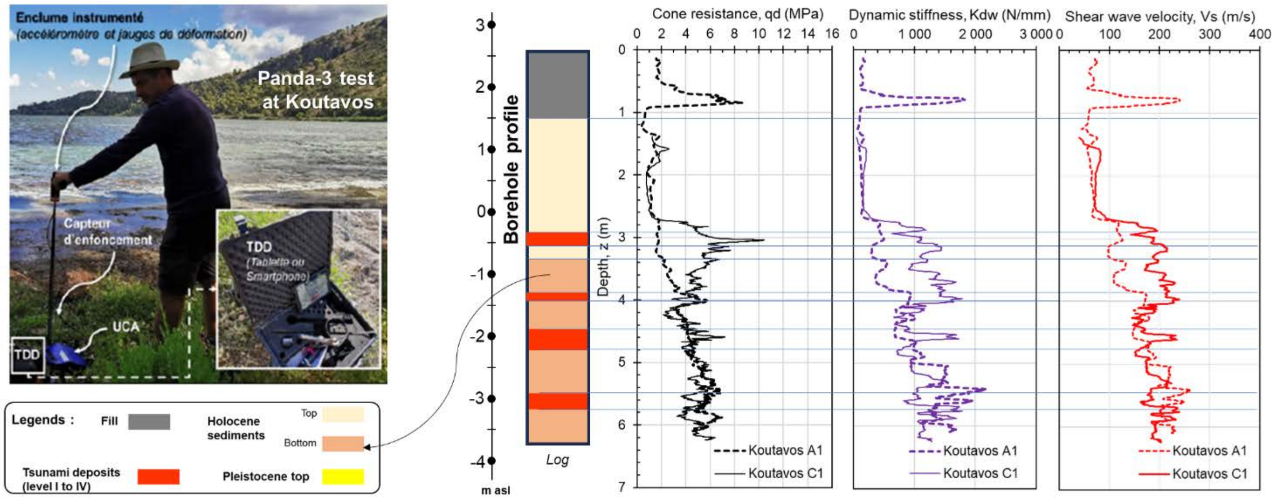

Figure 4. Geotechnical tests carried out at Koutavos lagoon (Cephalonia Island, Greece), A1 and C1 location– instrumented DCP test (Panda 3), geological profile, cone resistance, dynamic stiffness and shear wave velocity profiles.

Table 1. Main features of dynamic penetrometers

	SPT	Chinese DPT	Grizzly-3-EV	Panda & Panda 3
M (kg)	63,5	120	63,5	1,76
H (m)	0,76	1	0,16-0,76	variable
Vi (m/s)	3,9	4,4	1,8-3.9	2 to 12
Dr (mm)	50	60	32	14
Dt (mm)	50,5	74	50,5	22,5
Dt/Dr	1,0	1,2	1,6	1,6
At (cm2)	20	43	20	4
Cone angle	90°	60°	90°	90°
E_{theo} (J)	473	1177	100-473	3-126
Pp (kJ/m^2)	236	274	49-236	7,5-315
Instrumentation	optional	optional	included	included
Energy meas.	(option)	(option)	included	Included
Weight (kg)	> 1000	> 1000	~850	~23,5
Standard	ASTM, ISO	Chinese standard	ISO 22476-2	French Standard

3.2. Shear wave velocity assessment from instrumented DCP

In instrumented DCP, force, acceleration and displacement measurements are recorded for each blow. Benz (2009) and Benz et al. (2022) present the basic method to process these measurements. Teyssier et al. (2020) proposes a field correlation between shear wave velocity obtained from instrumented DCP and MASW measurements. In their work, the measurements performed during the penetrometer driving were analyzed by means of mechanical impedance method.

However, in this impedance method, which is time domain dependent, any lag or shift in the measurement can influence the results, particularly when deeper tests are analyzed. Consequently, we have chosen another approach presented in (Tran et al. 2016). This is a frequency-domain analysis based on wave decomposition. In this way, dynamic stiffness, $k_d(\omega)$, is obtained by mean of FRF (frequency response function) analysis of dynamic signals, as explained by (Tran et al. 2016). Dynamic rigidity $k_d(\omega)$ is calculated by considering the strength $F(\omega)$ as the input load and the penetration $S(\omega)$ as the output response.

$$k_d(\omega) = \frac{2\pi\omega}{\left[\frac{V(\omega)}{F(\omega)}\right]} \quad (1)$$

ω, $V(\omega)$ and $F(\omega)$ are the frequency, velocity and force spectrum respectively. If we consider a homogeneous elastic penetrometer of known geometry, when the frequency approaches to 0~Hz, the dynamic stiffness $k_d(\omega)$ approaches the static stiffness (k_s). However, in practice, the frequency of the dynamic impulse cannot be 0 Hz and a coefficient α representing the ratio between $k_d(\omega)$ and k_s, is introduced, where $1.5 < \alpha < 3.0$. Moreover, the cone soil-base model can be represented by the approach proposed by (Holeyman, 1984; El Naggar and Novak, 1994). In this way, soil stiffness can be explained as:

$$k_s = \frac{4G_S R_H}{(1-\nu_s)} \quad (2)$$

Moreover, it can be written

$$G_s = \frac{k_S(1-\nu_s)}{4R_H} \quad (3)$$

Where G_s= soil shear modulus, R_H = equivalent radius of conical model below the tip and ν_s soil Poisson's ratio ($\nu_s \sim 0.33$). The soil shear wave velocity Vs can be determined by:

$$V_s = \sqrt{\frac{G_s}{\rho_s}} \quad (4)$$

Where ρ_s is soil bulk density (considered ~1800 kg/m^3). In practice, for each blow performed and recorded during instrumented DCP driving, dynamic stiffness $k_d(\omega)$ is automatically computed from FRF curves. Assuming α = 2 and solving Eq. 3 and Eq. 4, shear wave velocity Vs can be established. In this work, Vs measured by instrumented DCP using the above approach, will be compared with MASW V_S assessments.

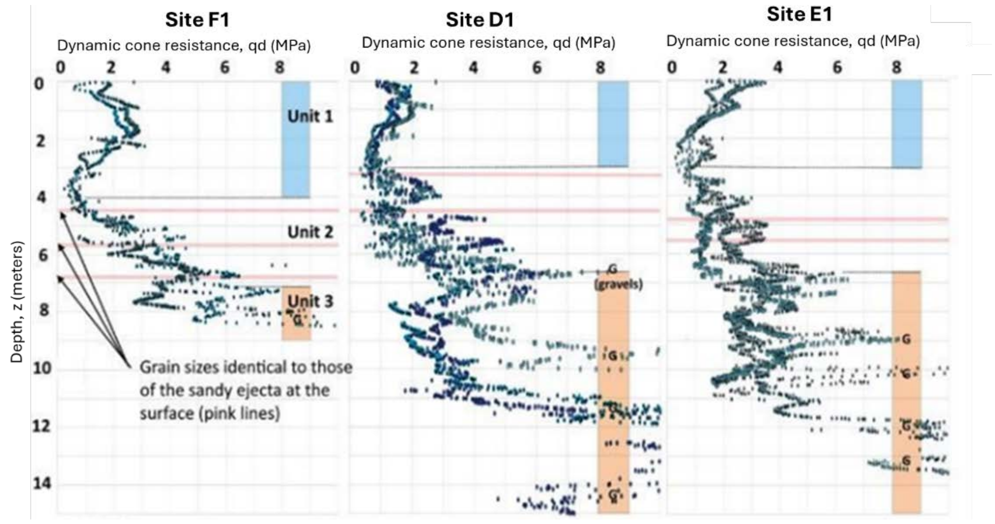

Figure 5. Petrinja area along the Kupa river, Croatia. Site E1 – Variations of cone resistance (qd) profiles obtained along the sites F1, D1 and E1. The lithologies encountered on the core-boreholes are in blue : Unit 1 (silt layers), in white : Unit 2 (alternation of fine and silty sands layers) and in pale orange : Unit 3 (gravels and coarser and fine sands layers)

4. Experimental campaign

4.1. Geophysical and geotechnical campaign at Petrinja, Croatia

In October 2022, we performed field investigation in the epicentral area, involving geophysical and geotechnical surveys. As mentioned above, different sites with sand ejecta or lateral spreading along the Kupa river (see **Fig. 2**) were studied. For each site, several geophysical methods - Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR) profiles, MASW profiles and HVSR measurements -, were carried out and complemented by geotechnical tests: instrumented DCPs test, geological boreholes and six trench to observe injections of sandy dykes linked to the 2020 event or older earthquakes. No skin friction along the rods during the test was observed.

In this work, we are interested in studying site E1 to build soil models from instrumented DCPTs and then will enable to map the liquefied bodies at depth. The other site, D1 and D2, will be employed to compared shear wave velocity measurements performed by instrumented DCPs and MASW method.

The site E1 is located on the eastern edge of a naturally or artificially abandoned former meander of the Kupa-river (**Fig. 1**). According to literature and geological borehole, in this site, three main layers can be identified (**Fig. 5**). From the ground surface, the alluvial material corresponds to 2 m thick clayey silts (Unit 1) overlying different sands layer (Unit 2) and then gravels and coarse sands (Unit 3). Their overall thickness is considered generally less than 5 m but may reach up to 9 m upstream of Petrinja. Hydraulically, these sediments are water-saturated by the alluvial aquifer of the Kupa whose level depends directly on that of the river.

Fig. 5 shows the results - cone resistance qd - obtained from 8 instrumented DCPT Grizzly-3-EV (see Fig. 3) carried out along a transverse profile at site E1, D1 and F1.

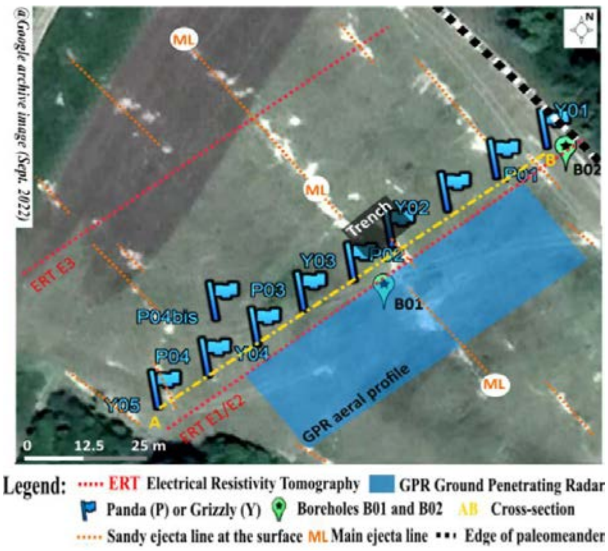

Figure 6. Petrinja, Croatia. Site E1 – Plan of geophysical and geotechnical soundings. SW to NE transversal line

It can be observed (**Fig. 5**) that the variations in cone resistance (*qd*) are very similar along the studied profile. The high resolution of the measurements carried out makes it easy to identify the main units. Unit 1 presents a decrease of cone resistance with values ranging from 3.5 MPa to less than 1 MPa below the topsoil. The change from silty layers (Unit 1) to the sands (Unit 2) is always underlined by an increase of *qd* and then values steadily continue to increase with the depth and could reach 5 and 7 MPa at the bottom of the Unit 2. In this Unit, some levels of low qd ($\leq$ 2 MPa) (loose sands) are found between 3 and 6 m of depth. Some low values $1 \leq qd \leq 3$ MPa are also measured in the Unit 3 between depth ranges 8-9 m and 10-11 m. The layers of gravels generally have a high q_d exceeding 6 MPa. Moreover, the same variations can be observed in the shear wave velocity V_S profiles, summarized, and presented later (see **Fig. 8**).

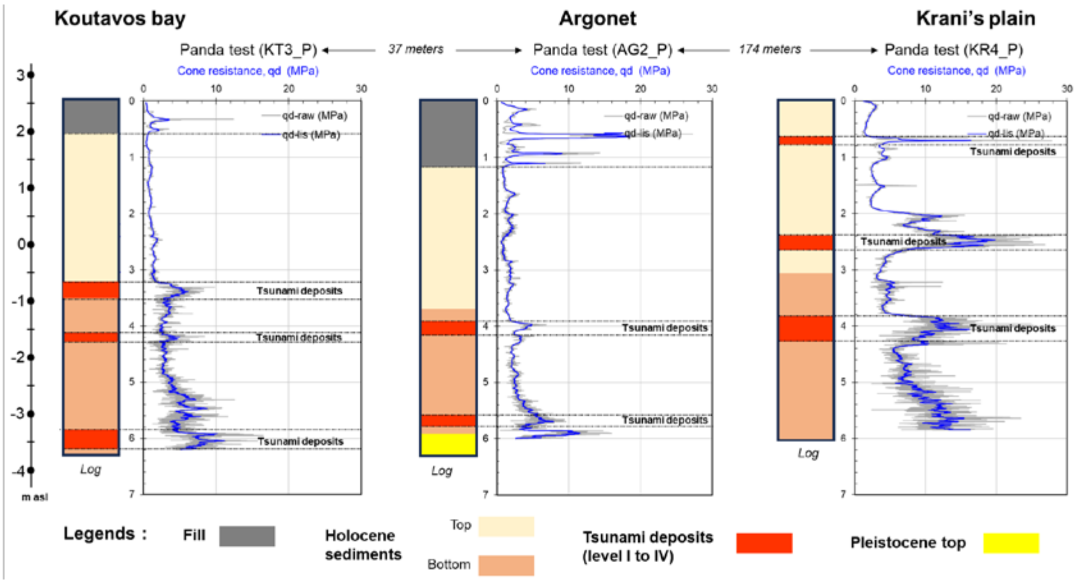

Figure 7. Koutavos bay results. Geological/stratigraphic and cone resistance profiles carried out at KT3_P, AG2_P and KR4_P location. Tsunami deposits and the different shallow layer can be easily identified from variations in penetrograms.

4.2. Geophysical and geotechnical campaign at Koutavos, Cephalonia Island, Greece

The Koutavos basin has been the subject of numerous experimental studies to investigate and characterise the formations at depth. However, the most superficial part of the basin, around ten meters thick, is still relatively unspecified. As these surface formations can exhibit non-linear behavior and affect soil/foundation interaction of buildings, a new experimental campaign was carried out in 2022 to better characterise them. The results of the investigations are then compared with the interpretation of shallow core drillings from a study carried with a view to searching for paleo-tsunamis features. The use of the light instrumented DCP made it possible to carry out these investigations at lower cost and under easy installation conditions, given the island context.

In situ, an initial field phase identified sites for the implementation of geotechnical measures, considering outcrop conditions. During this phase, pre-holes of up to 1.25 m were drilled with a perforator to allow the backfill to pass through. In total, 26 instrumented DCP were carried out in the Holocene part of the basin, including 10 Pandas 3 and 13 conventional Panda tests. Despite the help of the perforator, 8 Pandas did not exceed a depth of 2 m because the elements were too coarse (rubble, brick or rock). The other holes were drilled to a depth of between 3.6 and 7.45 m from the surface.

Fig. 7 shows the cone resistance profiles, as well as the borehole 1D column, obtained at points KT3_P, AG2_P and KR4_P along Koutavos Bay. For each analyzed DCP test, the results obtained are very sensitive to the stratigraphic variations presented at depth. They make it easy to detect the different layers and reconstruct a fairly accurate vertical model for each point tested.

Concerning the results and their interpretation, these investigations firstly confirmed and clarified the borehole observations reported in the literature as the following succession from the surface can be observed (see **Fig. 7**):

- a variable thickness of rubble and alluvial material characterized by high passages of peak resistance q_d between 10 and 20 MPa and which can locally exceed 20 MPa at the passage of an indurated debris. This layer is mainly found in the Koutavos park,
- fine soils at depths of around 2 to 6 m, marked by very low q_d values, less than 3 MPa in the upper part, increasing with depth to between 3 and 7 MPa; and
- the Pleistocene clay roof located at a depth of around 6 m and marked by a sudden increase in strength above 5 MPa.

Moreover, various levels of higher resistance are found in the Holocene at depths corresponding to those of the 4 paleo-tsunami layers founded in previous boreholes available. In addition, only the western edge of the basin has been investigated through boreholes KT4_P and KT1_P3 (located **Fig. 2**), which tend to confirm a westward rise in the Pleistocene roof at a depth of around 4 m and a reduction in the thickness of the Holocene, according to a spoon-shaped geological model with nested layers (Cushing et al. 2020).

The instrumented DCPT tests enable soil properties to be accurately estimated almost continuously as a function of depth, unlike the SPT test or geophysical borehole tests (down-hole or cross-hole CH-DH), where measurements are generally only taken at metric intervals. The use of this technique in the central part of the Koutavos basin has enabled the characteristics of the surface formations and their variability to be determined within the first seven meters from the surface.

These geotechnical tests confirm that the fine sediments of the Koutavos lagoon are subdivided at basin scale into 2 slow layers, intersected by shallow coarse levels linked to former tsunamis. The variability observed in 1D through this geotechnical test campaign would have little impact for small movements because of the control of seismic amplification by the slow layer outcropping or located under the embankments of variable thickness.

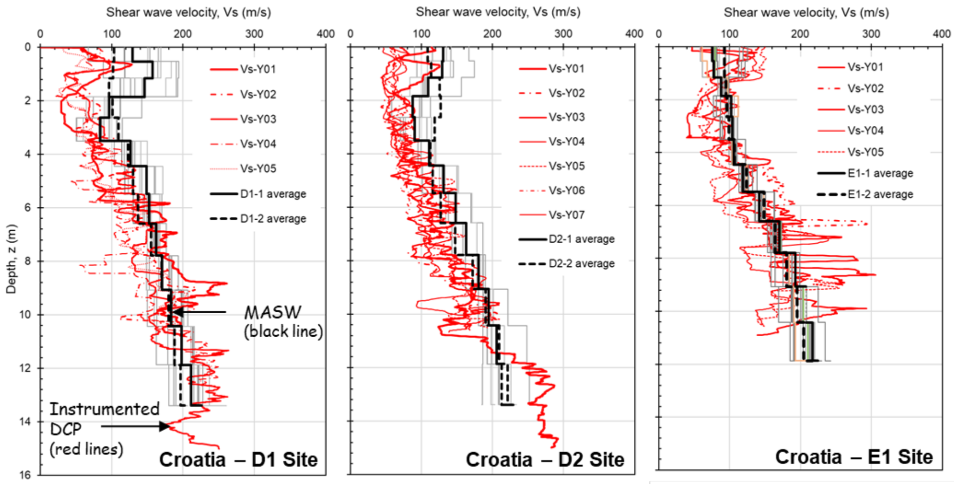

Figure 8. Petrinja, Craotie. Comparison of the shear wave velocity Vs obtained using the DCP instrument and MASW.

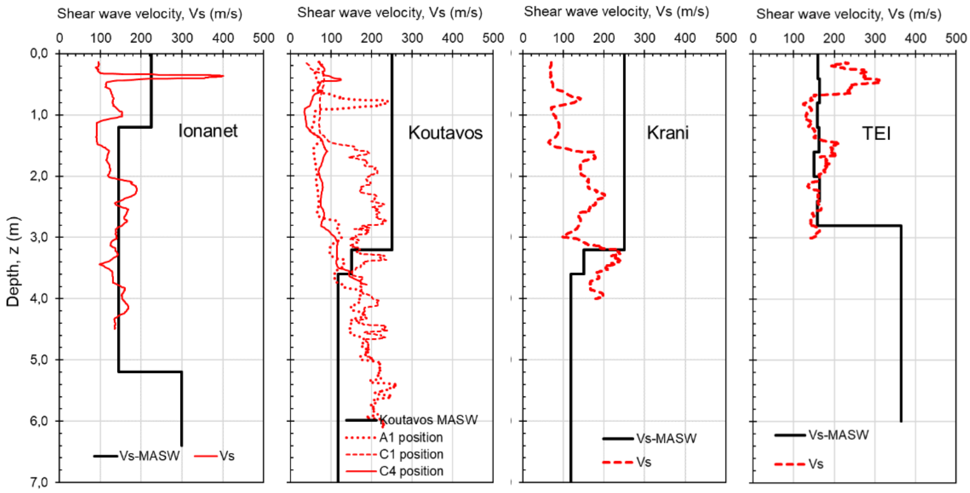

Figure 9. Koutavos lagoon, Grece. Comparison of the shear wave velocity Vs obtained using the DCP instrument and MASW.

5. Field shear wave velocity V_S assessment

The second objective of this work was to evaluate the characteristics of surface soils using instrumented penetrometers. Considering the general purpose of our studies in Croatia and Greece, we were interested in determining the shear waves velocity V_S of soils.In order to assess the relevance of the measurements carried out, we compared them with measurements performed with MASW-1D available for each site. In addition, we are interested in assessing the complementarity of these two techniques, which would improve the vertical resolution of measurements taken with surface seismic methods. **Fig. 8-9** shows the results obtained using both methods (instrumented DCP and MASW) at the Petrinja and Koutavos sites.

At the three sites studied and presented at Petrinja (**Fig. 8**), the measurement of V_S shows a good agreement, both in terms of vertical evolution and amplitude. However, and assuming no errors in MASW interpretation, it can be observed that the V_S values on the surface (0 < z < 4 m) are generally lower (by around 30%) than those deduced from the MASW tests, mainly for D1 and D2 site. However, it can be observed that the variations of cone resistance qd values in these first few meters are very similar to those observed in V_S values measured with instrumented DCP. A good agreement between both methods was obtained in site E1.

Fig. 9 shows the results obtained at Koutavos. Comparisons here show more variable results and should be analyzed carefully. The figure shows the average V_S results obtained in four locations: Ionanet, Koutavos, Krani and TEI. These are compared with the MASW-1D profiles available near at these locations. Except in the case of the Ionanet and TEI sites, which show a very good agreement in terms of V_S values and depth trends, this is not the case for the V_S profiles obtained at Koutavos and Krani. In this case, it can be observed that the V_S values measured with instrumented DCP still are around 100 m/s for the 3 first meter depth, whereas those measured with MASW are of the order of 250 m/s (very high and corresponding to firm, compact soils). After 3 meters depth, MASW values fall from 250 to 100 m/s, while instrumented DCP values rise from 100 m/s to 200 m/s. At Krani location, almost the same observations can be made. However, it can be observed also that the V_S values measured by MASW are quite high at the surface, although the cone resistance *qd* remains generally quite low (0,2 < *qd* < 2 MPa); whereas at depth, beyond 3-4 meters, they are much greater (*qd* > 5 MPa). Presumably, it would be necessary to work on the reliability of MASW data in Greece, but also to include other measurements or information, such as SPT, boreholes to increase the degree of reliability of these comparisons of *Vs* using DCP and MASW.

Despite everything, we can also observe that the vertical resolution of the measurement carried out with instrumented DCP and wave equation based is better, in the sense that it allows us to easily identify layers with thicknesses of centimeter or even meter, which conventional methods such as MASW do not allow us to highlight easily. Further analysis is underway to explain the differences observed at Koutavos (Greece) while comparisons are much better in Petrinja (Croatia).

6. Conclusions

In this study, we focused on investigating and characterizing two sites (Petrinja in Croatia, and Koutavos Lagoon, at Cephalonia Island, Greece) and various locations impacted by liquefaction or seismic events; aiming to provide concise vertical and spatial mapping of surface layers and their variability. The need for large quantities of reliable data, is satisfied in this study that aims to assess the instrumented DCP's efficacy in identifying and characterize, i.e., liquefied soil layers. The experimental campaigns carried out and the results obtained highlight the contributions of these techniques can have in study. The finesse of the measurement obtained, in terms of cone resistance qd, as well as shear wave velocity VS, allows easy and quick characterisation of shallows layers. We were interested in assessing the reliability of VS measurements and to this aim we compared the results obtained with MASW. The results are promising, but they need to be further developed to better interpret surface soil dynamic properties.

The reliability of the measurements taken with the device, combined with the simplicity, speed and high resolution of the signal obtained, make it a very interesting alternative for geotechnical engineers to assess the dynamic parameters of the soil during post-seismic studies, or during studies carried out to characterise a site of high seismic hazard, or studies of paleo-liquification of shallow surface soils.

Reliability of the measurements carried out with the device, combined with the simplicity, rapidity, and high resolution of the obtained signal, make it an interesting alternative for the geotechnical engineers in order to assess soil dynamic parameter during post seismic survey campaign, or during paleo-liquefaction shallow soil analysis. The instrumented DCP (Panda, Panda 3 or even Grizzly-3-EV) is a fast, easy, and cost-effective method for characterizing surficial soils.

Finally, although this method is an interesting one for characterizing surface soils, it is limited in depth (z < 15m). It would be interesting to assess the extent to which the data obtained using this method can be aggregated and fused with those obtained using MASW or/and other geophysical methods. This would provide a 1D or 2D soil model with better vertical resolution in greater depth. Combining instrumented DCP with MASW (or other geophysical methods) provides a viable alternative against time-consuming and costly Cross-Hole or Down-Hole methods, which remains primary approach for determining shear wave velocity and characterizing liquefaction potential down to a depth of 30m.

Acknowledgements

The authors are grateful for the financial support provided by funding of IRSN and CEA and the TelluS-Alea programme of the Institut National des Sciences de l'Univers, as well as for all the support provided by University of Zagreb, HGI and ITSAK.

References

Benz Navarrete, M. A., Breul, P., & Gourvès, R. (2021). Application of wave equation theory to improve dynamic cone penetration test for shallow soil characterisation. JRMGE. https://doi.org/10.1016/j.jrmge.2021.07.004

Benz Navarrete, M. A., Breul, P., & Moustan, P. (2019). Servo-Assisted and Computer-Controlled Variable Energy Dynamic Super Heavy Penetrometer. In Proc. PANAM, Cancun, Mexico, 65–72. https://doi.org/10.3233/STAL190024

Cushing, E. M., Hollender, F., Moiriat, D., Guyonnet-Benaize, C., Theodoulidis, N., Pons-Branchu, E., Sépulcre, S., Bard, P. Y., Cornou, C., Dechamp, A., Mariscal, A., & Roumelioti, Z. (2020). Building a three dimensional model of the active Plio-Quaternary basin of Argostoli (Cephalonia Island, Greece): An integrated geophysical and geological approach. Engineering Geology, 265.

El Naggar, M. H., & Novak, M. (1994). Non-Linear Model for Dynamic Axial Pile Response. Journal of Geotechnical Engineering, 120(2), 308–329.

Espinace, R., Villavicencio, G., Palma, J., Breul, P., Bacconnet, C., Benz, M. A., & Gourvès, R. (2013). Stability of chilean's tailings dams with the Panda® penetrometer. Experiences of the last 10th. 18th ICSMGE 2013, 1.

Gourvès, R. (1991). Le PANDA : pénétromètre dynamique léger à énergie variable pour la reconnaissance des sols.

Holeyman, A. E. (1988). Modelling of dynamic behaviour at the pile base. Proceedings of the 3rd Int. Conference on the Application of Stress-Wave Theory to Piles, 174–185.

López Retamales, S. (2022). Development of a method to evaluate the risk of liquefaction of sands from a dynamic penetrometer test. Phd Dissertation. Ecole des Ponts ParisTech.

Rollins, K. M., Talbot, M., & Youd, T. L. (2018). Evaluation of Dynamic Cone Penetration Test for Liquefaction Assessment of Gravels from Case Histories in Idaho. Geotech. Earthquake Engineering and Soil Dynamics V, 227–236.

Schnaid, F., Odebrecht, E., & Rocha, M. (2007). On the mechanics of dynamic penetration tests. Geomechanics and Geoengineering, 2, 137–146.

Schnaid, F., Odebrecht, E., Rocha, M., & Bernardes, G. (2009). Prediction of Soil Properties from the Concepts of Energy Transfer in Dynamic Penetration Tests. Journal of Geotechnical and Geoenvironmental Engineering, 135.

Teyssier, A., Navarrete, M. A. B., Tran, Q. A., Pellez, J. C., & Jacquard, C. (2020). Field correlation between shear wave velocity measured by Panda 3®, Ménard pressuremeter test (PMT), cone penetration test (CPT) and geophysical tests. In Proc of ISC'6, Budapest, Hungary, 406(2).