The light dynamic cone penetrometer and its use in geotechnical investigation for monuments and historic sites

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ABSTRACT

The Dynamic Cone Penetration-Light test (DCP-L) is widely used for the determination of soil strength in-situ and the compaction control of pavement layers. It is also used for geotechnical investigation of road and highway works, for soil classification, for stratigraphy determination and for earthworks construction quality control. The results of the test are correlated to SPT and other geotechnical properties, such as CBR, modulus of elasticity or resilient modulus, stiffness modulus, unconfined compressive strength, relative density etc. This test however can, with limited modifications, serve in every type of geotechnical investigation mostly thanks to the ease of transport and access of the equipment, the ability to perform the test faster than other means of including site investigation and the fact that no specialised personnel is needed to perform the test. It is also very useful, even for investigation to considerable depth, not so much in this case for estimation of parameters by empirical relations, as for the identification of stratigraphy, especially when other methods cannot be applied due to time, space or cost restrictions. Especially regarding space restrictions and minimum disturbance to surroundings, the DCP-L can often be the sole answer to in-situ geotechnical investigation for monuments and historic sites. The paper presents a large number of examples where DCP-L tests were used for geotechnical investigation of monuments and historic sites down to depths of even up to 9m. Common problems and benefits from these cases are identified and classified documenting this method for more extensive use in the field of monuments and historic sites preservation including its use for sensor installation using a modified cone.

Keywords: stratigraphy, cone tips, field sensors, sensor installation, access in narrow spaces

INTRODUCTION

Dynamic cone penetrometer tests are a common type of in-situ test used for geotechnical investigation. The method consists of a steel cone attached at the edge of rods hit at the surface of the ground by a weight of different values falling from various heights. The dynamic energy of the weight falling pushes the cone into the ground and the number of blows needed to insert the cone into the ground for a given depth (usually measured by notches along the length of the rods or an external ruler parallel to the rods) expresses the resistance of the ground to be penetrated (due to increased density or strength). The general array and equipment of the method is shown in Fig. 1. Provided the soil grains are sufficiently smaller than the cone being inserted, this resistance to penetration (usually expressed mathematically in terms of penetration length over blow, DPI or DCPI) can be related validly to the density, strength and/or deformability of the soil in-situ; the most common geotechnical properties correlated to DPI being the California Bearing Ratio (CBR), the dynamic Modulus of Elasticity (for pavement design applications), the unconfined compressive strength q_u or the Standard Penetration Test Number (N_{SPT}). More importantly than correlations to actual geotechnical parameters, the DCP test provides a very quick means of obtaining stratigraphy and its results are easily and quickly interpreted even by non-specialised personnel in the field as the test is being carried out. Although originally developed for pavement design applications (Scala, 1956), the test has been standardised by numerous international organisations for various falling weights, falling heights and cone sizes and geometries, as shown in Table 1a for falling weights allowing even manual execution and Table 1b for larger falling weights usually requiring mechanical means to lift the weight (after Stratakos & Bardanis, 2019). Of late it has been standardised for degree of compaction estimation in the field for very narrow space applications like backfilled trenches (ASTM D7380).

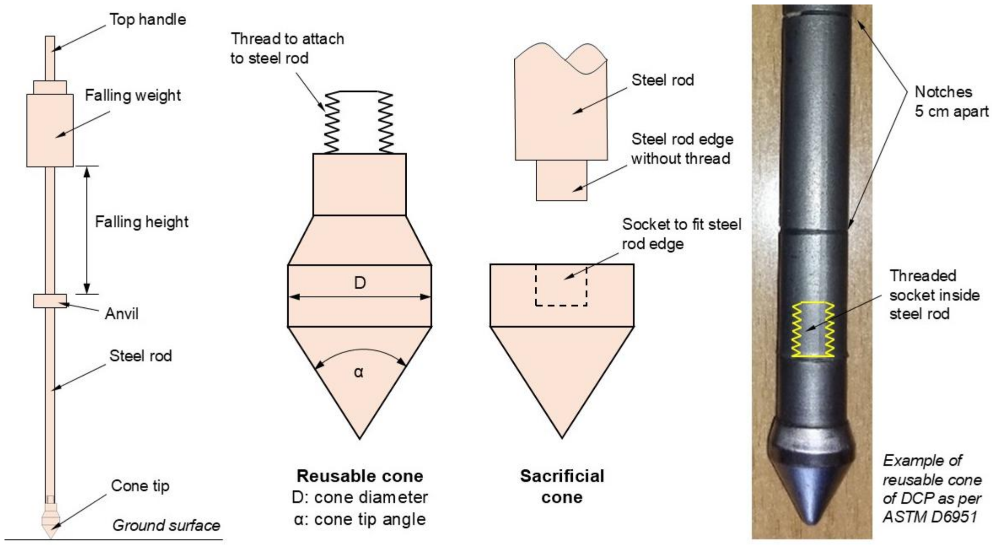

Figure 1. *General array and equipment of the dynamic cone penetrometer with reusable or sacrificial cones (example of reusable cone as per ASTM D6951 depicted –cone details may differ significantly)*

Table 1a. *Basic characteristics of light falling weight dynamic cone penetration tests*

Equipment	**"Utility" DCP**	**DCP**	**DCP**		**DPL (light)**
Characteristic	**Very small weight**	**This study for sensor installation**	**Small weight**	**Large weight**	
Falling weight (kg)	2.3 ± 0.1	4.6 ± 0.01	4.6 ± 0.01	8 ± 0.01	10 ± 0.1
Falling height (mm)	508 ± 10	575 ± 1	575 ± 1	575 ± 1	500 ± 10
Cone tip angle α (°)	25 ± 2	30	60 ± 1	60 ± 1	90
Cone diameter D (mm)	20	30 ± 0.25	20 ± 0.25	20 ± 0.25	35.7 ± 0.3
Cone tip surface (cm^2)	7	7	3.14	3.14	10
Impact energy per surface (kJ/m^2)	16	37	82	144	49 – 50
Standard	ASTM D7380	This study	ASTM D6951		DIN 4094-3 ISO 22476-12

Table 1b. *Basic characteristics of dynamic cone penetration tests with larger falling weights (cannot be performed manually)*

Equipment	**DPM (medium)**	**DPH (heavy)**	**DPSH (super heavy)**		**SPT**
Characteristic			**DPSH-a**	**DPSH-b**	
Falling weight (kg)	30 ± 0.3	50 ± 0.5	63.5 ± 0.5	63.5 ± 0.5	63.5 ± 0.9
Falling height (mm)	500 ± 10	500 ± 10	500 ± 10	750 ± 10	760 ± 30
Cone tip angle α (°)	90	90	90	90	-
Cone diameter D (mm)	43.7 ± 0.3	43.7 ± 0.3	45 ± 0.3	50.5 ± 0.5	50.8 ± 1.3
Cone tip surface (cm^2)	15	15	16	20	-
Impact energy per surface (kJ/m^2)	98	164	195	234	-
Standard	ISO 22476-12	DIN 4094-3 ISO 22476-12	ISO 22476-12		ASTM D1586

USE OF THE DCP FOR MONUMENTS AND HISTORIC SITES

Except for the ease of use and straightforward interpretation, the DCP test with falling weights smaller or equal than 10 kg has the additional advantage that the equipment used can easily be transported manually to very narrow locations with difficult access. On top of this, the very small footprint of the equipment, once assembled to perform the test, allows for performing the test at the exact spot or very near the exact spot where knowledge of ground conditions is required. These advantages allow the light DCP test to be performed easily in archaeological and historic sites where space is often very narrow both at the exact required location to perform the test and along the access path to this exact required location. Common uses of the test include execution to obtain stratigraphy (especially identification of a hard layer that can be used as a foundation layer), correlate properties, confirm visual observations of stratigraphy in cuts and trial pits and on occasion verify compaction of constructed new layers of compacted soil. Given these advantages it should be emphasised that DCP is by no means a non-destructive type of test. It is indeed destructive as it is intrusive and all precautions to protect findings and remains in a historical site should be exercised. On top of this, it should also be noted that although lightweight DCP uses smaller falling weights, impact energy per surface, especially for smaller diameter cones and larger falling weights is comparable to that of DPH or DPSH-a (Tables 1a and 1b).

Fig. 2 presents a typical case of stratigraphy identification and correlation of visual observations from the walls of a trial pit (Fig. 2a) to actual properties' values ("numbers assigned to pictures" logic) during a geotechnical investigation for a new museum in the area of Epidavros. Typical, softer, poorer properties, upper man-made ground, overlies a dense, stiff layer of alluvium gravel, itself overlying the weathered trachyte mantle of the area. One can proceed to the assignment of properties (N_{SPT}, CBR as in Fig. 2d, etc) which however is less important than the clear identification of differences or similarities in the properties of the formations penetrated: the man-made ground is clearly soft and of poor properties (blows/50mm as low as 3, corresponding to DPI as high as 17, and estimated CBR as low as 4-5%), while the alluvium gravel is much more competent but of similar properties (stiffness-wise) to the upper part of the trachyte weathering mantle; the latter estimated to be of approx. 50cm thickness only before the DCP cone reached the sound trachyte and could no longer penetrate it. This information may appear basic to trivial but it offers fundamental understanding of the ground conditions in the area of interest, which as it was supported by a large number of tests in full agreement with the visual observations from a similarly large number of trial pits, it fully supported engineering design decisions such as minimum depth of material excavated to build the foundation.

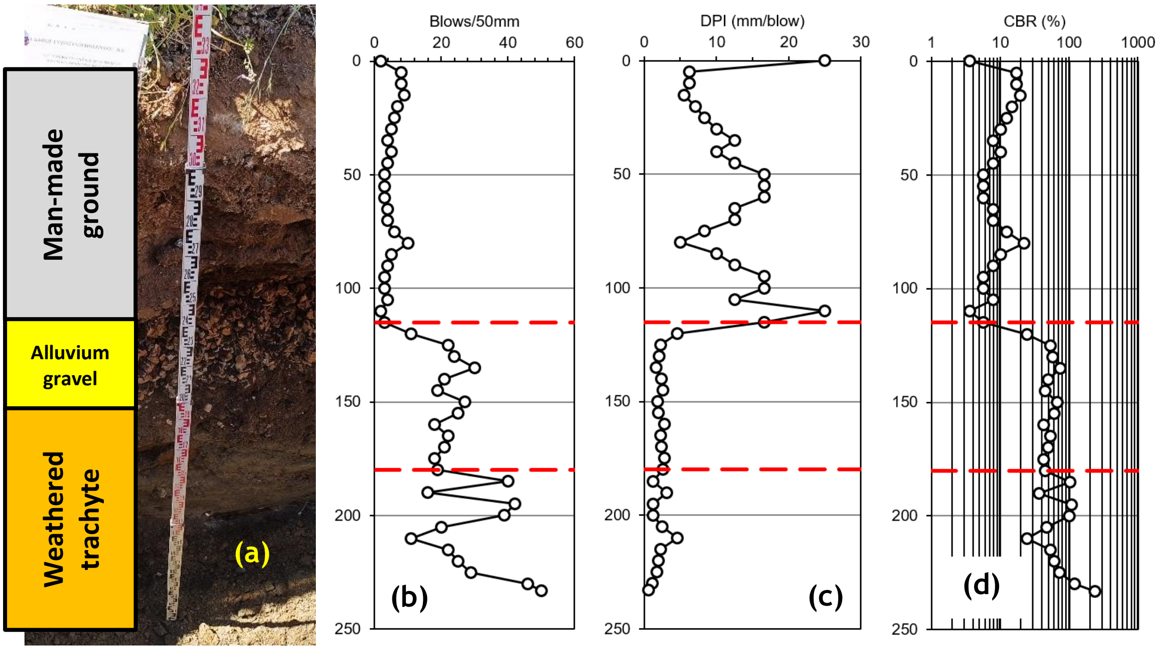

Figure 2. *Geotechnical investigation for the new Epidavros Museum, Greece, with trial pits and DCP (ASTM D6951 4.6 kg falling weight) tests: a) trial pit wall with layers identified, b) blow count per 50mm penetration with depth, c) DPI with depth, and d) estimated CBR with depth.*

Fig. 3a and 3b show the execution of a DCP test (using a 4.6 kg falling weight as per ASTM D6951) adjacent to the remaining ancient wall of the Elefsis sanctuary in Attica, Greece, in order to obtain stratigraphy and estimate soil properties for foundation calculations for the footings under the columns of the new shelter protecting the remains of the ancient wall made of mudbricks. The soil profile obtained in terms of blow count per 50mm penetration is shown in Fig. 3c and in terms of DPI is shown in Fig. 3d. To understand the use of the DCP and the profiles obtained, using Fig. 3d, three layers may be identified; a top, soft layer from 0 to 0.25m with DPI 50 mm/blow or higher, a second medium-strength layer from 0.25m to 2.35m with DPI ranging from 5 to 25 mm/blow with an average of 14 mm/blow and a standard deviation of 6 mm/blow and finally a very competent layer from 2.35m to 2.70m and deeper with DPI 2 mm/blow. Using the empirical relation by Patel & Patel (2012, Eq. 1, where q_u is in MPa and DPI in mm/blow using 8kg falling weight of DCP test as per ASTM D6951) these DPI values correspond to an estimated q_u value of 60, 150 and 940 kPa respectively for each layer. Notice that if a 4.6 kg falling weight has been used, DPI values have to be doubled in order to use this particular equation. This constitutes an example of stratigraphy identification and parameter estimation in a very narrow space but exactly at the location of the designed column and footing of the new shelter.

$$q_u = 3.1237\ DPI^{-0.865} \quad (1)$$

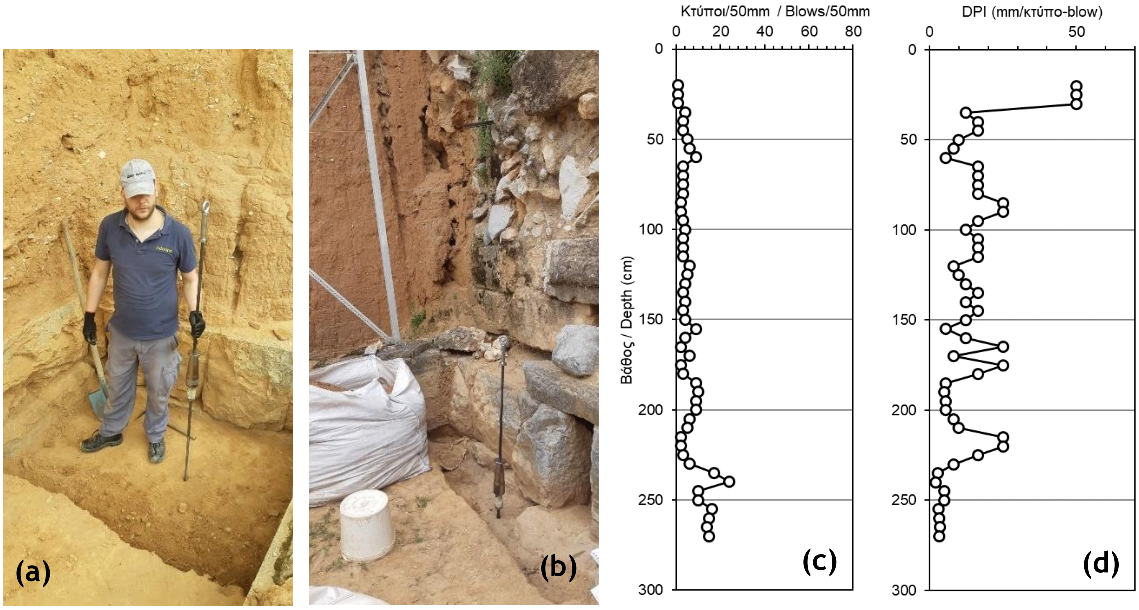

Figure 3. *Geotechnical investigation for the new protected shelter of the remains of the ancient walls of Elefsis Sanctuary, Attica, Greece a) execution of DCP test as per ASTM D6951 with 4.6 kg falling weight (man for scale), b) DCP test as close as only 20cm to the adjacent ancient wall, c) blow count per 50mm penetration with depth, and d) DPI with depth.*

Fig. 4a and 4b show the execution of a light DCP test at the boundaries of and inside the remains of the Old Palace in the Minoan city of Phaistos in Crete, Greece, in order to obtain the depth of the bearing layer to found the footings of the columns of the new shelter protecting the Old Palace. Both photographs indicate the ability of the manually operated DCP to approach enormously close to the point of interest without causing any disturbance either to transport the equipment or perform the test. Fig. 4c and 4d show two soil profiles obtained using the DCP tests performed for this new shelter (not corresponding to the photographs of Fig. 4a and 4b), the first showing how the bedrock was identified at a very small depth and the second how it was identified at a larger depth, while DPI above the bedrock recorded a large scatter indicative of the inhomogeneity of the material and the presence of larger particles in a matrix of softer soil material.

Fig. 5a shows a diametral section across the St Dimitrios Cavaliere in the old city of Chania in Crete, Greece (Bardanis & Dounias, 2026). Cavalieri were elevated banks of earth in the form of circular hills constructed uphill of bastions originally in Venetian forts. Their circular crest offered an elevated location to position artillery and offer it larger range because of the increased elevation, towards many directions from where the enemy could attack. The St Dimitrios Cavaliere has suffered by many failures of its walls and higher slope, which were thoroughly investigated in recent years (Bardanis & Dounias, 2026).

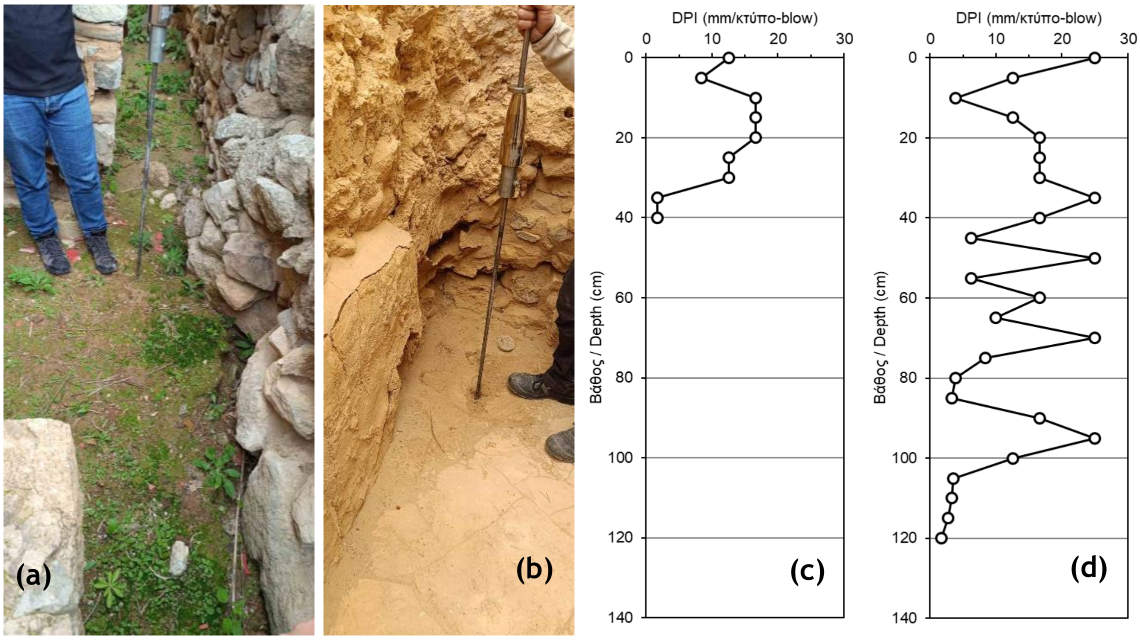

Figure 4. *Geotechnical investigation for the new protected shelter of the Old Palace in the Minoan city of Phaistos in Crete, Greece a) DCP test as per ASTM D6951 with 4.6 kg falling weight right outside the boundary of the monument (man for scale), b) inside the monument right beside an internal wall, c) DPI with depth at a location where the bedrock was identified at a very small depth, and d) DPI with depth at a location where the bedrock was identified at a larger depth.*

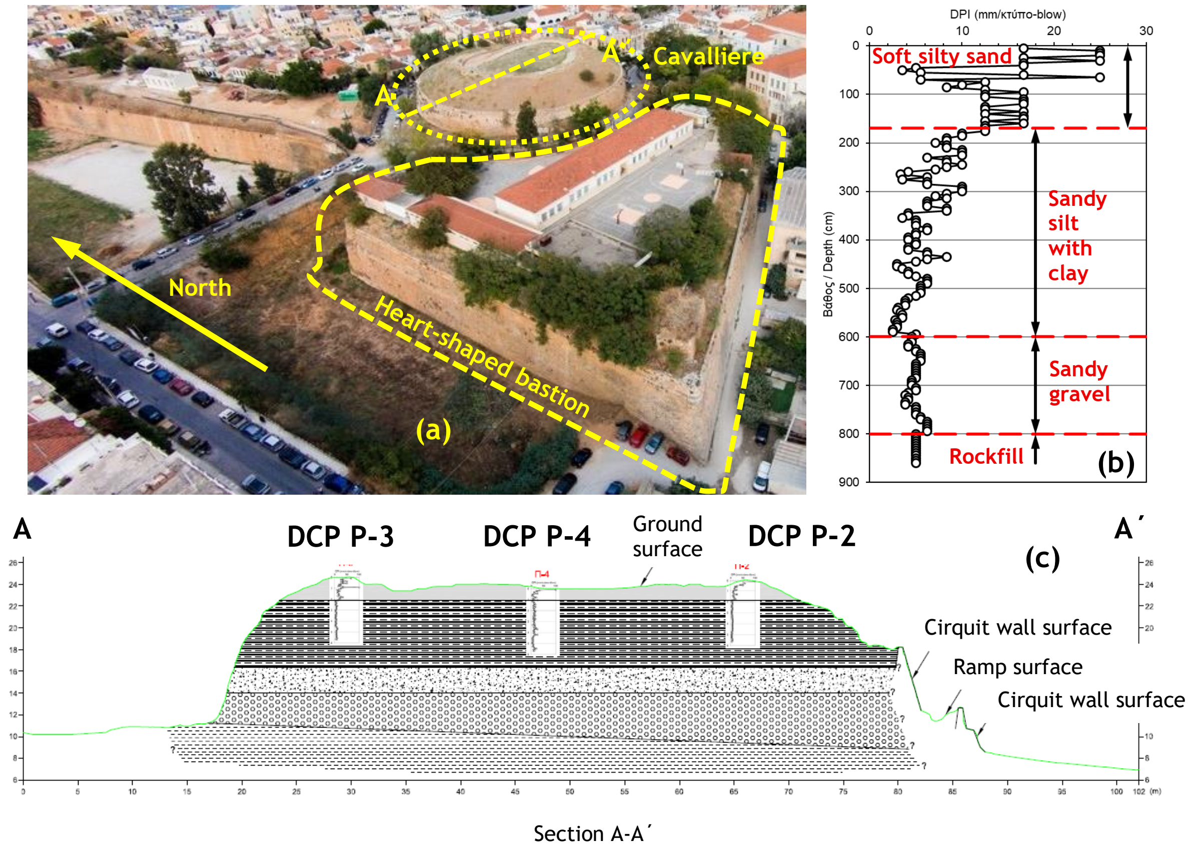

Figure 5. *a) Aerial view of the southwest part of the Venetian fortifications in the old city of Chania in Crete, Greece (before the failures), b) DPI with depth of DCP test P-9 performed at the crest of the St Dimitrios Cavaliere, & c) cross-section A-A´ across the St Dimitrios Cavaliere (indicated in Fig. 5a).*

Geotechnical investigation proved challenging as a circular ramp connecting the Cavalliere base with its crest was closed for vehicles. The only means allowing penetration of the soil layers of the Cavalliere would be either boreholes with drilling rigs that would have to be lifted from the road at the base of the Cavalliere to its crest (a costly, challenging undertaking not available given the urgency of the investigation) or manually performed DCP tests from the crest to the maximum possible depth that could be achieved. DCP was selected yielding a clear section like that in Fig. 5c, produced in combination with the observation of the back scarp of the failures, and reaching depths down to almost 9m with clear identifications of the layers externally observed (Fig. 9b, for more details: Bardanis & Dounias, 2026).

The examples mentioned showcase how when it comes to ground investigation within existing monuments, there is practically no other intrusive means of geotechnical investigation that can provide stratigraphical data of any significance in geotechnical investigation and evaluation to considerable depth. In fact this depth may be large enough to make the need for supplementary boreholes or trial pits smaller. Table 2 contains basic statistics of three types of geotechnical investigations of EDAFOS Engineering Consultants S.A. where the lightweight DCP test has been used for 13 years (2014-2026). As expected, the average number of DCP tests performed per project for pavements' investigation is the largest with the smallest average maximum depth of tests performed (no larger depth required technically). When it comes to geotechnical investigations performed for monuments and historic sites and non-related to monuments and historic sites, the average number of DCP tests performed per project is much smaller than when performing pavements' investigation, and the average maximum depth of tests performed is very much larger than for pavements. As for geotechnical investigations performed for monuments and historic sites, the average number of DCP tests performed per project is larger than that performed for geotechnical investigation non-related to monuments and historic sites, as DCP is often the only means of intrusive geotechnical investigation that can be performed, and also the maximum DCP depth is slightly larger.

Table 2. *Basic statistics of lightweight DCP testing for various types of geotechnical investigations*

Type of Geotechnical Investigation	No of DCP tests	Maximum DCP depth	Average no of DCP per project	Average maximum depth
Pavements	665	3.7m	14	1.6m
Non-related to monuments and historic sites	153	8.6m	7	3.4m
Monuments and historic sites	223	8.9m	9	3.6m

USE OF THE DCP FOR SENSORS' INSTALLATION

The standard lightweight cone penetrometer as per ASTM D6951 has a 60^o cone with a maximum diameter of 20mm followed by slightly smaller diameter rods of 16mm diameter (Table 1a). Several sensors like vibrating-wire piezometers and other types of sensors like porous-block suction measurement sensors have diameters close to or slightly larger than the diameter of the hole left in the ground after performing a DCP, even the lightweight one. For instance the TEROS22 porous-block suction measurement sensor by METER has a diameter of 20mm making the hole created by the standard lightweight cone penetrometer marginal for the sensor to freely pass after penetrometer removal to the bottom of the DCP hole. A new cone was therefore designed and built allowing for a wider hole so as the sensor can be more easily inserted to the bottom of the hole. In order to keep the benefits of transportability to remote locations of the lightweight DCP the cone was designed with a sharper tip of only 30^o angle. This was anticipated as a counter-measure for the larger diameter so that the same weight of the lightweight DCP could ensure penetration to considerable depths. A longitudinal section of the new cone is shown in Fig. 6a and the standard cone, the newly designed cone and the TEROS 22 sensor are photographed together in Fig. 6b.

Following construction of the new cone, it was first used in laboratory conditions. A large size sample of compacted clays was built in the laboratory (25cm high, 35cm wide, 50cm long) and four holes were opened with the standard lightweight DCP cone and the new one (two for each cone). Once these were opened, the sample was wire-cut down the long axis of the sample on which the 4 holes were made in order to have a clear view of the holes created by the two cones. A side view before wire-cutting is shown in Fig. 7a, a top view of the sample is shown in Fig. 7b (after the holes were opened and the

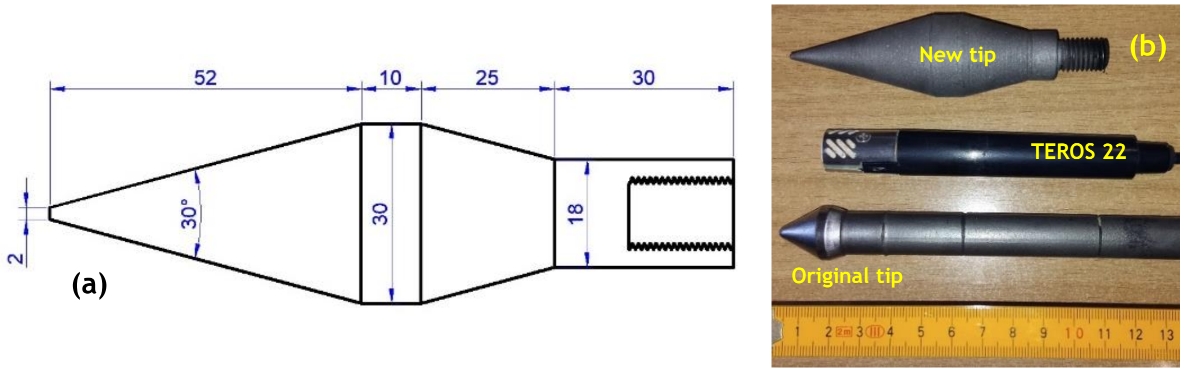

Figure 6. *The newly constructed DCP cone: a) On the left a ongitudinal section of the newly constructed DCP cone suited to the rods of DCP light (as per ASTM D 6951-03). All dimensions in mm. b) On the right, the newly constructed DCP cone (top), sensor TEROS22 (second from top), conventional lightweight DCP (as per ASTM D 6951-03) with cone and attached rod behind it with grooves marking 5cm intervals (second from bottom), and meter for scale (bottom).*

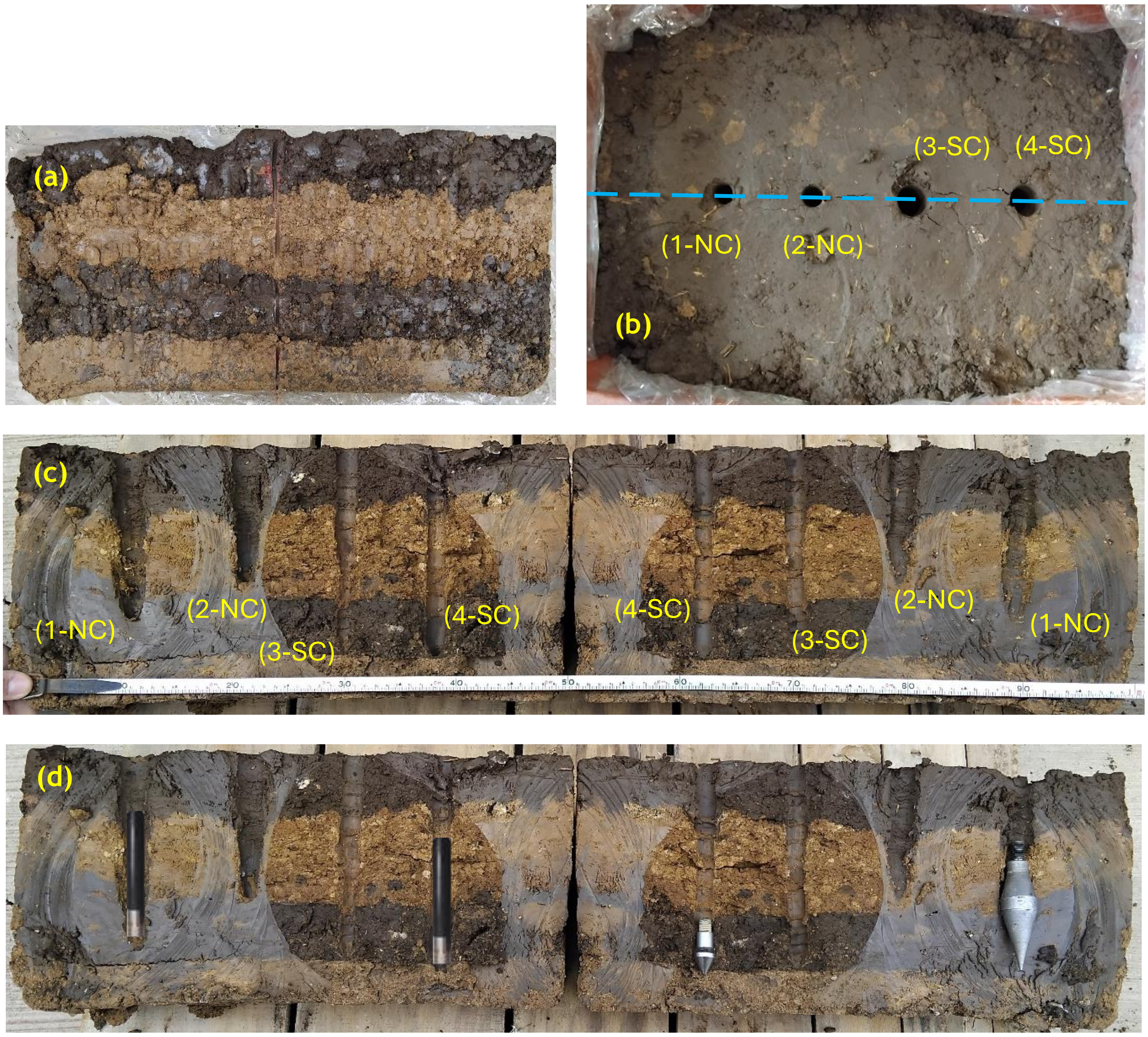

Figure 7. *a) Side view of the large compacted sample built after removal from the mould, b) top view of the large compacted sample after performing the four DCP tests, c) large compacted sample wire-cut down the axis of the tests with the holes of the tests shown, and d) the same section with the two different cones used placed on the right part of the cut sample and the TEROS 22 sensors on the left part of the cut sample.*

DCP removed) and the two sides of the section of the sample are shown in Fig. 7c without any instruments or cones and in Fig. 7d with the two cones on the side on the right and a scale adjusted image of the TEROS 22 sensor superimposed on the image on the side on the left. The sample was built using three different silty clays of medium to high plasticity with a water content above their plasticity limit. Compaction achieved corresponded to approximately 90-95% of the standard compaction energy per volume Proctor test. Under these conditions of moisture and density both cones clearly left behind them a stable penetration hole allowing access after the DCP cone removal. Still, it is clear from Fig. 7d that the TEROS 22 can hardly fit the hole on the left by the standard lightweight DCP cone (let alone be pushed down a long hole from this instrument). On the other hand, it seems that the TEROS 22 can fit into the hole left by the new cone and easily be inserted into the hole by means of a smaller diameter plastic or metallic tube. Depending on the density of the soil, the tube could be used to push the tip of the sensor into the edge of the hole left by the DCP tip to ensure good contact of the porous stones with the in-situ soil.

Following the qualitative test in the laboratory, the new cone was used to install a TEROS 22 sensor in an existing field station. The field station readily available with soil material in-situ anticipated as suitable for a first application was the Phaistos hill field station in Crete. The Phaistos hill is where the Phaistos settlement is located, one of the most important settlements for the study and understanding of the Minoan civilization. The northern side of the hill is under investigation for the slope instabilities taking place there and as part of these investigations, a series of field monitoring instruments have been installed which include TEROS 21 and TEROS 22 porous block sensors by METER installed at shallow depths due to limitation of excavation depth and size. These limitations were imposed due to the archaeological interest of the area and constitute typical limitations for various archaeological sites in Greece. The new combination of large diameter DCP cone and TEROS 22 sensor was anticipated as a means to alleviate excavation limitations. The DCP with the new cone achieved a maximum penetration depth of 1.40m (the other two depths of sensor installation are 0.30 and 0.80m). The sensor was pushed in the hole after cone removal using plastic tubes attached to the bottom of the sensor with the cable running through the holes and the void between the hole walls and the cable was filled with small chunks of the in situ soil pushed in place and compacted in the hole by a small diameter steel rod. The top 40cm of the void were filled with bentonite pellets and water was added from the ground surface in order to ensure appropriate insulation. Once installed, the sensor was connected to a logger and measurements are since recorded every 15min as with the rest of the sensors installed.

The measurements recorded from this sensor since its installation are presented in Fig. 8. The sensor was installed fully saturated and immediately after installation it follows a rapid equilibration stage that lasted approximately 4 days. Since then, it undergoes a gradual decrease possibly following the actual trend of suction that should be expected at this depth (given other long-term suction monitoring schemes in Greece: Bardanis & Loukidis, 2020, Bardanis & Kokoviadis, 2023, Belokas, et al., 2025). Monitoring is expected to continue for a fairly long time which will shed more light on the performance of this sensor and the installation method that was used.

CONCLUSIONS

The paper showcased the advantages of the use of the lightweight DCP (DCP-L) test in the context of geotechnical investigation for monuments and historic sites through examples of use from specific projects. The DCP test with falling weights smaller or equal than 10 kg has the advantage that the equipment used can easily be transported manually to very narrow locations with difficult access. On top of this, the very small footprint of the equipment, once assembled to perform the test, allows for performing the test at the exact spot or very near the exact spot where knowledge of ground conditions is required. These advantages allow the lightweight DCP test to be performed easily in archaeological and historic sites where space is often very narrow both at the exact required location to perform the test and along the access path to this exact required location. Given these advantages it should be emphasised that DCP is by no means a non-destructive type of test. It is indeed destructive as it is intrusive and all precautions to protect findings and remains in a historical site under the ground surface should be exercised. It should also be noted that although lightweight DCP uses smaller falling weights, impact energy per surface, especially for smaller diameter cones and larger falling weights is comparable to that of heavier weights DCP tests like DPH or DPSH-a (Tables 1a and 1b). Finally the combination of a specially constructed larger diameter, sharper tip cone with the rods of the lightweight DCP test and its falling weights can allow the installation of cylindrically shaped field sensors like vibrating-wire piezometers and porous-block suction measurement sensors, provided the test is performed in formations where the hole left after the penetration of the DCP can stand long enough to allow sensor installation. Examination of DCP holes created with the original cone and the newly constructed one in laboratory conditions indicated the feasibility of the exercise. Following this an experimental installation was made in the field with the measurements following since indicating good contact of the sensor tip and performance similar to that of conventionally installed sensors in excavation walls.

These results indicate the effectiveness of lightweight DCP testing use in geotechnical investigation for monuments and historic sites and possible new fields of application in this context and in general geotechnical investigation of all types for installation of cylindrically shaped field sensors like vibrating-wire piezometers and porous-block suction measurement sensors.

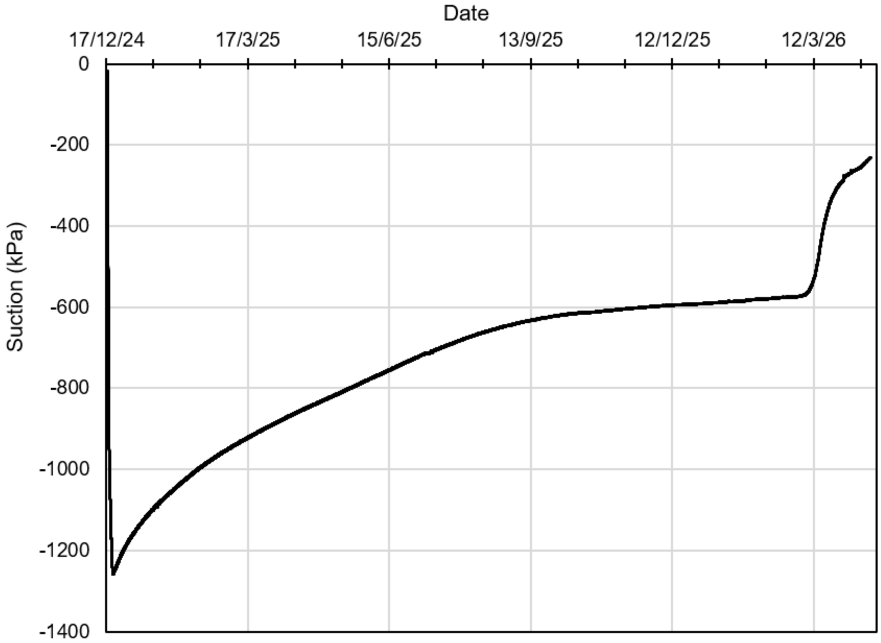

Figure 8. *Suction measured by a TEROS 22 porous-block suction measurement sensor by METER installed at a depth of 1.40m on the north slope of the Phaistos hill in Crete, Greece, using the lightweight DCP equipment combined with a newly developed larger diameter cone (Fig. 6) and 4.6kg falling weight.*

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