Use of a Portable Measurement While Drilling System for Shallow Subsurface Characterization

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ABSTRACT

The Portable Measurement While Drilling (PMWD) equipment designed by CEREMA engineers is an innovative and lightweight tool to perform rapid assessment of shallow subsurface conditions. The equipment consists of sensors mounted on a cordless rotary drill that records depth, downforce, rotation, torque, and time. This paper presents results obtained with the portable MWD under laboratory and field conditions, which were directly compared to soil resistance profiles obtained with a lightweight dynamic cone penetrometer (LDCP – PANDA). Results from 66 PMWD profiles and 87 LDCP profiles demonstrated the potential applicability of the portable MWD in shallow subsurface investigations. A linear correlation between the Somerton Index (S_D) and the LDCP tip resistance (q_d) was obtained in granular soils under controlled conditions, ranging from sand (SP) to sandy gravel (GP). The obtained relationship was applied to MWD results from a 180-m long, 50-m tall grassy slope in New Hampshire, USA. It was observed that the estimated q_d values from drilling parameters have a good correspondence with LDCP results at the same testing locations. Shallow subsurface characterization using MWD can potentially be used for shallow foundations, compaction control, pavement subgrade evaluation, and areas prone to geotechnical hazards not easily accessible through usual exploration methods.

Keywords: Measurement While Drilling; MWD; Dynamic Cone Penetrometer; DCP; PANDA; in situ testing.

1. Introduction

Measurement While Drilling (MWD) systems were initially developed in the oil industry in the 1960s to control or correct boreholes to reach target locations in the subsurface. Since the 1970s, adaptions and improvements have been made to MWD systems to perform geotechnical investigations. Several field assessments with MWD highlight the applicability of this test method to monitor drilling operations, characterize the subsurface stratigraphy, detect cavities, and assist in foundation and grouting projects (Girard, 1985; Reiffsteck et al., 2018).

The latest MWD systems consist of sensors installed on drill rigs that measure several parameters in real-time data, including time, depth, advance rate, down thrust pressure and/or force, holdback pressure, rotation rate, water/mud flow, and water/mud pressure. These sensors are directly connected to a junction box where data can be exported through USB or wirelessly, depending on the equipment available (Reiffsteck et al., 2018; Rodgers et al., 2018; Sadkowski et al., 2008). This test method is currently standardized in Europe by ISO 22476-15:2016, Part 15. In the United States, an AASTHO standard is currently in progress to provide drilling recommendations for uniform application of the technique.

Despite the versatility of MWD equipment and its rising interest in the geotechnical community, this in situ test requires the mobilization of large equipment and specialized drilling crew. The costs, efforts, and equipment size associated with a conventional geotechnical investigation for boreholes deeper than 1 m limit the applications of the current test methods.

To address this limitation, a portable MWD equipment was designed and built by the Center for Studies on Risks, the Environment, Mobility and Urban Planning (CEREMA) in France. The device, shown in Fig. 1, consists of sensors mounted on a cordless rotary drill that records time, depth, downforce, rotation, and torque. The system communicates wirelessly with a USB antenna installed on any computer, usually within up to 10 meters of the equipment. The cordless drill has two handles facilitating the drilling process, especially on hard ground.

This paper introduces the portable MWD equipment as an innovative and lightweight tool to rapidly assess shallow subsurfaces. 66 MWD profiles were obtained from laboratory and field tests on granular soils. The objective of this initial assessment was to establish a direct comparison between portable MWD results and a standardized testing method to measure soil resistance. For that purpose the Lightweight Dynamic Cone Penetrometer (LDCP – PANDA) was selected due to its portability and ease of operation especially on areas of difficult access such as rough terrain and slopes. The lightweight penetrometer is a standardized test method in France (NF P 94-105:2012) used in shallow geotechnical design applications, including compaction control, pavement subgrade evaluation, and shallow foundation design.

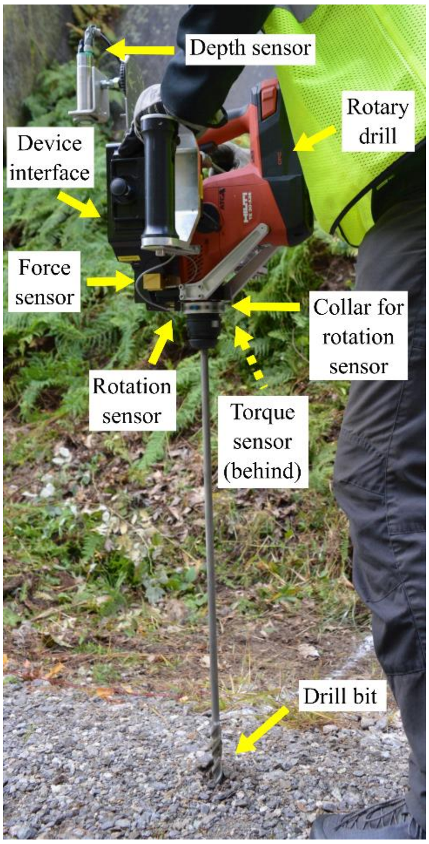

Figure 1. Portable MWD equipment and its constituting parts.

2. Methodology

2.1. Evaluation under controlled conditions

In order to perform an objective comparison between MWD and DCP measurements, tests were initially performed in soils prepared under controlled conditions. Two materials, 0-4 mm sand (Fig. 2a) and 0-40 mm sandy gravel (Fig. 2b), were consistently compacted in two layers of 20 cm using a plate compactor. The properties of the tested materials and their characteristics in-place are presented in Table 1. Two materials of different resistance and deformability after compaction were selected to evaluate a range of deformable granular soils often encountered in rockfall-prone areas.

Given the number of measured variables in each profile, and the uncertainty as to which parameters or combinations of parameters would yield any relationship between the penetrometer data, different compound parameters recommended by ISO 22476-15:2016 were evaluated. These parameters, detailed in Eqs. 2 to 5, consist of empirical indices or energies that combine two or more measured MWD parameters to reflect the resistance of the material to drilling. Although changes in drilling parameters often indicate changes in subsurface conditions, compound parameters normalize the effect of conditions imposed by the test operator, e.g., rotation rate and down force. Such normalization is indispensable to evaluate large data sets, even if the same test operator performed all tests.

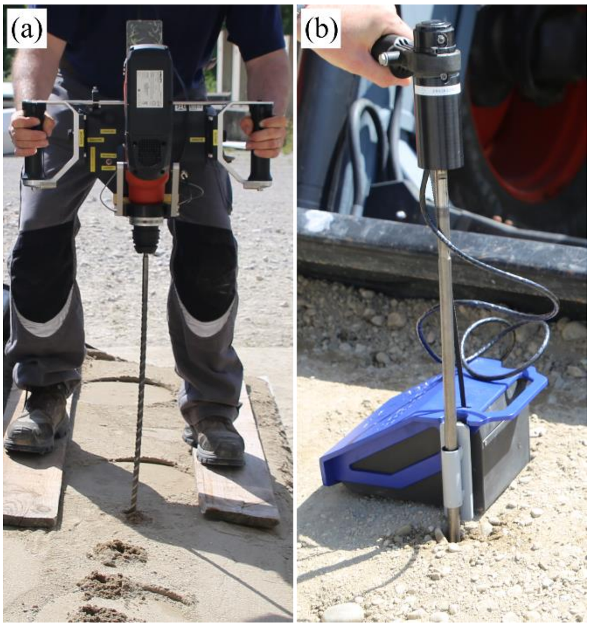

Figure 2. Tests under controlled conditions: (a) MWD on sand and (b) LDCP on sandy gravel.

Some compound parameters require the downforce to be transformed into pressure (Eq. 1). The drill bit used in this paper is 16 mm in diameter.

$$P_E = F_{down}/A_{drill\ bit} \tag{1}$$

Where P_E = downthrust pressure (MPa)
F_{down} = downthrust force (MN)
$A_{drill\ bit}$ = drill bit area (m²)

The Somerton Index (Eq. 2 – Somerton, 1959, modified by Girard, 1985) is a unitless empirical index that characterizes the drilling resistance of a material.

$$S_D = P_E * (V_R/V_A)^{0.5} \tag{2}$$

Where S_D = Somerton Index (unitless)
P_E = downthrust pressure (MPa)
V_R = rotation rate (rpm)
V_A = advance rate (m/s)

Table 1. Properties of the materials evaluated under controlled conditions.

USCS	**D_{10}** mm	**D_{30}** mm	**D_{60}** mm	**C_c**	**C_u**	**Fines** %	**c** kPa	**ϕ‘** °	**ρ_{total}** kg/m³	**ρ_{dry}** kg/m³	**D_r** %	**w** %
SP	0.20	0.31	0.60	0.8	3.0	3.5	0	35	2030	1920	55*	5
GP	0.15	0.75	7.2	0.5	48	7.9	0	49	2440	2350	70*	4

* Estimated with the lightweight dynamic penetrometer.

The energy used to drill shallow boreholes (Teale, 1965; Pfister, 1985), is calculated as shown in Eq. 3. Pfister (1985) also suggests a simplification where the thrust pressure is neglected and only the work produced by the torque is considered, as shown in Eq. 4.

$$E_S = P_E + (2 * \pi * V_R * T)/(A * V_A) \tag{3}$$

$$E_R = (2 * \pi * V_R * T)/(A * V_A) \tag{4}$$

Where E_S = specific drilling energy (MJ/m³)
E_R = drilling energy by rotation torque (MJ/m)
P_E = down thrust pressure (MPa)
V_R = rotation rate (rpm)
T = torque (MN.m)
A = drill bit area (m²)
V_A = advance rate (m/s)

Finally, the penetration resistance was also calculated for each time step (Eq. 5). It consists of the time in seconds for 0.025 m of penetration. The European standards recommend a depth of 0.20 m, but due to the shallow depths of the tests performed, the depth recommended by the upcoming US standard was chosen instead (0.025 m, or 1 inch).

$$P_R = (time)_{Z\,=\,0.025\,m} \tag{5}$$

Where P_R = penetration resistance (seconds)

2.2. Field assessments

A total of 33 PMWD and 77 LDCP profiles were obtained along a grassy slope in Enfield/NH, USA, where an experimental rockfall campaign was also conducted. The tested area, shown in Fig. 3, is 180 m long and 50 m tall. Cones were positioned every 10 m along the slope surface for a uniform distribution of tests based on a “reference line”, as shown in the figure. The average inclination between P01 and P10 is 20°, while the average inclination between P10 and P15 at the toe of the slope is 2°.

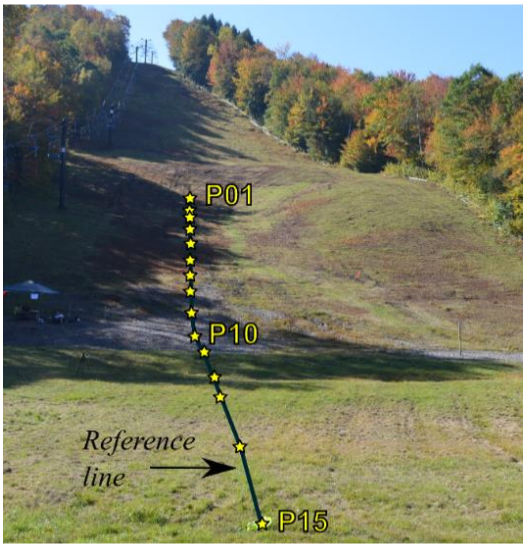

Figure 3. Test slope in Enfield/NH, USA. The spaces between each pair of stars measure 10 m along the slope surface.

Multiple soil profiles were obtained at the elevation of each reference point shown in Fig. 3. Tests were normally performed starting at the reference line, and additional test locations at each elevation were performed at regular distance increments parallel to the reference line. These increments corresponded to 1.5 m for the LDCP and 3 m for the PMWD. Fig. 4 displays the distribution of the profile locations given the upper view of the point cloud obtained at the site through photogrammetry. The dotted yellow lines delineate each profile location, and the blue colormap illustrates the distance increments for these tests.

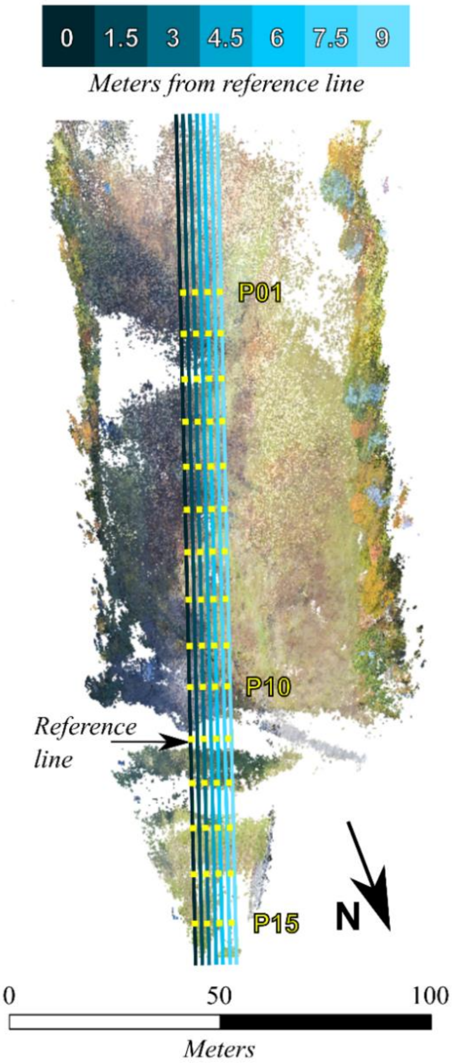

Figure 4. Distribution of test locations along the slope profile.

3. Results and discussion

3.1. Tests under controlled conditions

Each PMWD test provided a soil profile formed by parameters recorded individually by each sensor (i.e., drilling rate, rotation rate, down pressure, torque) and the compound parameters presented in section 2. Two typical profiles on sand and sandy gravel are shown in Fig. 5, as well as two examples of penetrometer profiles for each material at corresponding depths.

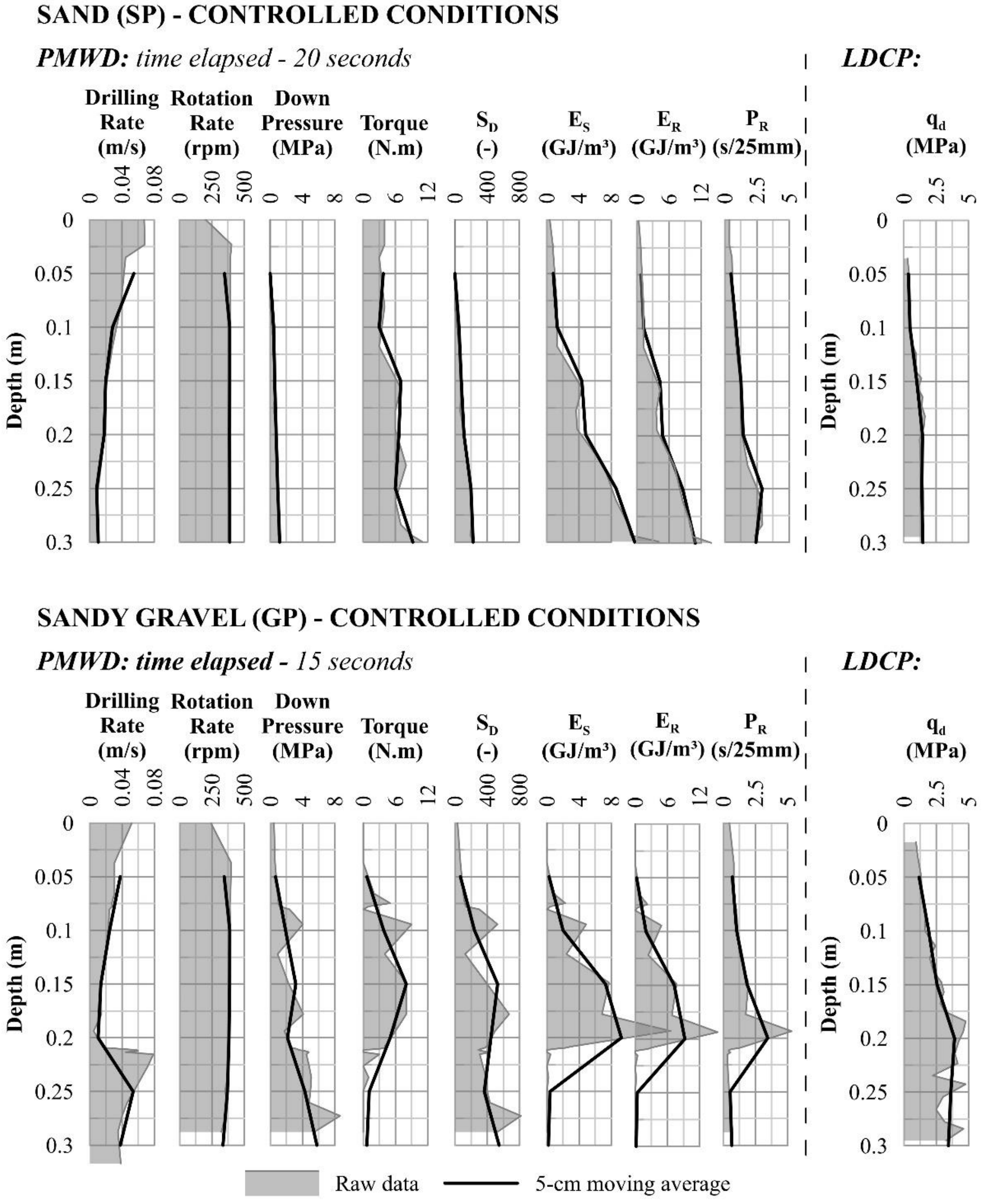

Figure 5. Examples of PMWD and LDCP profiles obtained under controlled conditions on sand and sandy gravel. The high variability due to the presence of pebbles requires the use of moving averages for a more objective interpretation of subsurface conditions.

The hatched gray areas represent the raw data, measured at irregular depth intervals according to the time step (PMWD) or increments per blow (LDCP). The black lines represent a 5-cm moving average of each plot. It is possible to observe that, while the sand plots show little to no variability, the sandy gravel has a significant variability in measured drilling parameters and tip resistance (q_d), attributed mostly to pebbles randomly distributed in the soil matrix. The parameter changes between 0.15 and 0.20 m illustrate the end of the first compaction layer.

The rotation rate (V_R) was kept approximately constant at 380 rpm for both materials. In general, higher drilling rates (V_A) indicate softer materials for a constant rotation and applied down pressure, while lower rates suggest the presence of harder ground. However, the V_A parameter cannot be assessed objectively as the operator needs to apply variable pressures to drill through materials. While a regular increase in P_E is observed on sand, variable pressures were recorded while drilling on sandy gravel as it was attempted to advance through the pebbles in the soil.

Variations in measured torque also accompanied these variations in down force.

The increase in soil resistance as the bottom layer is approached is observed with increasing Somerton Index (S_D) and drilling energy (E_S). The increase in resistance is also seen in the penetrometer profiles, where the sand presented a maximum q_d of 1.3 MPa and the sandy gravel recorded an average maximum value of 3.8 MPa. A similar increasing trend is observed in both materials for the Somerton Index, where a maximum value of 200 was obtained for sand and a maximum average value of 600 was recorded on gravel.

While correlations between the penetrometer tip resistance and PMWD results were attempted for all parameters shown in Fig. 5, this paper presents selected relationships established for both soils, as shown in Fig. 6. The 5 cm moving average from each profile was summed at each depth increment and divided by the number of tests. In the upper left plot, it was observed that the calculated S_D data from drilling parameters presents an approximately linear relationship for granular materials under controlled conditions, despite the heterogeneity observed in the sandy gravel. The relationships delineated in red are evaluated in field conditions in the following section. Although changes in down pressure were recorded in all tests, it is still possible to observe a relationship between the penetration resistance (P_R, directly related to V_A) and q_d for the sand, a relatively uniform material. This association is not observed for heterogeneous soil conditions, often expected in the field. In addition, a linear relationship between the tip resistance and the drilling energies (E_S and E_R, neglecting the thrust pressure) is also observed for the sand, as shown in the plots on the right of Fig. 6.

Although an empirical relationship could be obtained within the data, attention must be paid to the type and diameter of drill bit used. Previous research on conventional MWD systems performed by Reiffsteck et al. (2018) evaluated the Somerton Index on different materials, including sand, gravel, silt and chalk, drilled with five drill bit types. It was observed that, for a same material, different S_D values are obtained with different bit geometries.

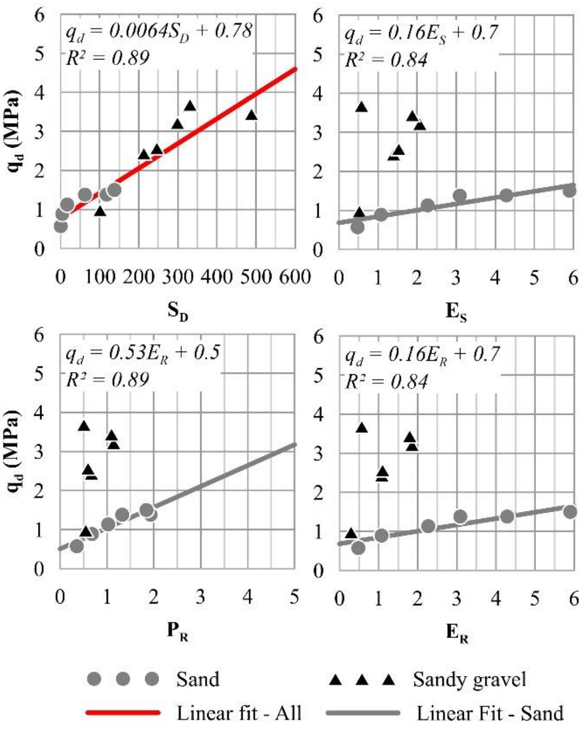

Figure 6. Relationship between the calculated MWD compound parameters and penetrometer tip resistance.

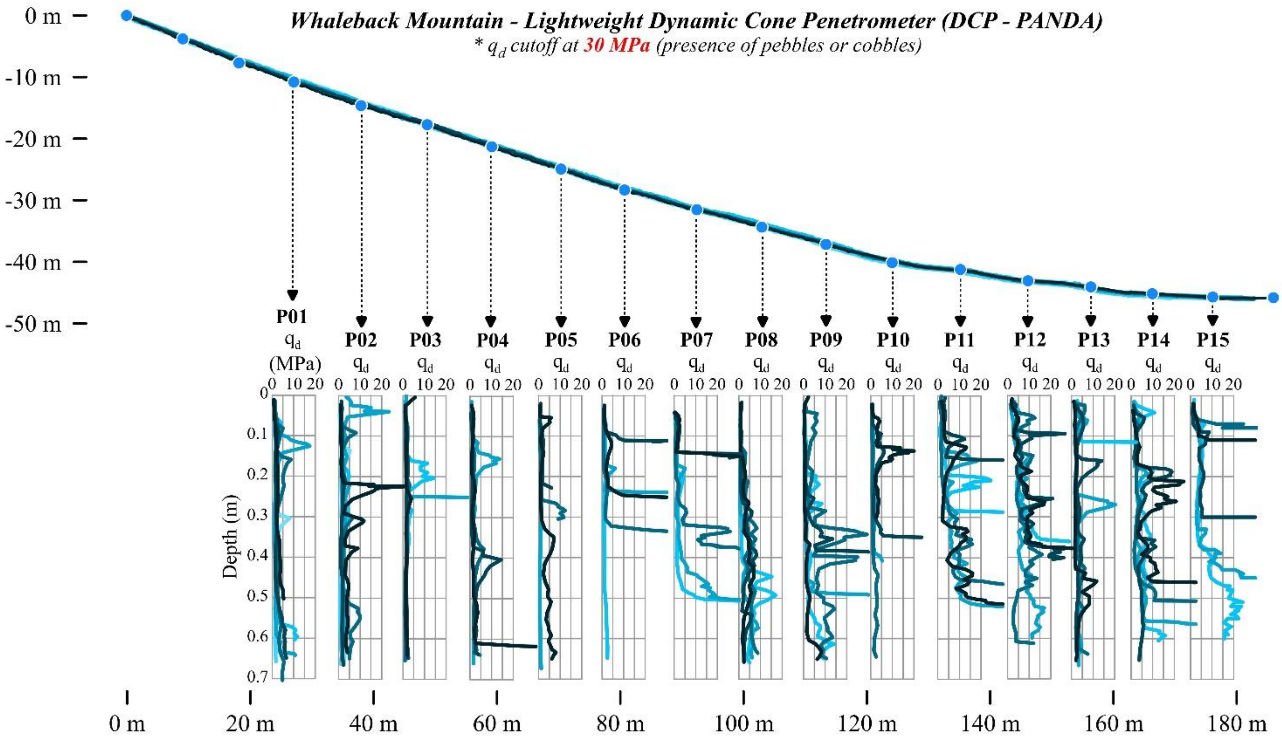

Figure 7. Distribution and results of LDCP tests along the test slope, with a cutoff of 30 MPa.

3.2. Field testing

Figure 7 illustrates a compilation of all slope profiles, plotted in different tones of blue matching the colormap shown in Fig. 4. Black plots represent the tests performed closest to the reference line, while gray plots indicate profiles away from the reference line. Below the slope profiles, a compilation of all raw LDCP measurements is presented following the same colormap. Although the tested slope presents a relatively uniform geometry and regular 2D cross-sections along its width, the PMWD and LDCP tests demonstrated that the ground presents significant variability at shallow depths.

Abrupt increases in q_d, mostly with nearly horizontal lines, indicate an increase in resistance due to the presence of pebbles or cobbles, which usually led to test refusal. The high variability in this extensive data set highlights the need to use a moving average for a more objective and consistent assessment of soil resistance and to compare both test methods. Fig. 8 presents the averaged data including the lower and upper boundaries determined by adding or subtracting the standard deviation, respectively. Each averaged data set included profiles from a single elevation.

The LDCP measurements suggest that there is an increase in soil resistance from profile 06 (P06), where test refusal is encountered at shallow depths (above 0.3 m, shown in Fig. 7). Between P01 and P06, the average q_d values range between 0 and 5 MPa, whereas a global increase in resistance, especially under 0.3 m, is observed between P07 and P15.

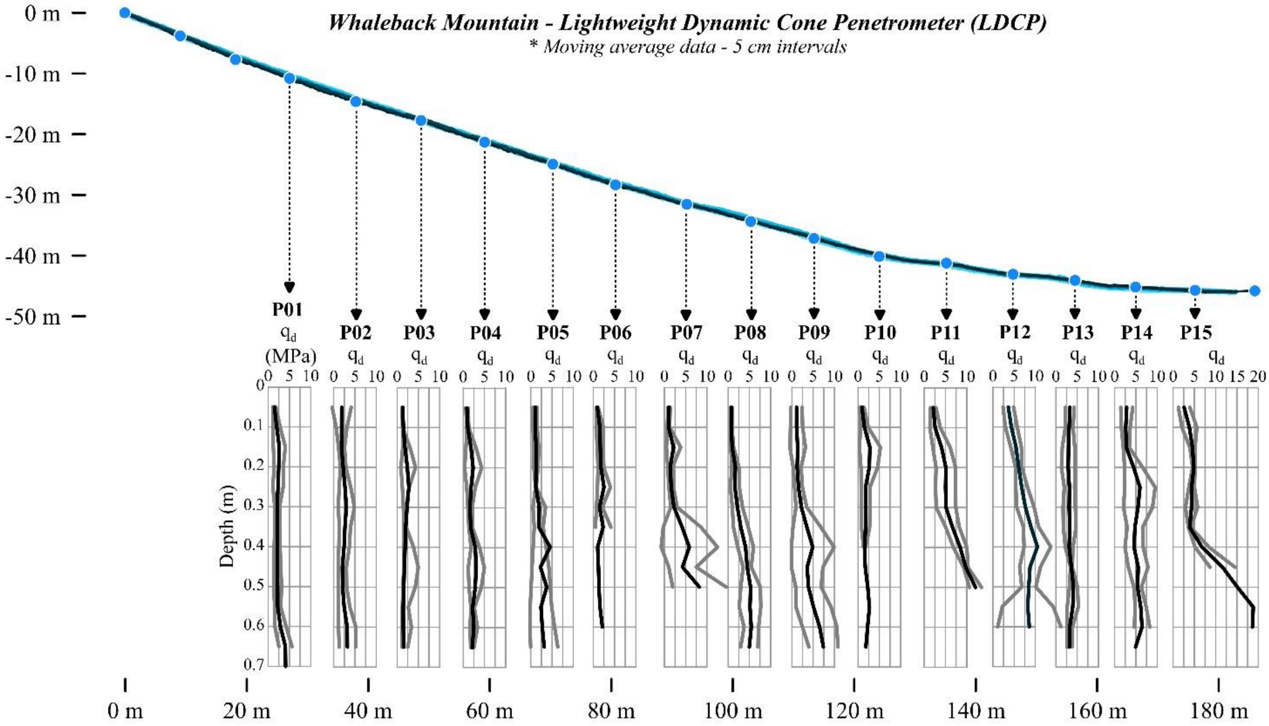

Figure 8. Distribution and results of DCP tests along the test slope, average data.

Figure 9 presents the average S_D values obtained along the test slope with the portable MWD. While each average profile was calculated from approximately 5 LDCP tests, the average PMWD profile was determined based on 2 to 3 tests at each elevation. S_D values over depth are uniform and present values below 300 between P01 and P05. An increase in resistance to drilling is also measured as tests move downslope, often recording values between 300 and 1000. As demonstrated by the tests under controlled conditions, the uniform sand recorded values between 0 and 150, while the gravelly soil recorded values within 100 and 600. Therefore, based on results from both test campaigns, it is estimated that the upper slope is mostly constituted by a granular soil of lower resistance, while the lower slope starting at P06 is mostly formed by a heterogeneous soil with erratic pebbles or cobbles.

The 5-cm moving average of each PMWD profile was compared to the penetrometer resistance at adjacent test locations. S_D results from the field tests were applied in the relationship presented in red in Fig. 6 and Eq. 6. The calculated q_d values from Eq. 6 were compared to the LDCP measurements at adjacent boreholes, as shown in Fig. 10. Despite the heterogeneity observed in all soil profiles, it is possible to observe that the estimated q_d values overall correspond well to the LDCP measurements.

$$q_{d\,(estimated)} = 0.0064\, S_D + 0.78 \tag{6}$$

Where $q_{d\,(estimated)}$ = estimated q_d value from empirical correlation at a given depth

S_D = calculated Somerton Index from PMWD measurements

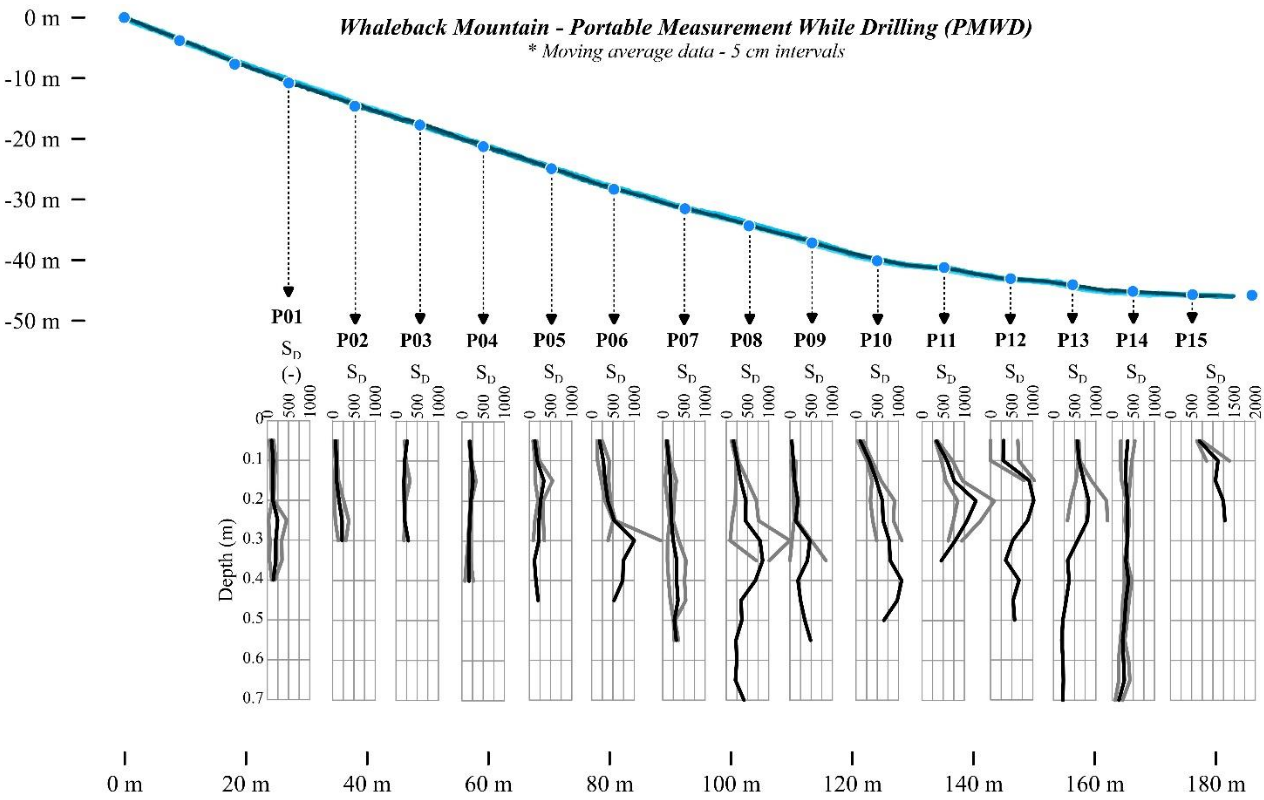

Figure 9. Distribution and results of MWD tests along the test slope, average S_D.

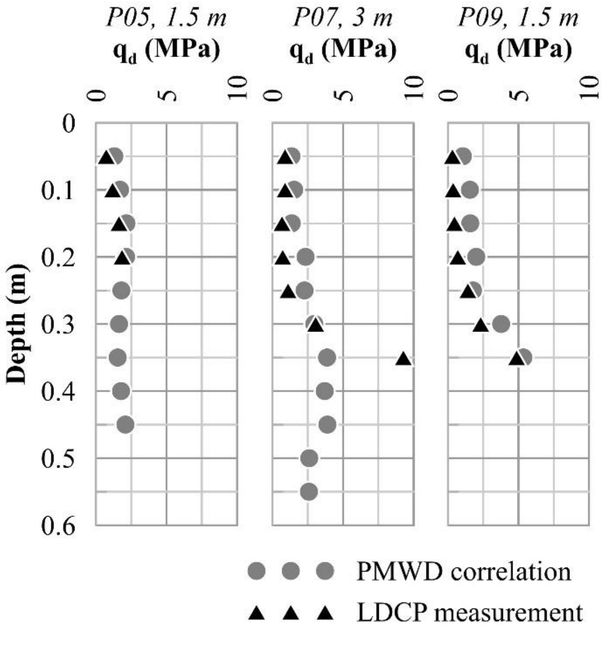

Figure 10. Comparison between the estimated resistance to penetration from Eq. 6 and the q_d values measured in the field with the LDCP.

4. Conclusions

The present paper introduced the portable Measurement While Drilling as an innovative device to assess shallow subsurface conditions. Opposed to conventional MWD systems, this lightweight device provides rapid profiles of drilling parameters, which are combined to obtain information on material resistance to drilling and heterogeneity. A full portable MWD profile of up to 70 cm is usually obtained within less than a minute. The data file is immediately saved after the test and ready for use.

Several MWD profiles were compared to a lightweight penetrometer (LDCP, PANDA), a standardized test commonly used in several shallow geotechnical design applications.

A comparison between PMWD and LDCP results under controlled conditions in granular materials led to linear relationships between PMWD compound parameters and the penetrometer resistance to penetration. These relationships were applied to PMWD measurements in the field, along a 180-m long and 50-m tall slope with heterogeneous soil conditions, formed by granular materials at shallow depths. A wide distribution of tests along the slope area provided an overall view of the soil resistance with the dynamic penetrometer. The relationships between PMWD and LDCP established under controlled conditions were successfully evaluated from the in situ profiles. It was observed that the estimated q_d values matched LDCP measurements at adjacent locations.

Although the use of the portable MWD was validated in this experimental campaign, further evaluations for different material types, including cohesive soils and rock, still need to be performed to demonstrate the applicability of the equipment on a wider range of geological materials and conditions.

Results from this experimental campaign will provide a better description of potential rockfall impact zones, which will ultimately help improve existing rockfall models and their predictions of the rockfall kinematics produced from the complex interaction between the falling block and the ground.

Acknowledgements

The authors would like to acknowledge Whaleback Mountain (NH, USA), in special Jon Hunt, for their collaboration in allowing us to perform this field experimental campaign. Acknowledgements also to the RRO technical team at Gustave Eiffel University for their assistance with test preparation under controlled conditions: Patrick Joffrin, Christophe Pruvost, and Nicolas Vermorel.

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