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Seismic piezocone and seismic flat dilatometer tests at Treporti

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ABSTRACT: Seismic piezocone tests (SCPTu) and seismic flat plate dilatometer tests (SDMT) were conducted prior to the construction of the Treporti embankment near Venice in order to characterize the geostratigraphy, soil strength, and small-strain stiffness profiles in these highly-layered soils. A low cost system was developed which adds seismic capabilities to a standard flat plate dilatometer system. Three SCPTu soundings were conducted in routine downhole manner using a pseudo-interval procedure, whereas three SDMTs were performed using a true-interval setup. For one SDMT, frequent-interval shear wave velocities were obtained at each 20-cm test depth, thus providing exceptional detailing of the V_s profile.

1 INTRODUCTION

Prior to the construction of a test embankment in the Venetian lagoon at Treporti, series of seismic piezocone penetration tests (SCPTu) and seismic flat dilatometers (SDMT) were hydraulically pushed to depths of 40 meters during one phase of the geotechnical site characterization. The soils conditions consist of a complex assortment of alluvial to deltaic to marine interbedded silts, sands, and clays from the uplands north of the Treporti area (Ricceri, et al. 2002).

The test embankment was eventually built to a final height of 6.7 m over a circular area 40 m in diameter in order to best gage the settlement response of the subsoils. Full details concerning the instrumentation and results of the settlement monitoring of the embankment are given elsewhere (Marchetti, et al. 2004). Representative reference laboratory data, mechanical properties, and soil parameters for nearby sites in the Venetian lagoon deposits have been presented by Ricceri, et al. (1997) and Cola & Simonini (2002).

2 FIELD EQUIPMENT

The seismic piezocone and seismic flat dilatometer tests were performed to provide detailed characterization of the geostratification and soil behavior with depth at both small- and large-strains (e.g., Burns & Mayne, 1996). Three pairs of SCPTus and SDMTs were located across the diameter of the planned loading embankment. Each testing location (Designate No. 14, 15, and 19) was approximately 15 meters apart with one SCPTu and one SDMT advanced within 1 m of each other by a 25-tonne cone truck (Figure 1).

The addition of seismic sensors to the standard CPT and DMT systems allows independent collection of both strength and stiffness parameters without additional geophysics testing (Campanella, et al. 1986; Hepton, 1988; Martin & Mayne, 1998). Another benefit is that multiple data types are measured at the same test locations.

Figure 1. Cone rig used to advance the SCPTu and SDMTs.

The SCPTu is capable of characterizing the soil with 5 types of measurements in a single sounding: tip resistance (q_T), sleeve friction (f_s), penetration pore pressure (u_b), dissipations with time (t_{50}), and shear wave velocity (V_s). For the testing at Treporti, the SCPTu equipment was an analog penetrometer with tip stress, sleeve friction, shoulder-mounted pore pressure element (u_2), inclinometer, and a geophone. The standard CPTu channels were recorded at 2.5 cm intervals while seismic data were collected using a pseudo-interval method at 1 m intervals during the pause at the end of each rod break. The seismic source was a short steel beam coupled to the ground by a leveling leg of the cone truck. A sledgehammer pendulum was used to strike the beam and generate horizontally polarized, vertically propagating shear waves.

The SDMT is also capable of providing 5 measurements from a single test: initial contact pressure (p_0), expansion pressure (p_1), closing pressure (p_2), A-reading dissipation (t_{flex}), and shear wave velocity (V_s). In Treporti, the flat blade dilatometer was provided and operated by the University of L'Aquila. It was not originally designed to incorporate seismic sensors, but the additional functionality was added with minimal machining and wiring. Two geophone modules were made from short segments of 44 mm diameter rod with cone rod threads on each end (Figure 2). The modules, separated by an assembled rod (0.95 m long), were aligned and attached behind the dilatometer blade in a true-interval downhole configuration (Butcher & Powell, 1996).

Figure 2. One of two seismic modules with miniature geophone

The geophones, just 16.70 mm in diameter, were mounted horizontally in the modules in order to detect the horizontally polarized shear waves. The signals were recorded with a battery-operated hand-held multi-meter/oscilloscope or scope meter (Figure 3). Each geophone was connected by a thin coaxial cable to the scope meter at the surface. The two small diameter coaxial cables fit easily inside the rods with the DMT cable. A notebook computer was used to download and store the recorded signals.

The battery-operated, hand-held scope meter was chosen for its small size and ability to operate for long periods without an external power source. Because the flat dilatometer test does not require a separate electrical power source, it was anticipated that a reliable power source might not be available. It was discovered during testing that, indeed, the electrical power, which the cone truck provided, could not be supplied continuously. The notebook and scope meter were at times required to operate for hours on batteries alone.

Figure 3. Hand-held battery-powered portable scope meter

For two SDMTs, seismic measurements were taken at each rod break. For comparison, both the pseudo-interval and the true-interval methods were conducted during the SDMT soundings.

For one sounding (No. SDMT14), V_s measurements were made at frequent 20 cm increments, which is the same interval as for the DMT A- and B-readings. The set interval between the geophones was 0.95 m, so the V_s measurements every 20 cm were actually overlapping intervals. The measurements for this frequent-interval procedure could be finished in less time than it took to make the DMT pressure readings, so there was no delay to the standard DMT testing procedure.

3 RESULTS

The soundings detailed a complex soil profile of alternating sands, clays, and silts in these Venetian sediments, as recognized from prior studies (e.g., Ricceri, et al. 2002). Figure 4 shows the results from one cone sounding taken to 40 meters. Of particular

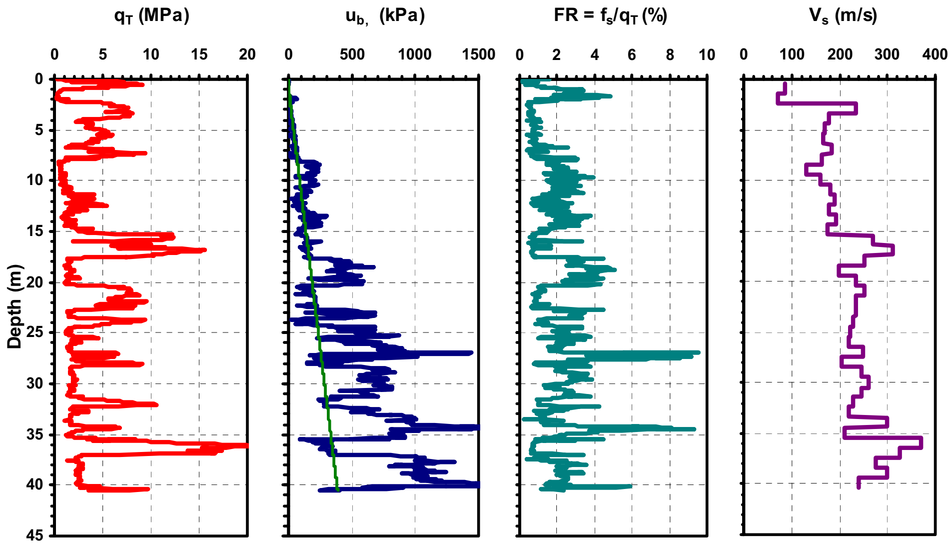

Figure 4. Representative results from seismic piezocone at the Treporti test embankment site (No. 19).

interest at this site, the CPTu soundings showed spikes in the q_t, f_s, and u_b, yet associated decreases in in V_s at depths of 27.4, 34.5, and 40.4 m (Figure 4), apparently associated with thin peat lenses or seams. In all three soundings, these respective trends were observed consistently at about the same elevations.

4 TRUE- VS. PSEUDO-INTERVAL TESTING

The pseudo-interval V_s measurement requires only a single receiver, either a geophone or an accelerometer, mounted horizontally inside the rod string. A seismic source at the surface generates a signal and triggers the data acquisition to start recording the signal from the receiver mounted in the rods. The receiver is then pushed to a new depth and a new signal is generated and acquired. To calculate the velocity, the difference in the travel path lengths from the source to the receiver at sequential depths is divided by the time difference between the signals at those depths.

The true-interval V_s measurement requires at least 2 receivers mounted inside the rods with a fixed distance between them. In this way, a single source signal is acquired at two depths simultaneously. The analysis is the same as the pseudo-interval method, but the effects of the uncertainty of the depth measurement and the trigger start-time are eliminated. Additionally, with the sensors spaced a fixed distance apart, overlapping measurements can be made by shifting the entire device less than the spacing between receivers. The V_s data will show detail and layer changes that have an appearance more similar to the CPT and DMT type measurements. A slight disadvantage with true-interval is the increased cabling through the rods.

Figure 5 shows the true-interval results plotted with the pseudo-interval results at location 19. In general, the profiles are in agreement, yet false highs and false lows are evident in the pseudo-interval profiles, due to slight errors caused by trigger tim-

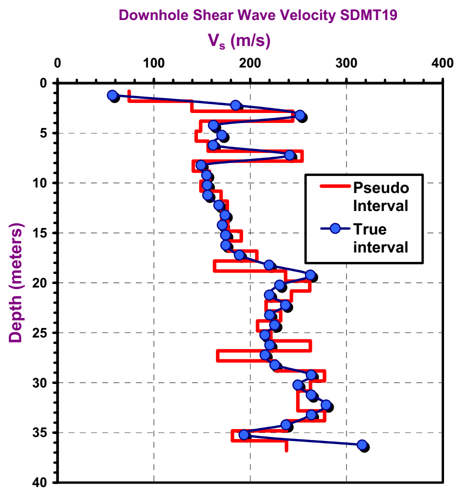

Figure 5. Comparison of true- and pseudo-interval V_s.

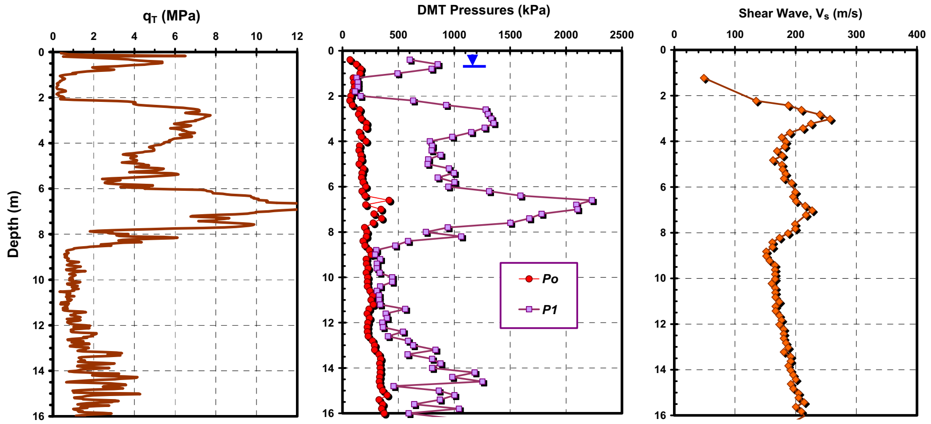

Figure 6. Frequent-interval shear wave velocity profiles taken during SDMT 14 with corresponding cone tip reading.

ing, source repeatability issues, and small inaccuracies in the depth measurement (Butcher & Powell, 1996). Similar comparisons were observed for data from locations 14 and 15. The true-interval result is more reliable because there is no trigger, the same signal is received at both receivers simultaneously, and the receiver distance is fixed.

5 FREQUENT-INTERVAL METHOD

In-situ testing methods provide highly detailed profiles of soil properties with depth. Rather than reduce all of the data to a few average values associated with layers, it is common to perform engineering calculations on a point-by-point basis using commercial spreadsheets or other computer software. Though the DMT measurements are made at 20 cm increments, and the CPT data are recorded at increments of about 2.5 cm, V_s is typically measured on one-meter intervals. The growing significance being placed on small-strain properties and consideration of thin layers demonstrates a need for V_s to be measured on a scale that is compatible with companion in-situ test methods.

During SDMT 14, frequent-interval measurements of shear wave were taken every 20 cm at the same time as the A-, B-, and C-readings. Figure 6 shows the profiles of p_0, p_1, and true-interval V_s for this sounding, indicating a rather fine detailing of the shear wave velocity not normally discerned. The frequent interval approach shows promise for improving the reliability and the quality of V_s. Because the measurements are overlapping, there can be no sharp changes in velocity. The profile should always have smooth transition from point to point. This is a current limitation of the method with respect to detecting layer boundaries and very thin layers, but the benefit is the identification of outliers.

6 DISCUSSION

The testing program demonstrates that seismic velocity readings can be incorporated into in-situ testing devices with minimal cost and effort. Aside from the two simple steel geophone modules, all the equipment was purchased and used without modification. The most difficult aspect was making durable water-resistant electrical connections that could fit inside the cone rods. The device was built as modules rather than a single piece in order to reduce the size and weight for shipping. All of the SDMT equipment fit neatly inside a suitcase packed with clothes. Additionally, the modular configuration was necessary to guarantee compatibility with the cone truck that was to be provided. Pushing long devices can be difficult for some trucks, as the distance between the ground surface and the upper limit of the pushing system is limited. Because the mechanical specifications of the cone truck were not known in advance, the device had to be able to be pushed in sections if necessary.

The portability of the seismic equipment complimented the portability of the DMT equipment, which requires only a 9 V battery and a cylinder of compressed nitrogen. Battery power was enough to last for a day of testing with the scope meter and notebook computer, with recharging at night.

For simplicity in the seismic testing, a single receiver provides reliable results. However, the true-interval method is recommended as it is more robust and can be used as pseudo-interval in the event a sensor should fail during a test. Extra care is needed for the depth measurements when operating a pseudo-interval test. The standard DMT does not have a device to measure depth of penetration. The truck operator pushes 20 cm at a time as viewed from the deck of the truck. Rod rebound or movement of the truck may interfere with the accuracy. The true-interval method is not sensitive to this issue as the receiver spacings are fixed.

The frequent-interval procedure with overlapping measurements provides a more detailed view of the shear wave velocity profile. More closely spaced measurements help with identification of layer boundaries, and also reduce the effect of any individual bad readings. However, because of the spacing between the geophones, the results will provide a smoothed picture of the actual velocities. Without frequent-interval measurements, the measured V_s values in a layer may appear to change from test location to test location due to the presence of thin layers.

Of additional interest are interrelationships between the measured shear waves and penetration test data. Correlations are available for sandy soils tested by CPT (e.g., Baldi, et al. 1989) and DMT (e.g., Tanaka & Tanaka, 1998), as well as clayey soils tested by CPTu (e.g. Mayne & Rix, 1995) and DMT (Kalteziotis, et al. 1991). Due to the complex geostratigraphy at Treporti, an empirical relationship proposed by Hegazy & Mayne (1995) for estimating shear wave velocity in clays, silts, and sands from cone tip stress and friction ratio ($FR = f_s/q_t$) was used:

$$V_s = [10.1 \cdot \log(q_t) - 11.4]^{1.67} \cdot [FR]^{0.30} \quad (1)$$

where V_s is in m/s, q_t in kPa, and FR in %. Using the corresponding data from SCPTu 14, Figure 7 shows that this empirical correlation appears to well map the detailed profile that was delineated by the frequent-interval shear wave results produced during SDMT 14.

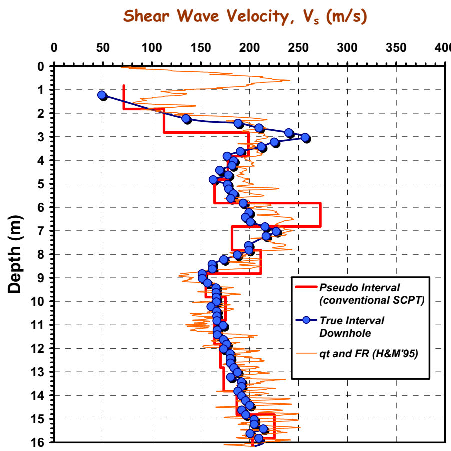

Figure 7. Frequent true-interval, coarse pseudo-interval, and empirically-estimated V_s at location 14.

7 CONCLUSIONS

A series of seismic piezocone and seismic dilatometer tests have been conducted in the Venetian sediments for site characterization related to the Treporti test embankment. A simple geophone module added to the flat plate dilatometer provided capabilities for downhole shear wave velocity determinations during field testing. The device obtained true-interval V_s measurements that were more well behaved and apparently more reliable than conventional pseudo-interval readings. A special series of frequent measurements at 20-cm depth intervals showed nicely behaved profiles of V_s that provided detailing not normally realized from conventional data obtained by crosshole, borehole downhole, and surface type geophysics at coarse depth resolutions.

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