Proceedings ISC-2 on Geotechnical and Geophysical Site Characterization, Viana da Fonseca & Mayne (eds.)

Site characterization and QA/QC of deep dynamic compaction using an instrumented dilatometer

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Keywords: dilatometer, instrumented dilatometer, deep dynamic compaction, unload-reload modulus

ABSTRACT: An instrumented dilatometer (IDMT) was one of several in situ testing tools that were used on a major highway relocation project in Carver, Massachusetts (USA). Parts of the new highway span former cranberry bogs. Sheet piling was installed along both sides of the new highway alignment, and organic material was dredged from between the sheet pile walls. The area was then backfilled with sands. Since most of the sand was placed in a fairly loose state under water, liquefaction was a potential problem. Therefore, deep dynamic compaction (DDC) was used to densify the fill. An extensive in situ testing program was instituted to characterize the site conditions prior to densification, and to assess the sufficiency of the DDC after treatment. The results of this study suggest that the IDMT can be used to provide accurate and cost-effective stratigraphic profiles. The IDMT was particularly helpful in identifying pockets of organic soils (i.e., peat) that were not completely removed during the initial dredging operations. In terms of compaction assessment, the modulus values determined from the IDMT appear to be very sensitive indicators of densification effects.

1 INTRODUCTION

The state of Massachusetts Highway Department is in the process of relocating a section of US Route 44 from the existing Route 44 in Carver, MA to US Route 3 in Plymouth, MA. The study described herein was conducted at a section where mechanically stabilized earth (MSE) walls will eventually be constructed through former pond and cranberry bog areas. The native site stratigraphy consists of standing water and/or peat deposits of varying thickness that extend in depth up to a maximum of about 9.8 m. Glacial outwash deposits consisting of loose to dense, coarse to fine sands with lenses of silt, clay and gravel exist beneath the peat.

The construction project started with the installation of steel sheet piling through the pond/bog sections. The sheeting was located about 23.0 to 24.6 m off the proposed highway centerline. After removal of the peat deposits from within the sheet pile walls, granular fill was placed between the sheet piling by pushing the material forward (from the "land side") with a dozer. Fill was place from the dredged mudline (which varied widely in elevation) to approximately Elevation 34.5 m (roughly 1.6 m above the static groundwater table). A typical grain size distribution curve, as well as upper and lower limits of the range of grain size distribution of the fill material is provided in Figure 1. The fill is classified as poorly-graded sand according to the USCS classification system. The mean D_{50} is approximately 0.4 mm.

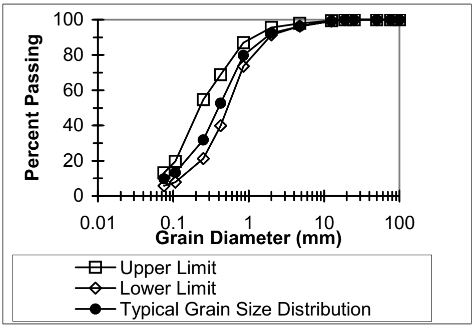

Figure 1. Grain Size Distribution of Hydraulic Fill Material

Since most of the sand was placed in a fairly loose state under water, the potential for liquefaction was a concern. Therefore, deep dynamic compaction (DDC) was used to densify the fill. In situ testing was conducted before and after compaction to obtain

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baseline soil parameters and to assess the sufficiency of the DDC treatment.

2 DEEP DYNAMIC COMPACTION PROGRAM

Deep Dynamic Compaction is a process whereby soil is densified by repeatedly dropping a massive weight from a crane to impact the ground. Dynamic energy is applied on a grid pattern over the site, typically using multiple passes with offset grid patterns. The DDC process, described in detail by Lukas (1995), is generally very effective in densifying loose granular deposits. The degree of improvement is a function of the applied energy per unit cross-sectional area, which is related to the tamper mass, the drop height, the number of drops and number of passes applied. The depth of improvement, which is a function of tamper mass and drop height, can be estimated using an empirical equation given by Lukas (1995). The maximum improvement resulting from DDC is predicted to occur within a zone from about 1/3 to 1/2 of the depth of improvement calculated using the equation proposed by Lucas (1995).

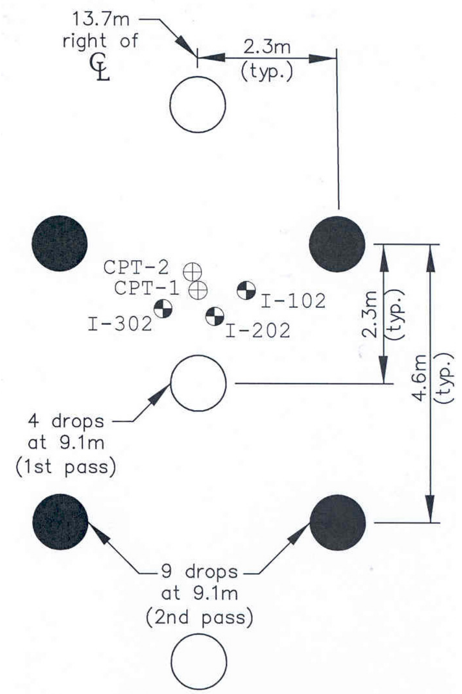

Figure 2. Details of Compaction Near IDMT Soundings

The DDC for this project was conducted using a tamper that weighed 15 Mg. The tamper was about 0.9 m high, with a hexagonal cross-sectional area of about 0.8 m on each side. Over the majority of the site, two passes of DDC were completed, each using a square grid pattern with a center-to-center spacing of 4.6 m (the grid pattern for the second pass was offset by about 2.3 m in each direction).

A drop height of 9.1 m was used for DDC within the vicinity of the in situ testing described in this paper. The number of drops applied at each drop location is shown in Figure 2. Based upon a 15 Mg tamper and a 9.1 m drop height, the depth of improvement computed using the empirical equation presented by Lucas is 5.9 m. The corresponding maximum improvement would then be predicted to occur within a zone between 1.9 m and 2.9 m below ground surface.

3 IN SITU TESTING PROGRAM

An extensive in situ testing program was carried out to provide baseline conditions of the hydraulic fill and to assess the degree of compaction resulting from the deep dynamic compaction. One of the field methods used in this testing program was a specially designed instrumented dilatometer (IDMT). A standard flat dilatometer was modified at the University of New Hampshire in an effort to better understand the mechanics and soil response during expansion of the dilatometer membrane (Stetson et al., 2003). This IDMT allows the continuous measurement of the complete membrane displacement range during the test, the pore pressure during insertion and testing and, the total pressure applied to the inside of the blade. These modifications were implemented without impacting the original blade design. Others similar probes have been previously designed and built for field testing and for use in calibration chambers (Motan and Gabr, 1985; Motan and Khan, 1988, Campanella and Robertson, 1991; Fretti et al., 1992, Kay and Chiu, 1993).

The testing procedure for the IDMT consists of hydraulically pushing the probe into the ground at a rate of 2 cm/s. Once the blade is at a testing depth, the downthrust is unloaded and the expansion of the membrane is initiated within the next 30 s. The rate of pressurization is designed to reach the A-reading within 30 to 60 s with the rate decreasing when approaching the A-reading to improve resolution at lift-off. For the remainder of the test, the pressure rate is kept nearly constant. To keep test times approximately constant, the average pressure rates during the pre-compaction and post-compaction profiles

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were 350 and 950 kPa/min, respectively. For each test, an unload-reload loop is conducted at a membrane displacement of approximately 0.6 mm. The final unloading rate is similar to the loading rate.

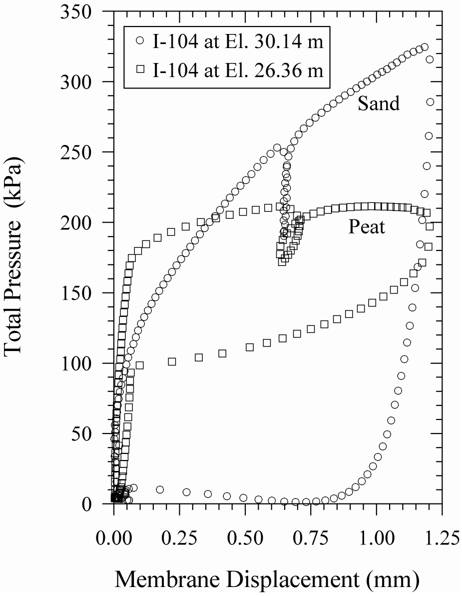

Figure 3. Typical pre-compaction IDMT tests in sand and in organic soil

Figure 3 shows two typical corrected pressure-displacement curves for that profile; test I-104 at El. 30.14 m was carried out within the hydraulic sands fill while test I-104 at El. 26.36 m was carried within a zone of soft organic material left in place prior to backfilling. Figure 4 shows the material index values, I_D, estimated from tests at I-104 and help confirm the type of soil in which the tests shown in Figure 3 were carried out. These IDMT test curves are corrected for membrane stiffness. The pressure-displacement curves are similar in appearance to self-boring pressuremeter curves. As the internal pressure approaches the lateral stress in the ground, the membrane starts lifting off. Because of soil disturbance due to blade penetration, excess pore water pressures are generated in the soft organic zone, leading to a substantial increase in lateral stress. That increase in lateral stress is reflected by the significantly higher lift-off pressure shown in Figure 3 for the test at 26.36 m. The response for the test in the soft zone is relatively flat following the unload-reload and actually shows a decrease in pressure with increasing displacement as the membrane stiffness becomes a significant component of the total pressure.

IDMT test profiles were carried out prior to and following deep dynamic compaction. Table 1 gives details relative to each sounding. Profiles I-102, I-202 and I-302 were carried out in the same vicinity, as shown in Figure 2, while profile I-104 was performed about 90 m away.

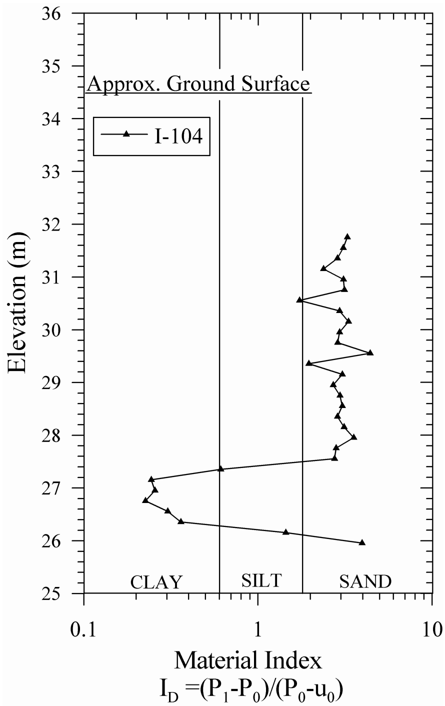

Figure 4. I_D values estimated from I-104

Table 1. Details of IDMT Soundings.

IDMT Profile	Surface Elevation (m)	Station I.D.[1] (ft)	Offset[2] (m)	Compaction Status	Date (M/D/Y)
I-102	34.48	156+00	14.5	Pre-DDC	12/10/02
I-202	34.58	155+98.6	14.0	Post-DDC	7/16/03
I-302	34.63	155+99	13.1	Post-DDC	8/15/03
I-104	34.56	159+04	1.1	Pre-DDC	12/11/02

[1] Station measurements in feet (1 foot ≈ 0.3 m)
[2] Distance to the right of centerline

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Figure 5 shows two IDMT tests carried out at approximately the same depth, before and after deep dynamic compaction. The pressure-displacement test curves clearly depict the improvement from the DDC. The improvement is reflected in terms of higher lift-off and thus increased horizontal stress (or K) as well as increase in stiffness as indicated by the significantly larger pressure required to reach 1.1 mm expansion. Increases in lateral stress have also been reported by others using the DMT for QA/QC of deep dynamic compaction (Schmertmann et al., 1986, Marchetti et al., 2001). An enlarged view of the unload-reload loops for each of those two tests is shown in Figure 6. A straight line between the start of reloading and the loop closure is used to calculate the unload-reload modulus. It should be noted that the test curves in Figure 5 show every 5 data points recorded while the unload-reload loops in Figure 6 show every data point.

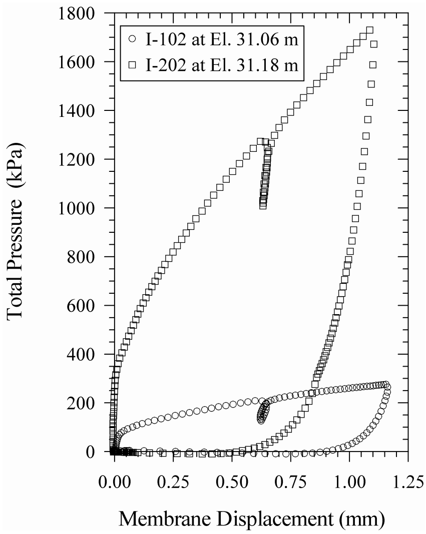

Figure 5. Pre- and post-DDC IDMT test curves

Figure 7 shows unload-reload modulus values for soundings I-102, I-202 and I-302. Those values were calculated according to Fretti et al. (1992). Average strain levels were calculated from the unload-reload loops for each of the four IDMT profiles. Prior to compaction, average strain levels for tests conducted in the hydraulic fill ranged from 3.2 to 3.6 x 10^{-4} mm/mm. After compaction, average strain values in that material ranged from 4.1 to 4.6 x 10^{-4} mm/mm. Within the peat layer in I-104, the average strain level was 1.2 x 10^{-3} mm/mm.

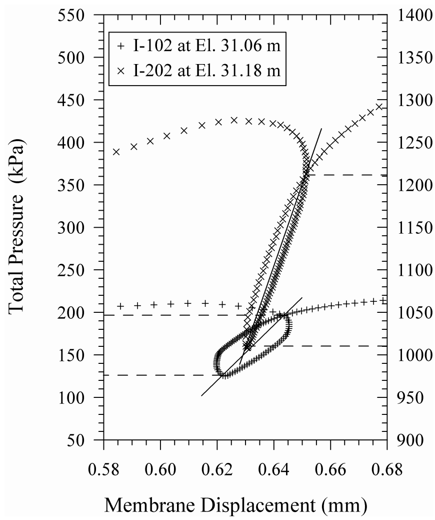

Figure 6. Pre- and post-DDC IDMT unload-reload loops

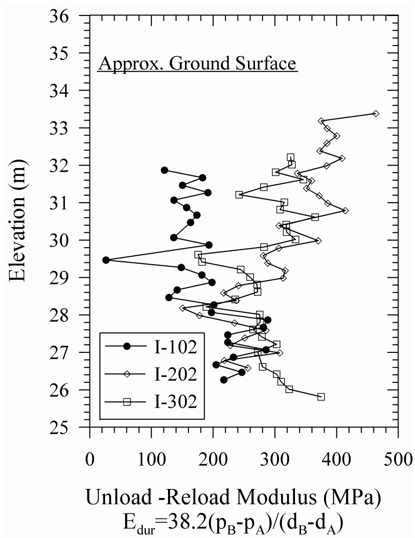

Figure 7. Profiles of unload-reload modulus, E_{dur}

As expected, the modulus values are greater following compaction with the most significant increases above Elevation 28. According to Lukas (1995), the maximum improvement should be ap-

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proximately between Elevations 31.6 and 32.6. The results shown in Figure 7 indicate that the maximum improvement zone may extend somewhat deeper than those elevations. Post-compaction modulus values in the maximum improvement zone are about two times larger than the pre-compaction values. The native material is at an Elevation of about 28, and little improvement in modulus values has occurred below that elevation. The pre- and post-compaction modulus values seem to indicate the presence of a soft organic pocket at Elevation 29.5 m, and also a relatively soft zone at about Elevation 28.2 m.

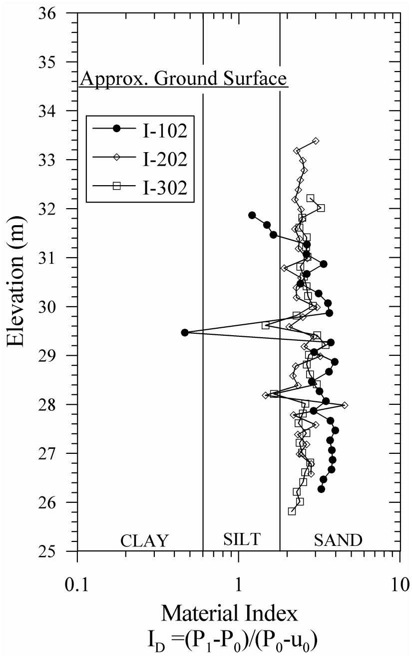

Figure 8. I_D values estimated from IDMT tests near Sta. 156

Figure 8 presents I_D values calculated from using the IDMT data and clearly shows that the soil at Elevation 29.5 m contains a clayey material. It should be noted that because of the impact of the unload-reload loop on the total time necessary to carry out an IDMT test, the IDMT indices might not be directly applicable in conventional Marchetti type correlations. On the average, each test took less than 5 minutes to carry out including one unload-reload loop and full unloading. With the compaction, the zone of organic soils was probably mixed with the surrounding sand and thus is identified as silt in profile I-302. The presence of the soft zone may also explain the lower degree of improvement to the native soil below that elevation. The organic material likely served as a damping layer, preventing full benefit of DDC below that zone.

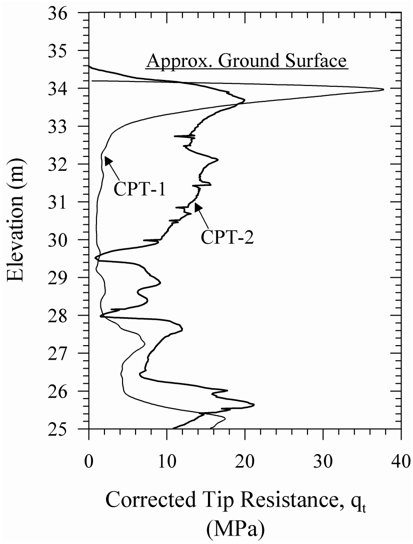

Figure 9. q_t values from CPT tests near Sta. 156

Table 2. Details of CPT Soundings.

CPT Profile	Surface Elevation (m)	Station I.D.[1] (ft)	Offset[2] (m)	Compaction Status	Date (M/D/Y)
1	34.48	156+00	13.7	Pre-DDC	1/15/03
2	34.58	155+01	13.6	Post-DDC	7/16/03

[1] Station measurements in feet (1 foot ≈ 0.3 m)

[2] Distance to the right of centerline

The results of the IDMT tests near Station 156 can also be compared with data from two cone penetrometer tests (CPT-1 and CPT-2) performed in the same general vicinity. Details relative to each sounding are given in Table 2. Plots of corrected tip resistance values for those CPT tests are shown in Figure 9. Interestingly, while the pre-compaction test (CPT-1) does not clearly identify the soft organic pocket at Elevation 29.5 m, the post-compaction CPT test does indicate significantly weaker zones at both Elevation 29.5 m and Elevation 28.2 m. It should be noted that the locations of these soft zones are erratic

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and of limited extent across the site. Similar to the trend with the IDMT unload-reload modulus values, the CPT tip resistance values following compaction show significant increases above Elevation 28, with only modest increases occurring in the native material below that elevation. The maximum improvement occurs approximately between Elevations 31 and 32.2, which is in close agreement with the maximum zone of improvement predicted by Lukas (1995).

4 CONCLUSIONS

The results of this study suggest that the IDMT is a very useful tool for providing stratigraphic profiles as well as parameters for QA/QC on in situ densification projects. The IDMT pressure-displacement curves are similar in appearance to self-boring pressuremeter curves, and enable a better understanding of the mechanics and soil response during expansion of the dilatometer membrane. During preliminary site investigations, the material index values estimated from the IDMT tests were particularly helpful in identifying pockets of soft organic soils (i.e., peat) that were not completely removed during the initial dredging operations. After compaction, the IDMT pressure-displacement curves and the unload-reload modulus values clearly depict the improvement that resulted from the DDC, with post-compaction modulus values in the maximum improvement zone of about two times larger than the pre-compaction values.

And finally, the IDMT proved to be helpful in understanding some of the factors that govern soil improvement resulting from DDC. IDMT unload-reload modulus values suggest that the maximum zone of improvement occurred approximately between Elevations 30 and 32, which is slightly deeper than the zone estimated using the equation proposed by Lucas (1995). In addition, the IDMT data indicate the presence of a very soft organic pocket at Elevation 29.5 m, and also a relatively soft zone at about Elevation 28.2 m. Those zones likely served as damping layers during the DDC, reducing the amount of energy transferred to the underlying material. The reduced effectiveness of the DDC in the material beneath those soft zones was confirmed by the minimal increases in IDMT unload-reload modulus values that resulted in that material.

ACKNOWLEDGEMENTS

The writers wish to acknowledge the Massachusetts Highway Department for their financial support for this research. Additionally, several MassHighway personnel provided much assistance in conducting the field testing for this project. Mr Peter Connors, Mr. Edward Mahoney, and the entire staff of the MassHighway Route 44 Field Office in Carver, MA are acknowledged in that regard. And finally, the writers appreciate help with field testing, data reduction, and preparation of figures that was provided by undergraduate research assistants Nicholas Yafrate and Tracy Willard.

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