



Assessing the Bearing Capacity of Backfills by Stress Wave Velocity and Cone Penetration Resistance

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Abstract. Sand-cone test is one of the most common tests performed to assess the compaction quality of backfills for earth works. However, performing such test is time consuming and can only obtain the density and water content of backfills. In order to obtain their engineering properties, such as strength or bearing capacity, additional tests such as California Bearing Ratio (CBR) test or plate loading test must be performed. In this study, a miniature dynamic cone penetrometer was developed. The feasibility of assessing the bearing capacity of backfills by stress wave velocity and dynamic cone penetration resistance was investigated. Samples of a silty clay were compacted with various compaction energy and moisture contents. In addition to the density and moisture content, the CBR, P-wave and S-wave velocity, as well as penetration resistance of a mini cone of these samples were measured. Linear relationships between the CBR and S-wave velocity/penetration resistance were found. Therefore, it is feasible to assess the bearing capacity of backfills by these two techniques.

1 Introduction

In engineering practices, the sand-cone test (ASTM 2007) is usually performed to assess the compaction quality of pavement subgrade, pavement bases, pavement sub-bases, embankments, retaining wall backfills, etc. However, the sand cone test is a destructive test and performing this test is labor intensive and time consuming. Alternatively, a neutron probe can be used for rapid determination of moisture content and density of soil and soil-aggregate (ASTM 2010). However, potential health risks to the operator, and the costs of complying with the special requirements for operation and storage of the nuclear gauges, prevent them from been used widely.

Several investigators have been devoted their efforts to develop a more economical and efficient technique to assess the compaction quality of backfills. For examples, Yu and Drnevich (2004) proposed using a time domain reflectometry (TDR) probe to measure the gravitational water content and dry density of compacted soils. Dynamic cone penetrometer (DCP) was adapted for soil compaction determination at shallow

depths (ASTM 2008). Briaud et al. (2009) developed a new instrument called Briaud Compaction Device (BCD) to measure the soil modulus near the ground surface. Comhuri et al. (2009) calibrated an intelligent asphalt compaction analyzer (IACA) based on neural network technology to measure the density of an asphalt pavement continuously during its construction in real time. Lai et al. (2011) investigated the feasibility of evaluating the compaction quality of backfills by stress wave velocities. Kim et al. (2010) used both DCP and Clegg hammer tests for the quality control of roadway compaction. The American Society of Agricultural and Biological Engineers (ASABE 2013) recommended a soil cone penetrometer as a measuring device for characterizing the penetration resistance of soils. The force required to press the circular cone through the soil, expressed in kilopascals, is an index of soil strength called the cone index. Donohue et al. (2013) and Ni et al. (2018) evaluated the compaction quality of backfills by measuring their shear wave velocity using multi-channel analysis of surface wave (MASW) test. Based on the above literature reviews, it seems that both the DCP and the stress wave velocity measurement are all very suitable as alternatives to the sand cone test for the assessment of the compaction quality of backfills.

2 Methodology

The objective of this paper is to compare the advantages and disadvantages between the DCP test and stress wave velocity measurement in assessing the compaction quality of backfills. Because the ASTM DCP is too big to be used for testing samples prepared with a standard compaction mold, a down-sized miniature dynamic cone penetrometer was developed for the use of this study. As shown in Fig. 1, the miniature DCP has a drop weight of 3.92 N (400 g) and a falling distance of 305 mm (12 in.), with a cone tip angle of 30°.

A silty clay of low plasticity was used as testing material for the comparison. The silty clay contains 18% of fine (particle size < 0.075 mm), and has a liquid limit and plasticity index of 24% and 7%, respectively. It is classified as a silty clay with sand (CL-ML) according to the Unified Soil Classification (UCS) system.

A specimen was made by compacting the silty clay in 5 layers with a modified Proctor hammer following the ASTM D1557 Method-C standard procedures. Three different moisture contents (7.5, 10, and 12.5%) and compaction energy (37, 56, and 75 blows per layer) were used in preparing the specimens. Because the stress wave velocity measurement is non-destructive, after a specimen was compacted, the apparatus shown

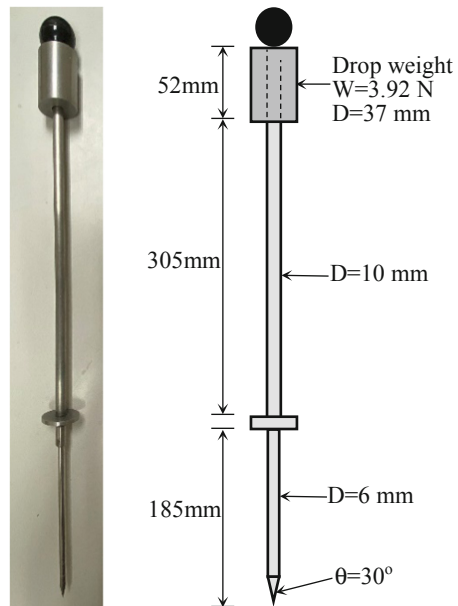


Fig. 1. Schematic drawing of the miniature dynamic cone penetrometer (DCP).

in Fig. 2 (Lai et al. 2011) was used to measure both the P-wave and the S-Wave velocities of the specimen at first. Then, the ASTM D1833 standard procedures were followed to measure the California Bearing Ratio (CBR) on the top surface of the specimen. The miniature DCP was then used to measure the penetration resistance at four different locations on the bottom surface of that specimen. Finally, the soil was extruded out and the weight and moisture content of that specimen were measured.

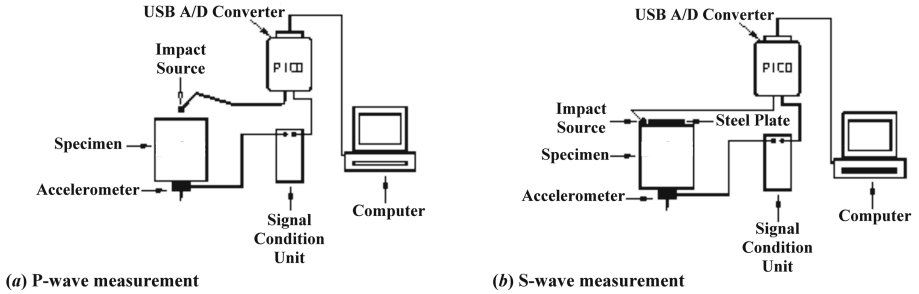


Fig. 2. Schematic drawing of the test setup for stress wave velocity measurement

3 Results and Discussion

3.1 Penetration Resistance Determination

Two different types of penetration resistance are usually used in a DCP test – the penetration depth after a certain number of blows, or the # of blows required for the cone to penetrate a certain depth. For field measurements, it would be more convenient to use the later. In order to obtain an optimum penetration depth and the effects of testing location, a series of DCP tests were performed on the top and bottom surface of compacted specimens and the penetration depth after 5 and 10blows were recorded. Results of these tests are shown in Fig. 3.

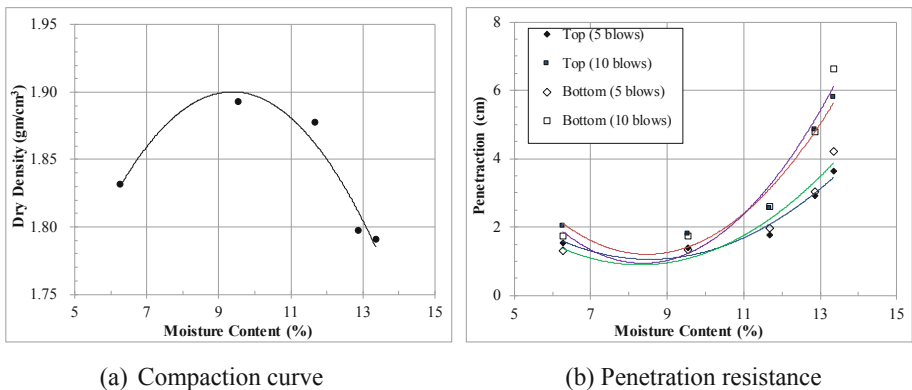


Fig. 3. Results of trial penetration resistance tests

It can be seen from Fig. 3a, the silty clay has a maximum dry density of about 1.90 g/cm^3 , and an optimum moisture content of about 10%. As shown in Fig. 3b, the penetration depth increases nonlinearly as the moisture content increases for the two different blow counts. Furthermore, for a given moisture content under the same blow count, the penetration depth of the bottom surface is lower than that of the top surface and the difference is smaller near the OMC.

Based on these preliminary test results, it can be seen that, except for the very wet specimen, most of the penetration depths fall between 1–3 cm. Therefore, it is decided to perform the comparison tests at three different moisture contents (OMC and $\text{OMC} \pm 2.5\%$) with three different compaction energy (37, 56, and 75 blows per layer) and measured the # of blows required to penetrate 1.27 cm (0.5") and 2.54 cm (1") for the comparison tests.

3.2 Density Measurement

Relationship between the dry density and the measured stress wave velocity of the specimens are shown in Fig. 4. It can be seen that both the P-wave velocity (V_p) and the S-wave velocity (V_s) increase as the dry density increases. There is a linear relationship between the dry density and the stress wave velocity. However, the coefficients of correlation are not very high (0.34 for V_p and 0.35 for V_s). Since the stress wave velocity is a function of density, moisture content, as well as soil type rather than density alone, a low coefficient of correlation can be expected. This observation is in accord with the previous finding (Lai et al. 2011).

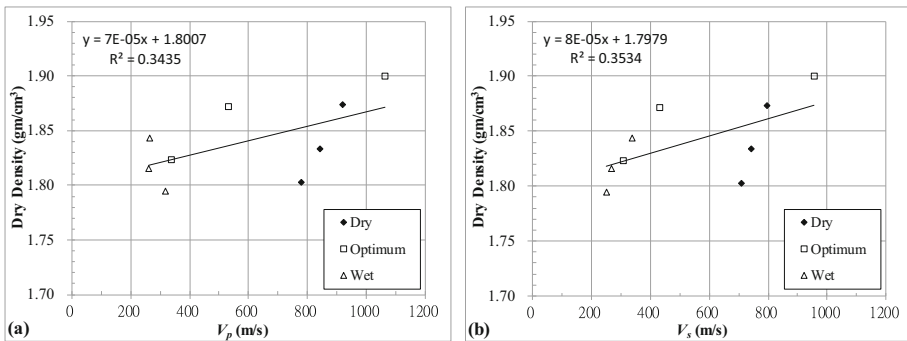


Fig. 4. Relationship between the dry density and stress wave velocity

Relationship between the dry density and the measured DCP resistance of the specimens are shown in Fig. 5. It can be seen that, as the dry density increases, the number of blows required for 12.7 mm and 25.4 mm penetration are all increase. There is also a linear relationship between the dry density and the DCP resistance. However, the coefficients of correlation (0.23 for 12.7 mm and 0.21 for 25.4 mm) are even lower than those of wave velocity measurement.

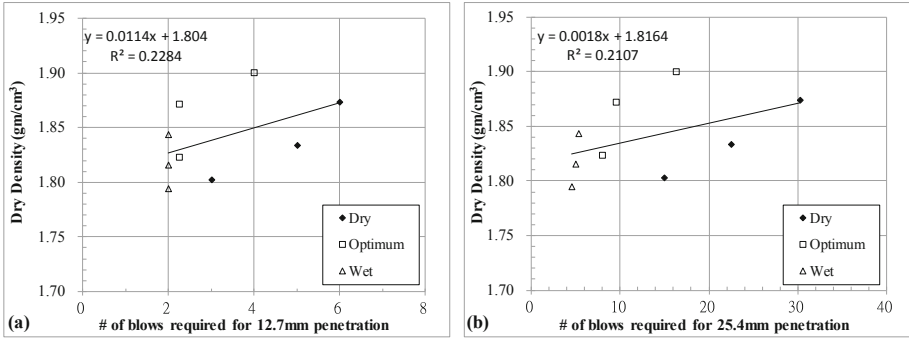


Fig. 5. Relationship between the dry density and DCP resistance

3.3 Moisture Content Measurement

Relationship between the moisture content and the measured stress wave velocity of the specimens are shown in Fig. 6. It can be seen that both the V_p and the V_s increase as the moisture decreases. There is also a linear relationship between the moisture content and the stress wave velocity. The coefficients of correlation are 0.61 for the V_p and 0.58 for the V_s , respectively. These coefficients of correlation are a little better than those of the dry density and stress wave velocity correlation. It is thus concluded that the moisture content plays a more important role in wave velocity than does the dry density.

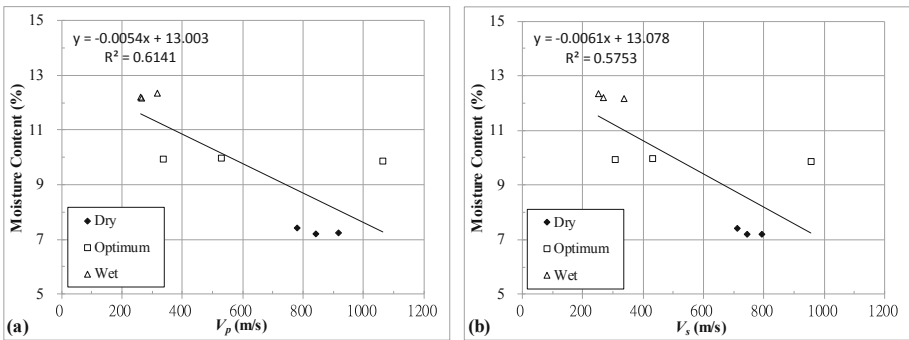


Fig. 6. Relationship between the moisture content and stress wave velocity

Relationship between the moisture content and the measured DCP resistance of the specimens are shown in Fig. 7. It can be seen that, the # of blows required for 12.7 mm and 25.4 mm penetration all increase as the moisture content decreases. There is also a linear relationship between the moisture content and the DCP resistance. In contrast, the coefficients of correlation (0.63 for 12.7 mm and 0.77 for 25.4 mm) are higher than those of wave velocity measurement. Therefore, the DCP resistant performs better in moisture content determination than does the stress wave velocity. Furthermore, measuring the # of blows required for 25.4 mm penetration is better than for 12.7 mm penetration.

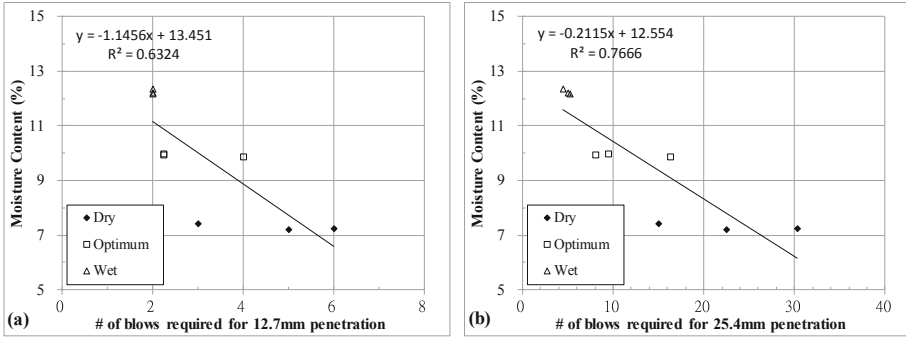


Fig. 7. Relationship between the moisture content and DCP resistance

3.4 California Bearing Ratio Measurement

Relationship between the CBR and the measured stress wave velocity of the specimens are shown in Fig. 8. It can be seen that both the V_p and the V_s increase as the CBR increases. A very good linear relationship between the CBR and the stress wave velocity is obtained as indicated by the high coefficients of correlation (about 0.97 for both the V_p and the V_s). Since the CBR and the stress wave velocity are all overall result of the summation effects of the type, density, moisture content, ... of soils. A good linear relationship between the CBR and the stress wave velocity thus can be expected. This observation is also in good agreement with the previous study (Lai et al. 2011).

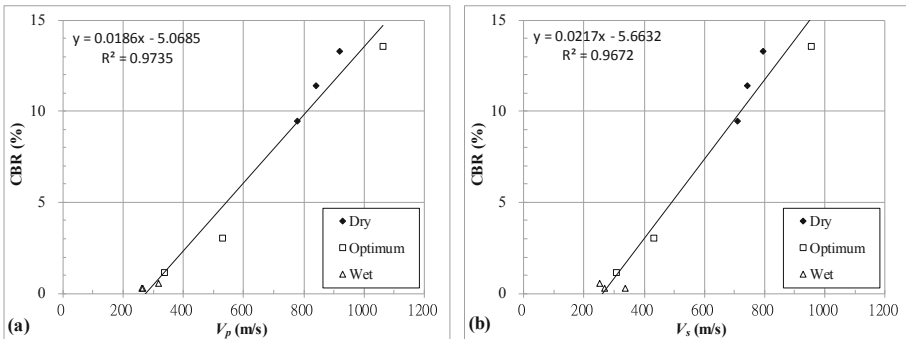


Fig. 8. Relationship between the CBR and stress wave velocity

Relationship between the CBR and the measured DCP resistance of the specimens are shown in Fig. 9. It can be seen that the DCP resistance increases as the CBR increases. There is a relatively good linear relationship between the moisture content and the DCP resistance with coefficients of correlation around 0.8. The coefficient of correlation for 25.4 mm (0.81) penetration is again slightly higher than that of 12.7 mm penetration (0.80), which means a penetration depth of 25.4 mm is more suitable for compaction quality control application.

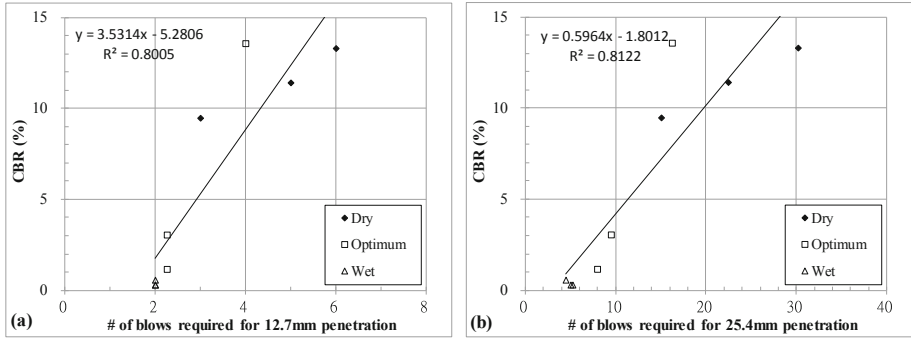


Fig. 9. Relationship between the CBR and DCP resistance

3.5 Correlation between Stress Wave Velocity and DCP Resistance

Relationship between the measured stress wave velocity and the DCP at 25.4mm of the specimens are shown in Fig. 10. It can be seen that both the V_p and the V_s increase linearly as the DCP resistance increases with a fairly good coefficients of correlation around 0.7. Therefore, in addition to the moisture content and CBR, the DCP test can also be used to evaluate the stress wave velocity of compacted soils.

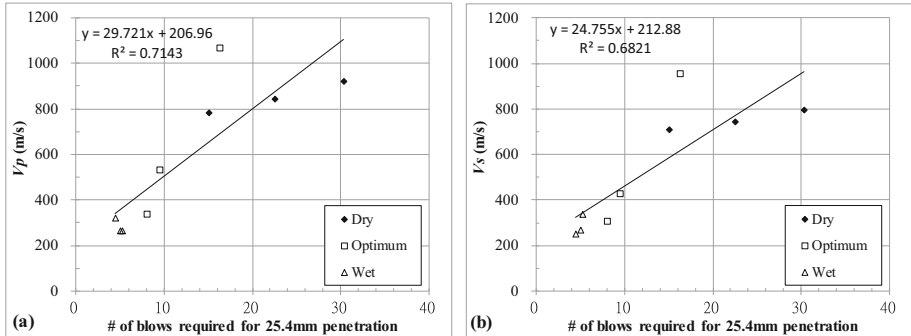


Fig. 10. Relationship between the stress wave velocity and DCP resistance

4 Summary and Conclusions

Both the DCP resistance and the stress wave velocity measurement have long been used for the assessment of the compaction quality of earthworks. In this study, a miniature dynamic cone penetrometer was developed. A series of compaction tests with measurements of CBR, stress wave velocity, as well as DCP resistance were performed. The advantages and disadvantages between stress wave velocity and DCP resistance in assessing the compaction quality of backfills are compared. Based on the results of these tests, the following conclusions can be drawn:

1. Good linear relationships were found among the moisture content, CBR, stress wave velocity, and DCP resistance. Therefore, it can be concluded that both the stress wave velocity measurement and the DCP test can be used to assess the moisture content and CBR of the compacted backfills.
2. The stress wave velocity measurement outperforms the DCP test in assessing the CBR of backfills. On the other hand, for assessing the moisture content of backfills, the DCP test performs slightly better than the stress wave velocity measurement.
3. Although not as accurate as the stress wave velocity measurement, the miniature DCP has the advantages of economic and rapid. Therefore, it should be a promising tool for the determination of the compaction quality of backfills and deserves more investigation in the future.

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