NEW DOWN-HOLE PENETROMETER (DHP-CIGMAT) FOR CONSTRUCTION APPLICATIONS

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Abstract

Drilled shafts are increasingly used as foundations to support bridges and transportation structures in geomaterials such as soft-rocks and hard clay. Locating the bottom of the borehole during construction with the required strength is critical. Hence developing a simple device that could be easily adapted/used with the drilling tool was of interest in this study. Determining the shear strength of the geomaterial in the borehole and at the bottom of the borehole can lead to better quality control of construction by identifying the various layers based on strength.

In this study, a down-hole penetrometer (DHP-CIGMAT) was designed, built and tested to determine its effectiveness in measuring the strength of soil/soft rock. Based on limited field tests, linear correlations between geomaterial strengths and DHP-CIGMAT deflection have been developed. Finite element analysis was used to verify the DHP-CIGMAT test results.

Introduction

For site investigation, in-situ tests are increasingly used to determine the soil properties for geotechnical analysis and design (Ampadu and Arthur 2006; Hsu and Huang 1999). Static and dynamic penetration resistances have been used to classify and characterize subsoil (Ahmadi et al. 2005). The penetrometers evolved from the need of acquiring data on sub-surface soils that could not be easily sampled by any other method. Laboratory testing undisturbed samples, requires great care to avoid disturbance during handling, or systematical disturbance during testing, and it may be difficult to relate the laboratory test results to the in-situ properties of the soil (Sanglerat 1972). There is always a certain degree of disturbance to the samples because the confining pressures, which exist in the ground, are forcibly changed when the sample is collected.

In order to support high loads on bridges and other transportation structures and/or based on the near surface geological conditions, more and more drilled shafts are being socketed into soft rocks and hard clay. During the construction of drilled shafts in soft rock or hard clay, it is critical to identify the top of the geomaterial stratum during the drilling process so that the drilled shaft could be correctly socketed in the soft-rock or hard clay. This is one of the major challenges on the construction sites.

Determining the shear strength of the geomaterial in the borehole and at the bottom of the borehole can lead to better designs by identifying the various layers based on strength. Although static (Cone Penetration Test, Vane Shear Test) and dynamic penetrometers (Standard Penetration Test, Dynamic Cone Penetrometer) are being used to determine the in-situ soil properties for designing deep foundations, these devices cannot be used to characterize the geomaterials in the borehole of the drilled shaft due to the difficulty in incorporating the operations during the construction phase. Hence, at present, there is no commercially available tool to determine the clay and soft-rock strength at the bottom of the borehole of a drilled shaft during construction.

In order to overcome this difficulty a Down-Hole Penetrometer was designed and built at the University of Houston, Houston, Texas (DHP-CIGMAT) to determine the in-situ strength of various geomaterials. The device was field tested at few sites and correlations between geomaterial strengths and penetrometer deflection have been developed.

Objective

Overall objective was to develop and calibrate the DHP-CIGMAT for use in determining in-situ strength of soil and soft rocks. The specific objectives are as follows: (a) design the DHP-CIGMAT to be easily adopted with drilled shaft construction; (b) calibrate the DHP-CIGMAT in the laboratory and (c) verify the performance of the DHP-CIGMAT in the field.

Downhole Penetrometer (DHP-CIGMAT)

The DHP-CIGMAT consists of a piston, sliding ring and series of springs. This configuration allowed the DHP-CIGMAT to be used even in drilling mud, making it a versatile tool for use under various field conditions (Vipulanandan and Hussain 2006). The penetrometer was attached to a Kelly Bar adopter using a 25 mm diameter metal pin. The Kelly bar adopter and the penetrometer together weight about 14 kg (30 lb). The Kelly bar adopter was so designed that a thin wall sampler (high strength steel) could be attached to directly sample the soil or soft rock. During the test, the Kelly bar is released to apply the load the piston to fail the soil/soft rock below the piston bearing capacity failure below the piston. This allows the ring to be displaced based on the strength of the geomaterial.

If the ring displacement was δ, since it is assumed that the failure (q_{ult}) under the piston was due to bearing capacity failure, the following relationship is proposed:

$$q_{ult} = A\delta + B = NS_u \qquad (1)$$

Where parameters A and B are the DHP-CIGMAT calibration factors which which are determined by directly calibrating the DHP-CIGMAT in the laboratory. N is the bearing capacity factor and S_u is the undrained shear strength of the geomaterial being tested.

Equation (1) can be rearranged as follows:

$$S_u = (A/N)\delta + (B/N) \qquad (2)$$

In this study, S_u was determined directly from the soil or rock samples collected using the wall sampler. In the field, DHP-CIGMAT with various stiffnesses (parameters A & B) can be used for soils and rocks with various strengths.

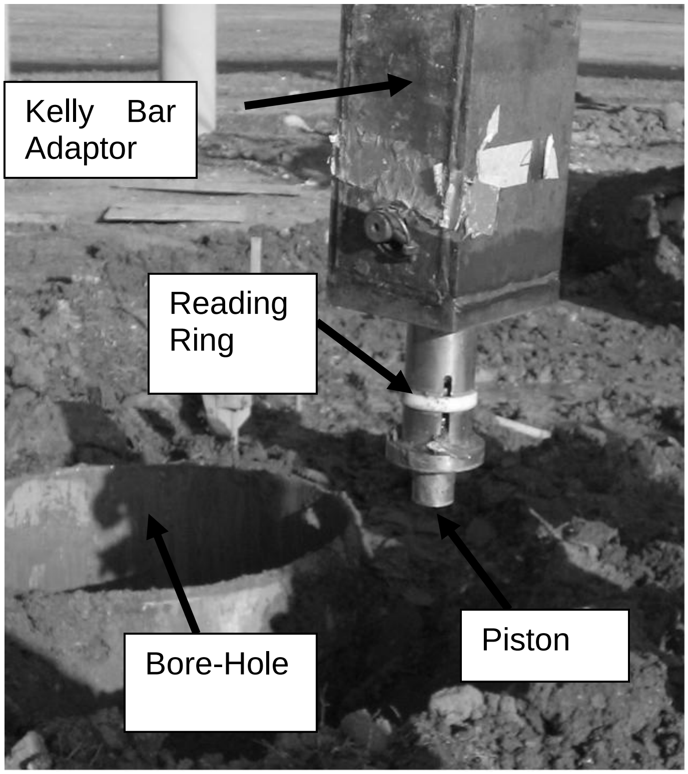


Figure 1. DHP-CIGMAT Penetrometer After A Field Test

Field Test Sites

To investigate the relationship of deflection obtained from DHP and undrained shear strength of soil/soft rock, field tests were performed at the drilled shaft construction sites in Houston and Dallas, Texas. At all the soil sites, boreholes were filled with drilling mud and DHP-CIGMAT tests were performed at various stages construction to determine the bottom of the borehole based on design values. In Dallas, tests were performed on clay shale, soft rock, the bore holes were dry. The depth of the boreholes varied from 15 to 30 m (50 to 100 ft). In these test sites CH, CL and clay shale were the major soil formations.

Clay samples were obtained from five boreholes in various locations in Houston, Texas and DHP-CIGMAT tests were performed in these boreholes. The first drilled shaft construction site was located at the intersection of I-10 West and Beltway 8, which was a part of highway construction. Series of field tests were performed at three different boreholes drilled at that location. The soil profiles consist of very stiff clay down to 4.6 m (15 ft), silty sand layer from 4.6 to 14 m (15 to 45 ft) and stiff to hard clay down to 23 m (75 ft). Within the depth of 23 m (75 ft), the moisture content ranged from 14 to 23%, for the clay soils the liquid limit ranged from 48 to 69% and plasticity index varied from 30 to 45%.

The second soil site (Goodyear Drive) was located near to the intersection of Loop 610 and Highway 225. The soil deposits consist of 3 m (10 ft) of stiff to very stiff clay layer, silty clay layer from 3 to 6 m (10 to 20 ft) and sandy layer from 6 to 16 m (20 to 53 ft).

The third soil site where tests were performed was located near to I-10 East and Beltway 8. The soil profile had a 6 m (20 ft) sandy/silty clay fill lying over a thick (>12 m (40 ft)) deposit of very stiff clay. Within the depth of 18 m (60 ft), the moisture content ranged from 22 to 33 %, for clays the liquid limit ranged from 31 to 74%, plasticity index ranged from 15 to 42.

Two series of field tests were performed in a soft rock formation at two Drilled Shaft construction sites in Dallas, TX. The first site which was located at the intersection of Interstate Highway 30 and Loop 12, consisted of about 24 m (80 ft) of mixed clay and sandy material overlying a deposit of clay shale.

The second location of the DHP tests for soft rock was at the reconstruction site of Trinity Bridge at North Hampton, in Dallas. The soil profile consisted of medium clay of about 6 m (20 ft) overlying a deposit of dark grey clay shale to a depth of 30 m (100 ft). Bottom of drilled shaft was located 16 m (54 ft) from the ground level.

Numerical Analysis

Finite Element Model

In this study, the finite element analysis (using commercially available PLAXIS software) was used to develop a model to predict the DHP deflection obtained from field tests in terms of ultimate strength. Similar FEM study was done to determine the effects of core holes on the drilled shaft capacity (Vipulanandan et al. 2006, 2007)

A typical finite element mesh used in predicting DHP field tests is shown in Fig. 2. A 15 node, triangular elements were used in the axi-symmetric analysis. The clay soil was modeled as elastic – perfectly plastic material, with Mohr-Coulomb failure criterion (Vipulanandan et al. 2007).

The constitutive model used to simulate the soil and soft rock behavior, required following input parameters-initial elastic modulus (E), Poisson’s ratio (υ) , cohesion (c), friction angle (φ) and unit weight (ρ). Simulations were performed with various friction angles keeping the compressive strength constant (Table 2). Poisson ratio was assumed to be 0.3. In order for the mesh size to have a negligible effect on the results, two cluster refinements resulting in a mesh element size factor of 0.5 was used. The number of mesh elements used was 659.

Based on the laboratory calibration of DHP, it was possible to determine the penetrometer capacity q_{ult} from the deflection of the ring (Equation (1)) and the measured field results are summarized in the second column in Table 2. Using the finite element model for clay soil, penetrometer capacity was predicted and compared with field test results (Table 2). As summarized in Table 2, the FEM under predicted the penetration resistance (ratio) by a factor of 1.02 to 2.76. The bearing capacity factor N in Equation (1) varied from 14 to 25.

Table 1. Predicted (PLAXIS) and Measured DHP-CIGMAT Capacity

Field Location in Houston	Measured Penetrometer Capacity q_{ult}=k*δ/Area (psi)	σ_c (psi)	Predicted Penetrometer Capacity (psi)	Depth (ft)	Soil Density (pcf)	Soil Pressure (psi)	Ratio
I-10 West I	57-66	8.0	56.3	57	120	31.6	1.02-1.18
I-10 West II	206-220	17-25	98-123	75	125	41.4	1.79 - 2.10
Goodyear Dr.	236-345	22-27	106-125	53	128	32.9	2.23-2.76
I-10 East	235-597	24-88	121-326	54	136	36.4	1.83-1.94

(1 psi = 6.9 kPa, 1 ft = 0.3 m and 1 inch = 25.4 mm)

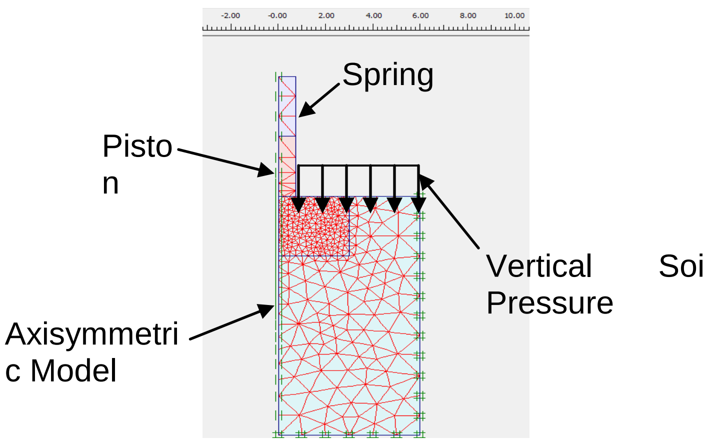


Figure 2. Typical Finite Element Mesh of DHP-CIGMAT Test

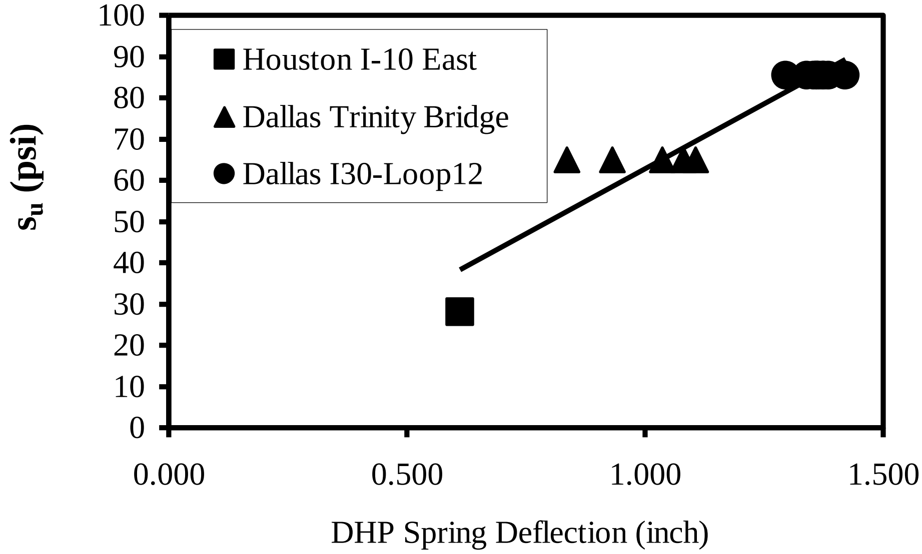
Results and Correlations

The main focus of this study was to investigate the relationship between the undrained shear strength of soil/soft rock and the deflection obtained from DHP –CIGMAT with various stiffness to cover the wide range of geomaterials (Figure 1). Unconfined compression tests were performed to measure the undrained shear strength of samples which were collected at the same borehole at the same elevation with DHP-CIGMAT-1800.

After the tests the DHP deflection readings were recorded immediately by measuring the displacement of the ring using a digital caliper with 0.001 in resolution. Figures 3 and 4 show the correlations of DHP-CIGMAT deflection and undrained shear strength (S_u) of soils and soft rocks. Because of relatively higher strength for soft rocks and hard soils, stiffer DHP-CIGMAT was used. Based on limited field test data, the relationship between unconfined compressive strength of soft rock and hard clay and penetrometer displacement readings showed good agreement and the relationship is shown in Figure 4. Based on the linear regression analysis of the data, the following correlation was obtained for DHP-CIGMAT deflection and undrained shear strength of soil:

$$S_u = 62.8\ \delta \qquad \text{(15 data)} \qquad (3)$$

It must be noted that the term B/N in Eq (2) was neglected in this relationship. The relative stiffness of this penetrometer was 1800. The coefficient of variation (R^2) for this relationship was 0.90.



(1 psi = 6.9 kPa and 1 inch = 25.4 mm)

Figure 3. Undrained Shear Strength versus Deflection Relationships for DHP-CIGMAT-1800

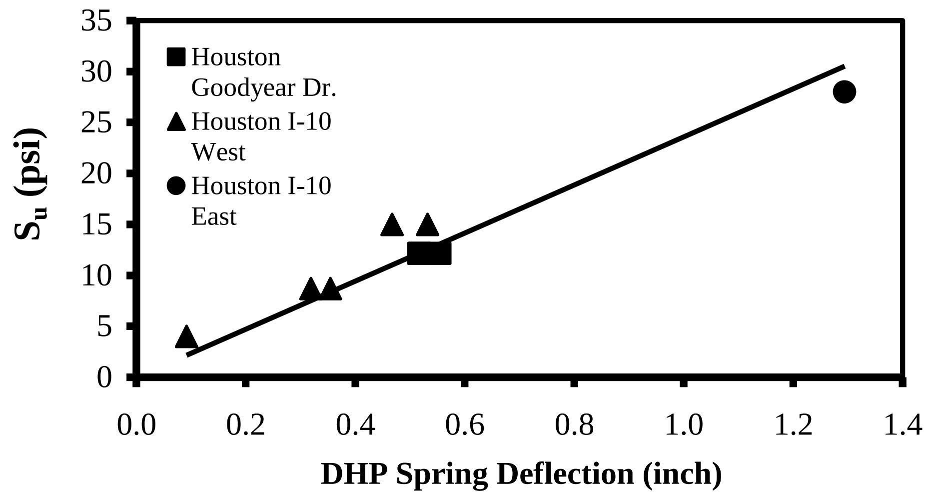
Less stiff DHP-CIGMAT-1100 was used for clay soils. Based on the linear regression analysis of the data, the following correlation was obtained for DHP-CIGMAT-1100 deflection and undrained shear strength of soil (Figure 4):

$$S_u = 26.6\ \delta \qquad \text{(8 data)} \qquad (4)$$

The coefficient of variation (R^2) for this relationship was 0.93.

Conclusions

A new device to measure the undrained shear strength of soils and soft rocks during drilled shaft constructions has been developed. This device can be easily adopted with the Kelly Bar during the construction to determine the undrained shear strength of geomaterials at the bottom of the borehole. Based on the limited field data, linear correlations between the undrained shear strength of the geomaterials and deflection of various DHP-CIGMAT have been developed. Based on the undrained shear strength of geomaterials, DHP-CIGMAT with different stiffnesses can be used.



(1 psi = 6.9 kPa and 1 inch = 25.4 mm)

Figure 4. Undrained Shear Strength versus Deflection Relationship for DHP-CIGMAT-1100

Acknowledgement

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