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PREDICTION OF DYNAMIC COMPACTION POUNDER PENETRATION

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ABSTRACT

A semi-empirical computational technique is presented for predicting the depth of craters formed by dynamic compaction (DC) pounders after the first impact. This technique utilizes a correlation developed between the initial shear strength of the soil beneath the pounder, determined by a CPT profile, and the impact energy per unit area (*specific impact energy*). First, the correlation is established by a series of model impact tests involving different drop heights, drop weights and impact areas. Then, the correlation is verified by the results from a full-scale field test performed by the authors. Further, data from a DC project performed elsewhere is also shown to support the predictive technique. An illustrative example is provided to demonstrate how typical CPT data can be adapted to predict the crater depths during DC projects for a given level of applied impact energy. On the other hand, this method can be used to determine the maximum impact energy that can be applied without causing excessive *initial* penetration of pounders and thus preclude the need for trial impacts. Hence well in advance of heavy equipment mobilization, this technique can certainly aid in effective planning of DC projects on particularly weak ground where penetration predominates heave.

Key words: CPT, crater, dynamic compaction, dynamic replacement, organic soil, pounder, specific impact energy (**IGC:** K3/K5)

INTRODUCTION

Dynamic Compaction (DC) is a ground modification technique used to densify loose soil deposits as deep as 10 meters below the surface. The DC process entails dropping a large weight or pounder onto the ground to be compacted. Although dynamic compaction is reported to be effective both above and below the ground water table, certain construction difficulties arise if the water table is not maintained at least 2 m below the ground surface. This is achieved by dewatering or raising the grade (Lukas, 1986). Raising the grade by the addition of a sand layer can aid the ensuing construction by providing a working mat. Moreover, when unusually soft soils are to be modified, the sand furnishes a replacement material that is driven into the underlying soft layer. The latter process, Dynamic Replacement (DR), has been shown effective in stabilizing weak compressible soils that have poor consolidation properties (Ramaswamy et al., 1979; Lo et al., 1990; Chow et al., 1992; Mullins, 1996).

During DC or DR, the first penetration of the pounder is an uncertain parameter that can cause considerable construction difficulties especially in the case of softer soils. A pounder that penetrates too deeply can develop such high suction forces during withdrawal that it cannot be recovered without additional equipment. To prevent this, the common practice is to limit the crater depth to "the height of the pounder plus a few feet" (Lukas, 1986). Because of the uncertainties involved Lukas (1986) states that it is not possible to predict precisely the crater depth, prior to impact and suggests that the information obtained during the first pass be used as a guide to establish a criterion for subsequent passes. However, this exercise involves mobilization of heavy equipment and thus it cannot be utilized for preliminary project surveys.

Typically, the energy application for the first impact on soft soils is governed by experience or general guidelines formulated on the basis of the drop energy (WH). As an example, the National University of Singapore's experience suggests limiting the first impact drop energy to 150 tonne-meter (Chow, 1995). It is evident therefore, that accurate predictions of the crater depths are useful for efficient implementation of DC or DR processes. Chow et al. (1992) proposed a model to predict the penetration depth based on the one-dimensional wave equation. However, since its application involves determining a number of soil parameters from additional laboratory tests, its field applications may be limited. The new method presented herein predicts crater depths on the basis of impact energy per unit contact area and the soil strength obtained from the routinely conducted Cone Penetration Tests. The new technique has been de-

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veloped based on laboratory impact tests and validated by full-scale field studies.

EFFECT OF SPECIFIC IMPACT ENERGY

The effect of the impact area of a pounder has not been adequately addressed in the literature when considering the depth of improvement. Despite Lukas' (1986) realization that contact pressure (W/A) must affect the depth of improvement, the following relationship presented by Menard et al. (1975) is used most commonly:

$$D=n\sqrt{WH} \tag{1}$$

where: D = depth of improvement, m
W = weight of pounder, tonnes
H = drop height, m
n = an empirical coefficient (less than 1)

The empirical coefficient, n, accounts for variability in soil types and layers, contact area of the pounder, and the efficiency of the drop mechanism. The strong correlations that evolved into this relationship exist possibly due to the uniformity of contact pressures for DC pounders (generally 40 to 75 $\mathrm{kN/m^2}$). Lukas (1986) proceeds to advise that pounders with lower contact pressures create a shallow densified crust of soil and are generally used for the ironing pass. Pounders with higher contact pressures can cause excessive penetration or punching failure of the soil surface. However, these considerations qualitatively address drop energy as well as contact pressure and fail to quantitatively incorporate the effects of all pertinent parameters, pounder weight, drop height, contact area, and pounder base width. Another drawback of the current guidelines for determining the crater depths is the absence of soil strength criteria since it is obvious that the crater depth must depend on the soil strength properties. The proposed method addresses these issues by introducing specific impact energy and the soil strength as the key parameters controlling pounder penetration.

PROPOSED METHODOLOGY

In terms of quantifying the soil strength, the Cone Penetration Test (CPT) is preferred over Standard Penetration Test (SPT) especially in soft soils. This is primarily for two reasons: (1) the high sensitivity of an electronic cone penetrometer, and (2) the test provides a continuous record of soil resistance with respect to depth. The proposed approach utilizes the sensitivity and continuity of CPT data and incorporates the *specific impact energy* of the pounder to predict initial impact penetrations.

The *specific impact energy*, E, is defined as the impact energy per unit area as shown in Eq. (2).

$$E=\eta\frac{WH}{A} \tag{2}$$

where E = specific impact energy
A = contact area
η = drop energy reduction factor = $(V_0/V_t)^2$
V_0 = observed impact velocity
V_t = theoretical impact velocity ($\sqrt{(2gH)}$)

The energy reduction factor (η) accounts for the amount of energy lost to cable drag and the spool inertia. For a given soil profile and drop energy (pounder weight and drop height), one would expect deeper crater depths for smaller contact areas and *vice-versa*. Further, the depth of penetration is dependent on the variable soil strength profile as evidenced by different crater depths observed in essentially the same soil profile. Hence the depth of penetration must be a function of the *specific impact energy* (energy per unit area) and the shear strength characteristics of the soil profile. In this regard, one can assume that the cone resistance, q_c, at a given depth, indicates soil shear strength at that elevation. The validity of this assumption is further discussed in the next section.

In an attempt to formulate the above speculated relationship, the authors semi-empirically correlated the *specific impact energy* and the cumulative shear resistance encountered by the pounder up to the depth of penetration. The technical basis for the existence of such a correlation is described below.

If the initial ground heave is insignificant, the *specific impact energy* can be equated to the work done to overcome the shear resistance of the penetrated soil per unit pounder base area as expressed in Eq. (3).

$$E=\int_0^{z_p} q_c dz+\epsilon \tag{3}$$

where: E = specific impact energy
q_c = cone resistance at any depth z
z_p = effective depth of penetration
ϵ = error term due to losses.

It has been assumed that the local shearing resistance encountered by the DC pounder at any penetrated point can be expressed by its q_c value. However, since the mechanisms of ground penetration are different in DC and CPT, there are limitations to the applicability of this method. In light of the discussion on penetration resistance of soils offered by Schmertmann (1978), one can visualize two basic differences between these two penetration mechanisms. They differ in (1) the shape of the penetrating object and (2) the rate of penetration. In this newly introduced practical correlation between impact energy and penetration resistance, the authors compute the total penetration resistance encountered by the pounder by integrating the CPT profile from the ground surface to the depth penetrated by the pounder. Hence the shape difference will be insignificant if one assumes that the cone tip is small enough to present data representative of any point under the pounder base, at any depth.

On the other hand, there is a marked difference in the penetration rates especially when the pounder first touches the ground with a free fall penetration rate much higher than the 2 cm/s advancing rate of the cone. Rapidly penetrating objects can impede pore pressure dissipation thereby lowering the effective stresses and the penetration resistance, in turn. However, this phenomenon is certainly limited to saturated soils with low hydraulic conductivity (k) values. According to Schmertmann (1978), this "k" threshold is around 10^{-5} cm/s. Therefore, the above assumption would be reasonable for dynamic compaction of granular and silty soil deposits as well as unsaturated clays. Unrelated laboratory hydraulic conductivity tests on the tested organic soils revealed k values in the range of 10^{-4}–10^{-5} cm/s. Thus, no significant pore pressure effects were expected in this particular study. Further support for this assumption is offered in the section on Correlation of Results.

Equations (2) and (3) verify common experience that larger-width pounders penetrate less than smaller-width pounders in the same soil for a given impact energy. The integration term in Eq. (3) can be graphically illustrated in Fig. 1 as the area under the q_c profile. However, z_p (in Eq. (3)) cannot be simply the crater depth, but rather the effective depth of the active soil wedge advancing with the pounder as shown in Fig. 2. This is because a part of the impact energy is also utilized in mobilizing some shear resistance in the soil wedge beneath the pounder. If it is assumed that the active soil wedge resembles one that is formed during typical bearing capacity failures, one can approximately determine the effective depth z_p as follows.

Due to the variable cross-sectional area of the active soil wedge and possible variations in cone resistance over the entire depth of the wedge, Eq. (3) can be expanded to differentiate two separate zones: (1) the zone penetrated by the full area of the pounder (A_p), and (2) the zone affected by the varying area of the failure wedge, $A(z)$.

$$E=\int_0^{z_c} q_c dz+\int_{z_c}^{z_c+h} q_c \frac{A(z)}{A_p} dz+\epsilon \tag{4}$$

where z_c=crater depth
h=height of the wedge
$A(z)$=cross sectional wedge area at depth z
A_p=projected area of the pounder base

The first integral term expresses the energy required to overcome the shear strength of the crater per unit area of the pounder. The second term on the other hand expresses the energy required to mobilize shear strength in the failure wedge per unit area of the pounder.

The depth of the failure wedge will be relatively small for small pounders such as the one used in the model study herein. Hence, q_c will be essentially constant over the entire depth of the failure wedge reducing Eq. (4) to:

$$E=\int_0^{z_c} q_c dz+q_c\int_{z_c}^{z_c+h} \frac{A(z)}{A_p} dz+\epsilon \tag{5}$$

It can be shown that the second integrand in Eq. (5) is mathematically reduced to $h/3$. Then,

$$E=\int_0^{z_c} q_c dz+q_c(z_p)\frac{h}{3}+\epsilon \tag{6}$$

where

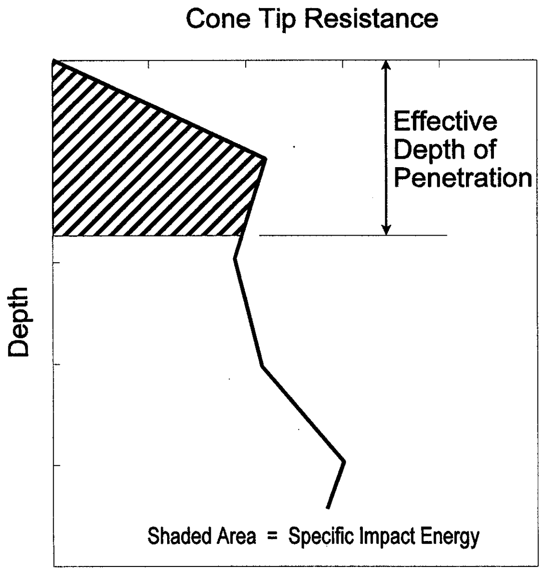

Fig. 1. Penetration calculated from a given specific impact energy

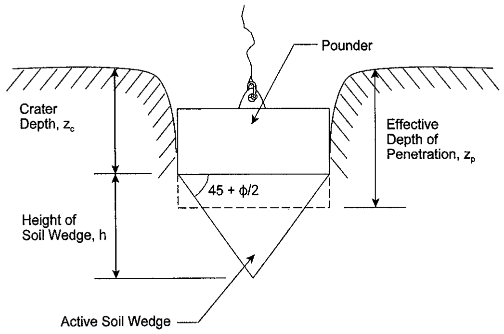

Fig. 2. Effective depth of penetration in advancing soil wedge

$$z_p=z_c+\frac{h}{3} \tag{7}$$

given that from Fig. 2, h can be approximated by

$$h=\frac{B}{2}\tan\left(45+\frac{\phi}{2}\right) \tag{8}$$

and

B=pounder base width
ϕ=angle of internal friction

Therein, the crater depth can be estimated by finding the appropriate z_p to satisfy Eq. (3) and then combining Eqs. (7) and (8) in the following form:

$$z_c\cong z_p-\frac{B}{6}\tan\left(45+\frac{\phi}{2}\right) \tag{9}$$

The angle of internal friction can be approximated by employing any one of the common correlations that are available between q_c and ϕ (Robertson and Campanella, 1983).

For relatively large pounders, the depth of the failure wedge will be significant, possibly penetrating a number of variable layers. In such situations, one must use Eq. (4) for varying q_c values beneath the pounder. This requires an iterative approach in that z_c depends on $A(z)$, h, and the average ϕ beneath the pounder, and ϕ depends on the depth to which the pounder penetrates, z_c.

Based on Eqs. (3) and (9) and data from a number of model tests, the investigators developed a correlation between the specific impact energy E and the area under the q_c profile as shown in Fig. 1.

MODEL TESTING

A series of DR tests was conducted in order to investigate the effects of pounder weight, drop height, impact area, number of impacts and initial soil strength on the pounder penetration. Although the primary objective was to develop guidelines for efficient implementation of DR in weak soils, the results were used to develop the correlation between impact energy and the pounder penetration.

The tests were conducted in a 2.44 m square, 1.22 m deep test pit. The test pit was equipped with a sand-gravel drain and a 3.5 m high, steel lifting frame shown in Fig. 3. The frame was supported by four rollers which rested on two parallel steel angles serving as guides on opposite sides of the pit. A drop mechanism was attached to the upper I-beam of the frame via a trolley and pulley system. The rollers and trolley provided 2 degrees of freedom allowing the drop mechanism to impact soil at any desired location in the pit. The drop mechanism could deliver free-fall impacts from a maximum height of 3 m. A 1 m deep bed of organic rich soil was prepared in 15 cm lifts and compacted with a WACKER BS-45-Y vibratory rammer. In order to prevent excessive compaction of the soil, the rammer was modified with a larger base. The soil was obtained from a site in Central Florida with an organic content ranging from 50 to 90%. Since organic soils are generally classified based on organic content or the moisture content, the consistency limits were not determined. However, further classification revealed the soil to be silty sands mixed with amorphous organic matter. Although care was taken to prepare a homogeneous bed of soil, a cone penetrometer was used to establish the soil strength profile at 24 locations within the bed to detect local variations. The penetrometer was specifically designed to register low stresses (2200 kPa capacity) such as those typically encountered in organic soils.

Four 177.56 N square pounders were fabricated with base areas ranging from 58 to 232 cm^2. Each of the pounders was dropped from five different heights (H=0.9, 1.2, 1.5, 1.8 and 2.1 m). As a result, 20 specific impact energy levels were analyzed. Figure 4 shows the plan view of the test bed which includes the 20 impact locations, contact areas (A), and the impact energies (WH).

CORRELATION OF RESULTS

The effective depth of penetration for each initial impact was used as the upper limit of numerical integration (Eq. (3)) of the CPT profile from its respective print location. The area estimated from the CPT curve from $z=0$ to $z=z_p$ is shown in Fig. 5 for a typical initial impact (a numerical example of the prediction methodology is presented in Appendix II). The computed areas for each test were then compared to the specific impact energy (E) of the corresponding pounder. Figure 6 shows the plot of E versus 'Area under CPT curve' for impact tests on the organic soil used in the model test. A sandy soil was used in the test pit to provide a blanket for dynamic compaction of the organic soil. As one would expect, punching through the sand blanket with the pounders produced sand columns in the organic soil at the impact locations. Linear regression with a coefficient of correlation of 0.93 confirms the relationship in Eq. (3) with an efficiency of energy transfer (η) of 98%. It is also seen from Fig. 6 that the energy loss term (ϵ) appears to be negligible for the model tests.

The results from impact tests on both the organic and sandy soil were re-evaluated to *predict* z_c based on the pounder drop energy and the q_c profile. Equations (3) and (9) were used in this exercise by assuming zero energy

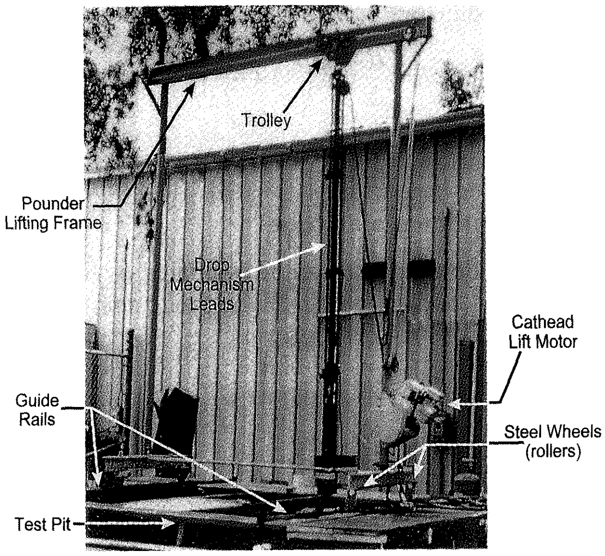

Fig. 3. **Frame assembly used to lift and release the pounder over the test pit**

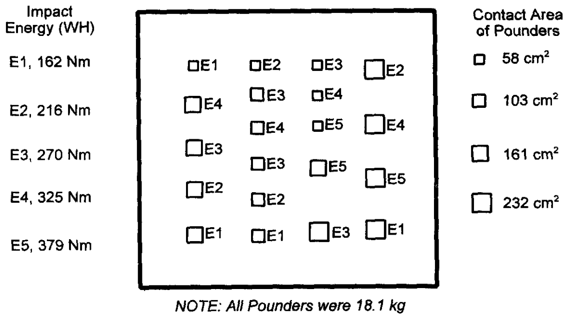

Fig. 4. **Layout of test pit showing print locations, contact area, and applied impact energy**

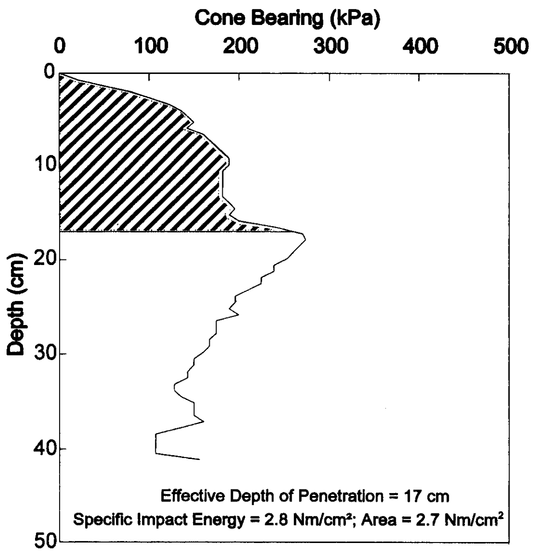

Fig. 5. Typical numerical integration results

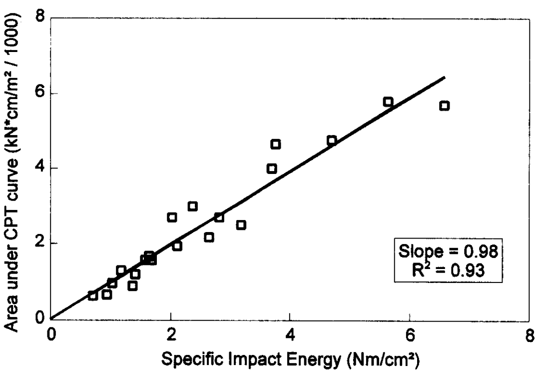

Fig. 6. Comparison of specific impact energy with area under CPT curve

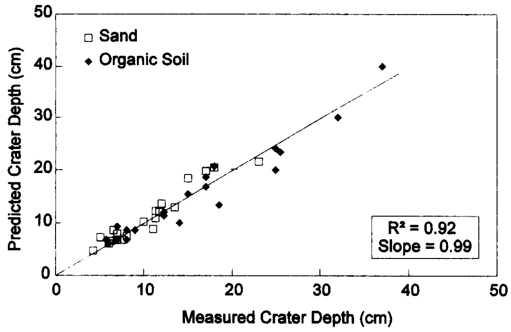

Fig. 7. Crater depth predictions for model test impacts

losses. Figure 7 shows the comparison of predicted penetrations and measured penetrations for all of the model tests. The linear correlation along a slope of 0.99 with a coefficient of correlation of 0.92 indicates the potential of this new method in accurately predicting crater depths.

It is recalled that the crater depth prediction technique advanced in this study stems from the assumption that q_c values represent the shear resistance encountered by the dynamic pounder at every depth. A clear affirmation of the validity of this assumption for many field situations is seen in the results of this study itself. In this respect, Figs. 6 and 7 show that, for the tested organic soil and sand, the difference in the penetration resistance manifested for the cone and the pounder is insignificant *for all practical purposes.*

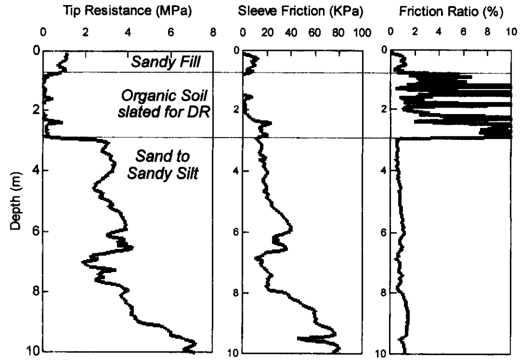

Fig. 8. Cone penetration sounding prior to DR process in Plant City, Florida

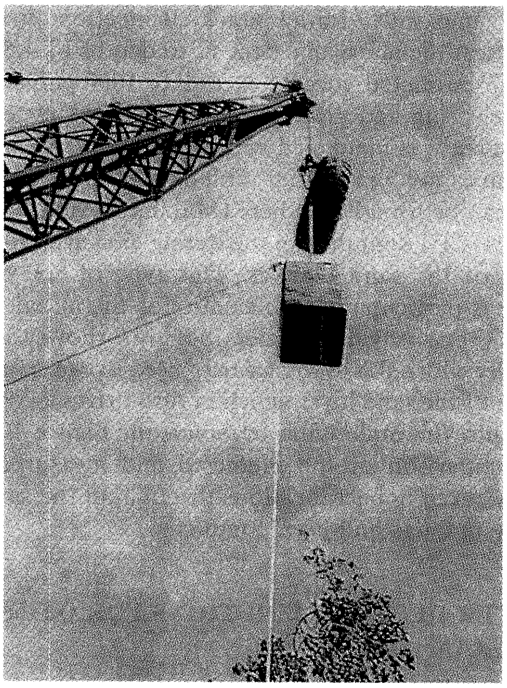

Fig. 9. Pounder (36 kN) designed for DR

FIELD VERIFICATION

The results of the model study predictions were verified during a full-scale Dynamic Replacement project conducted as part of the I-4 expansion project in Plant City, Florida. Therein, a portion of the *Exit 13* westbound on-ramp was set aside for experimental ground modification using DR as an alternative to replac-

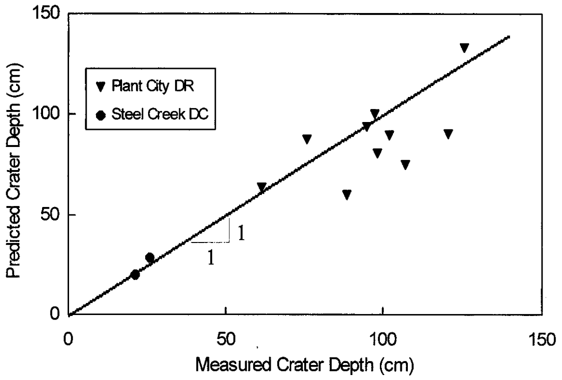

Fig. 10. Comparison of predicted and field measured crater depths

ing organic soils. Initial muck delineation probes revealed a surficial organic deposit to depths of 4.5 meters with an estimated volume exceeding 1000 cubic meters. After clearing and grubbing the site, an 18 meter by 45 meter area was blanketed with approximately one meter of clean sandy fill material. Full details of the entire program can be found elsewhere (Mullins, 1996). Figure 8 is a typical CPT sounding in the testing area after the application of the sand blanket. This type of soil strength profile is particularly problematic for the initial impacts due to excessively deep craters. Figure 9 shows the 36 kN pounder with a 0.6 m square base used to cause punching failure of the sand layer which in turn drives a column of sand into the underlying organic soil. Figure 10 shows the comparison of the predicted and measured crater depths at ten impact locations throughout the site where CPT soundings had been conducted.

CRATER DEPTH PREDICTIONS FOR OTHER DC PROGRAM

Crater depth predictions were also made using CPT data supplied by GKN Hayward Baker, Inc. from the Steel Creek Dam project on the Savannah River south of Augusta, Georgia, USA. This project entailed the construction of a 600 meter-long earthen dam up to 25 meters above the original stream elevation. To alleviate the problem of excessive penetration during DC with a 266.7 kN pounder dropping from a 30 m height, a 168.6 kN pounder dropping from a 15 meter height was used for the first pass in order to densify upper layers enough to withstand blows from the heavier pounder. The two pounders were of cross-sections of approximately 2 m × 1.3 m and 1.3 m × 1.3 m, respectively. The compacted soil was predominantly sandy with a clay layer appearing from about 1 to 3 meters. The entire DC process was performed in four passes totaling over 1300 impact locations (prints). The print pattern and spacing was based on a 15 m square configuration and the crater depths were typically recorded after 5 to 10 drops. In a few locations where initial impacts were recorded and CPT data were available, the predicted crater depths matched reasonably with those recorded in the field (Fig. 10).

CONCLUSIONS

An empirical-mechanistic method is presented for predicting the initial crater depth created by a dynamic compaction pounder after the first impact on a soil. This computational technique will be particularly useful for dynamic compaction projects on weak soil types where the ground heave is expected to be negligible. In this approach, the *specific impact energy* (impact energy per unit area) of dynamic compaction is equated to the cumulative area under the CPT curve between the ground surface and the effective depth of penetration. Hence it certainly addresses shortcomings of the current methods of evaluating the depth of pounder penetration which account for neither the soil strength nor the pounder surface area.

Although the correlations leading to the prediction technique are based on a large number of model tests, full-scale dynamic replacement results are used to verify it. Further, field data obtained from dynamic compaction tests performed elsewhere have been used to corroborate the new technique. Although the methodology is intended for use in uniform soft soils, its application also can be extended to non-uniform soils. A numerical example (Appendix) illustrates how typical CPT data can be adapted to predict the effective depth of penetration and subsequently, the crater depth. The newly developed method is expected to enable engineers to determine approximately the optimum impact energy that can be used in dynamic compaction without causing excessive initial penetrations, based only on cone penetration test results. Furthermore, since the ensuing impacts carried out on refilled craters do not generally cause deeper penetrations than the initial one, the initial crater depth can provide an approximate idea of the influence zone. Hence the predictive technique will furnish an effective planning tool for dynamic compaction programs on sites with weak soils, well before the mobilization of heavy equipment.

ACKNOWLEDGMENTS

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APPENDIX

Numerical Example

To illustrate the new method of predicting crater depths, Eq. (3) is rewritten for discrete CPT values in Eq. (10). Assuming the typical depth recording interval of a mechanized cone to be Δz and the average cone resistance q_c over each interval as a discrete value, a cumulative $q_c \Delta z$ is computed as a function of depth (z). Then z_p can be determined as the depth at which the cumulative $q_c \Delta z$ equals the specific impact energy for the given drop configuration.

$$\sum_{0}^{z_p} q_c \Delta z = \eta E \qquad (10)$$

where: q_c = average CPT value over that depth interval
Δz = depth recording interval (typically 5 cm)
η = drop efficiency ($\eta \approx 1$, for free-fall)
$E = WH/A$

Assume that CPT data from a site in Central Florida where predictions of crater depths due to free-fall impacts are needed are shown in CPT data below:

Given: $W = 6$ tonnes (58.9 kN)
$H = 20$ meters
$B = 1$ m square ($A = 1\ \text{m}^2$)
$\phi = 35$ degrees,

predict the initial crater depth.

Cone Penetration Test Data for Numerical Example

SOUNDING DATA IN FILE 6 02/05/95 14:42
ENGINEER: W. R. MCLAUGHLIN LOCATION: 6
CONE ID: 271 JOB #: 99901 1521
FLORIDA DEPARTMENT OF TRANSPORTATION
BARTOW DISTRICT

Depth (meters)	TIP resistance (kPa)	Local friction (kPa)	Friction Ratio (%)	Inclination (deg)	Cumulative area under CPT (z)
0.00	0.01	0.00	0.00	−0.1	0
0.05	512.68	1.08	0.21	−0.2	12.82
0.1	769.01	1.92	0.25	−0.2	44.86
0.15	1412.11	4.24	0.3	−0.2	99.39
0.2	2202.11	8.37	0.38	−0.2	189.74
0.25	2784.74	9.75	0.35	−0.2	314.41
0.3	3356.32	12.08	0.36	−0.2	467.94
0.35	3432.11	11.67	0.34	−0.2	637.65
0.4	3920.21	9.80	0.25	−0.2	821.45
0.45	4052.11	13.37	0.33	−0.2	1020.76
0.5	3927.37	18.46	0.47	−0.2	1220.24
0.55	3905.26	31.24	0.80	−0.2	1416.06
0.6	3773.68	40.38	1.07	−0.2	1608.03
0.65	3695.79	32.15	0.87	−0.2	1794.77
0.7	3737.37	16.44	0.44	−0.2	1980.6
0.75	2001.05	8.80	0.44	−0.2	2124.06
0.8	2511.05	14.06	0.56	−0.2	2236.86

The prediction process involves three steps:

1. Estimate the cumulative area under the CPT curve at different depths.

   This is recorded at each depth in the last column of Table 1.
2. Determine the *specific impact energy* (E) for the given drop mechanism, assuming a free fall.

   The specific impact energy = 58.9*20/1.0 = 1177.2 kN/m.
3. Estimate the effective penetration depth where the cumulative area equals the *specific impact energy*.

Thus, z_p can be estimated to be 49 cm. Then, by using Eq. (9) the crater depth is predicted to be 17 cm.