International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1991 - Second International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

14 Mar 1991, 2:00 pm - 3:30 pm

Impact Response of Granular Soils

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Recommended Citation

Poran, C. J.; Rodriguez, J. A.; and Heh, K. S., "Impact Response of Granular Soils" (1991). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 5.
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Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,
March 11-15, 1991, St. Louis, Missouri, Paper No. 10.4

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SYNOPSIS: The paper describes results from an extensive experimental model study of response of dry sand to impact of a rigid pounder. In the laboratory tests a circular steel pounder was repeatedly dropped on sand contained in a large tank. Measurements included pounder acceleration and soil pressure at impact, pounder settlement, and soil densities and strains. Effects of pounder drop height, weight and contact area were investigated. A method is presented for the evaluation of global dynamic stiffness of the soil mass affected by the impact by calculating a dynamic settlement modulus (DSM). The DSM values are determined from integration of the impact acceleration record with respect to time using measured integration constants. DSM values show good correlation to soil densities and corresponding elastic moduli obtained from laboratory tests. The proposed method may have immediate construction application as it offers a reliable and cost effective alternative to quality control of dynamic compaction.

INTRODUCTION

Dynamic compaction (DC) is a soil improvement method which is rapidly gaining acceptance in the United States and abroad . The method involves the repeated dropping of a heavy pounder on the soil surface, compacting the soil strata to considerable depth. The method is particularly effective in granular soils, deposits of rubble, and landfills. Although the method is widely used in such soils, the dynamic soil-pounder interaction at impact is not well understood and there is a lack of comprehensive models to quantify the impact induced deep densification and its relationship to the characteristics of the impact.

Several researchers have conducted analytical and experimental investigations of soil-pounder interaction and impact response of granular soil. Forssblad (1963) suggested that the kinematic impact energy can be equated to the volumetric strain energy in the affected soil mass by integration over the affected volume. Orrje and Broms (1970) reported results from a laboratory study of DC where pounder-soil interaction during impact was investigated for different soils and densities. Wang and Deng (1983) correlated the depth of the compacted soil mass to impact energy and to the characteristics of the shear waves induced by the impact. Ellis (1986) reported on DC laboratory tests and crater development in different soils. None of these investigations directly correlated soil-pounder interaction during impact to the permanent effect of that impact on soil density and deformation characteristics.

This paper includes a description of an extensive laboratory model study of DC of dry sand. The measurements included pounder acceleration and soil pressures during impact, and soil densities and strains before and after impact. A procedure is presented to analyze the dynamic results and a dynamic settlement module (DSM) is calculated as subsequently shown.

EXPERIMENTAL STUDY

An extensive laboratory model testing program was conducted to investigate impact response of dry sand as described by Heh (1990). The soil properties, testing setup, procedures and program are described in the following sections.

Soil Tested.

The soil used for this research was dry Boston sand with particle diameters ranging between 0.09 mm and 0.9 mm, with D_{10} = 0.28 mm, and D_{60} = 0.73 mm. The sand is classified as SP according to the USCS. Other properties were tested in accordance to ASTM standards and the results are summarized in the following:

Maximum Dry Density, γd_{max}=17.10 KN/m^3
Minimum Dry Density, γd_{min}=15.05 KN/m^3
Maximum Void Ratio, e_{max}=0.74
Minimum Void Ratio, e_{min}=0.53
Specific Gravity, G_s=2.674

For the impact tests the sand was placed in the test tank with a unit weight of 15.5 KN/m^3 which corresponds to a relative density, D_r, of 25%. Friction angles of 34.2° and 42.1° were evaluated from triaxial compression tests for the sand in loose and dense states. Elastic modulus and Poisson ratios were also estimated based on static triaxial and oedometer test results.

DC Test Setup and Instrumentation.

The test layout is shown in Figure 1. It consists of a 1.22 m by side cubic steel tank filled with sand. The pounders were assembled from circular steel plates in three diameters:

22.9, 15.2 and 10.2 cm, which were setup in various specified pounder weights. The pounder was lifted with an electromagnetic mount for quick release and free fall. The release also triggered the data acquisition system. Generally, there were two accelerometers mounted on top of the pounder for redundancy. The accelerometers and soil pressure transducers were connected to a digital oscilloscope system operating with a microcomputer. Also, as shown in Figure 1, electromagnetic induction soil strain sensors were used with a special measurement device. A portable nuclear instrument was used to measure sand density at the end of each test.Several key system components are described as follows:

Accelerometer: after testing several accelerometers, the Endevco 2262A-200 model was selected for this investigation. This instrument has a sensitivity of 2.667 mv/g with a ±200g range and a shock acceleration limit of 2000g, and it was not affected by the electromagnetic field induced by the mount.

Soil Pressure Transducers: measurement of dynamically induced stresses in a soil mass is difficult since the presence of the transducer produces local changes of stresses and strains. In this case the Kulite model 0234 transducers were used. These devices use a silicon pressure transducer as the basic sensing element, coupling extreme robustness with high output. Cell thickness was 1.2 cm with overall diameter of 5.5 cm, and an active area of 3.6 cm diameter.

Soil Strain Measurements: the strain measuring was based on Bison Instruments Inc., strain gauges model 4101A. It consists of two basic components: (i) pairs of embedded electromagnetic induction sensors, each having a disk shaped coil encapsulated in a plastic cast, and (ii) an external instrument package.

Digital Oscilloscope: a four channel digital oscilloscope was used for the acquisition and processing of the dynamic data from the accelerometers and the soil pressure transducers. This hardware-software system was made by Rapid Systems of seattle, washington. A microcomputer was used for data acquisition and display.

Tailor made software was developed and used in conjunction with the DADisp program from DSP Corporation in Massachusetts for rapid signal processing and visualization.

Test Procedures

(a) The tank was filled with sand at the predetermined relative density. The sand placement was conducted through a 94x94 cm No. 14 wire mesh kept at a constant height of 20 cm above the sand surface. This placement technique resulted in a uniform sand of 15.5 KN/m^3 density which corresponds to a relative density of 25%.

(b) The filling process was interrupted when the sand reached a desire depth where pressure transducers or strain sensors needed to be placed.

(c) After tank filling the DC test was conducted according to the following steps:

i. Readings were obtained from the soil strain sensors to determined the initial sensor spacing.
ii. Verification check of the data acquisition system was conducted.
iii. The special software was activated to setup all the input channels.
iv. The pounder was raised to the required height.
v. Data acquisition system (DAS) was set to the automatic trigger mode and the electromagnetic switch was turned off. The pounder was released from the electromagnetic mount and dropped on the sand surface. Data was processed on the DAS and digital oscilloscope.
vi. New readings of the soil strain sensors were recorded after the impact.
vii. Crater dimensions were measured.
viii The pounder was removed from the crater and the test procedures were repeated for the designated number of drops.
ix. Removal of sand started after all the drops were completed. Sand density was mapped with the nuclear density instrument as the sand was vacuumed out by layers of 15 cm at a time.

TESTING PROGRAM

First some 12 initial tests were conducted. Results from these tests helped in identifying potential problems and selecting appropriate transducers, system layout, and test procedures. Then a total of 12 DC tests were carried out as shown in Table 1. Three tests (21,22 and 25) were conducted twice. Results of each pair of these duplicate tests were essentially similar.

TABLE 1 - DC Testing Program

Test No.	Pounder Wt. N	Pounder Diameter Cm	Drop Height m	Energy/ drop N-m
21*	220	22.9	2.0	440
22*	220	22.9	1.0	220
23	220	10.2	2.0	440
24	220	10.2	1.0	220
25*	220	15.2	1.0	220
26	220	15.2	2.0	440
27	332	15.2	0.67	220
28	332	15.2	1.99	660
29	332	15.2	1.33	440

Note:* indicates that the test was conducted twice to verify reproducibility of results. All tests were carried out to 18 drops.

DATA ANALYSIS

The data analysis procedure developed for this study is based on simple dynamics concepts. The response of soil strata to an impact of a large pounder is influenced by global properties of a large soil mass under the impact point. Therefore, this response realistically

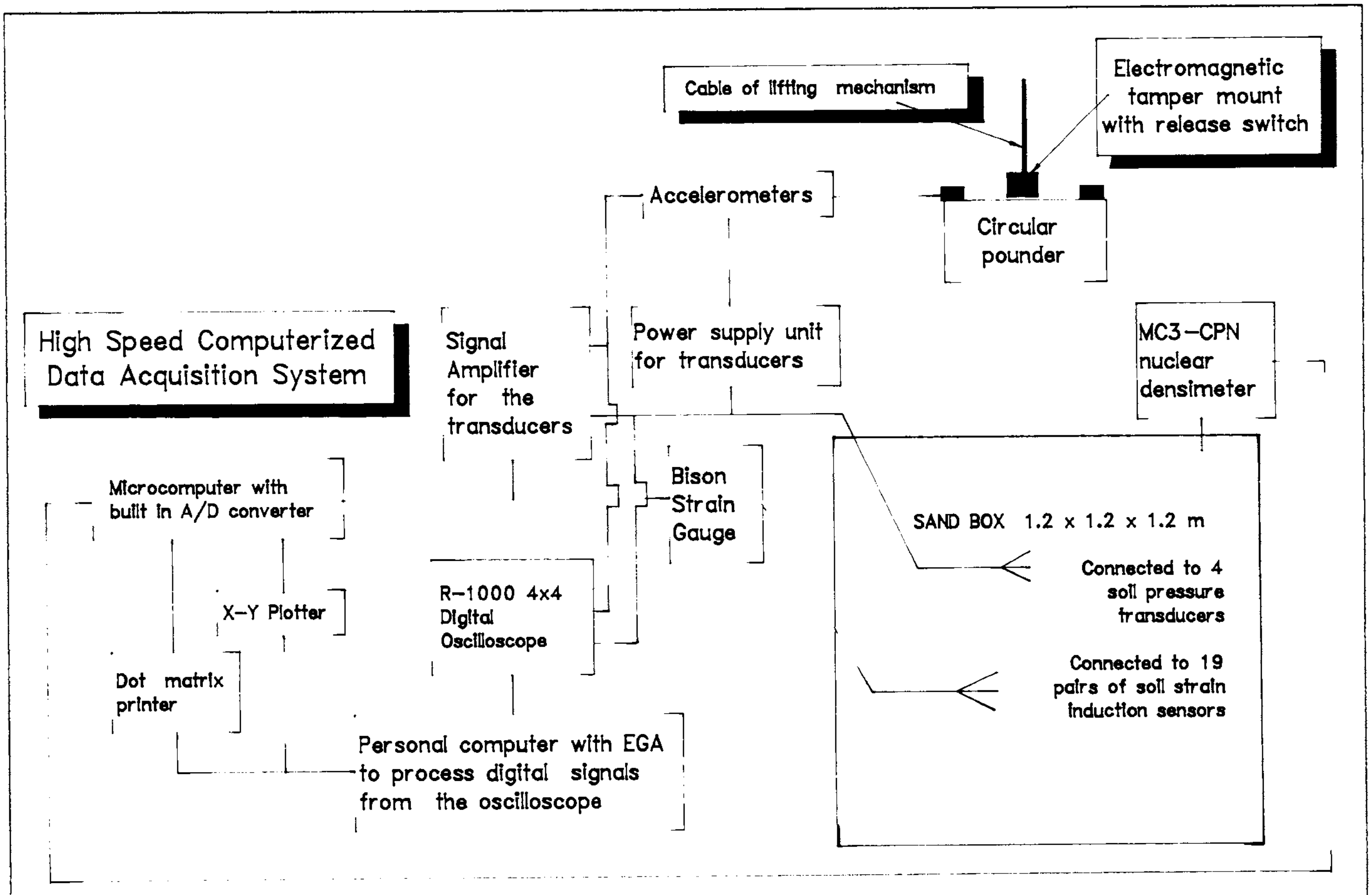

Figure 1 - Schematic Layout of Model Testing

represents these properties. The pounder-soil interaction is defined by the boundary conditions and soil properties.

This global response is believed to be much better suited to represent the variable soil conditions encountered in may DC sites. The dynamic soil-pounder interaction during impact is therefore the key to successful interpretation of such global soil properties. The concept, based on the dynamic settlement modulus (DSM), is described as follows.

The DSM Concept.

Typical accelerations recorded on the pounder during impact are shown in Figure 2. Based on Lucas (1986), these records are also typical to what was observed in field monitoring of DC projects. It may be noted that as the number of drops increase so does the global dynamic stiffness of the compacted sandy soil mass, as reflected by the increase in the acceleration peak and the shortening of the response duration as was found in the test results.

In the first processing step, each acceleration record, a_t, was integrated once with respect to impact time, t, to obtain the pounder velocity V_t, as:

$$V_t = \int a_t dt + C_v \qquad (1)$$

where C_v was determined at the end of the acceleration record when $V_t = 0$. C_v could also be determined at t=0, when the velocity at impact is known. A typical adjusted velocity record is shown in Figure 3. This and the following integrations were performed simultaneously by a microcomputer with a high speed special software and the DADisp program, which enabled rapid visual inspections and modifications of the digitalized records as appropriate at any time during the signal processing.

The next step was to obtain pounder displacement record, d_t, by integrating the digitized velocity record as:

$$d_t = \int V_t dt + C_d \qquad (2)$$

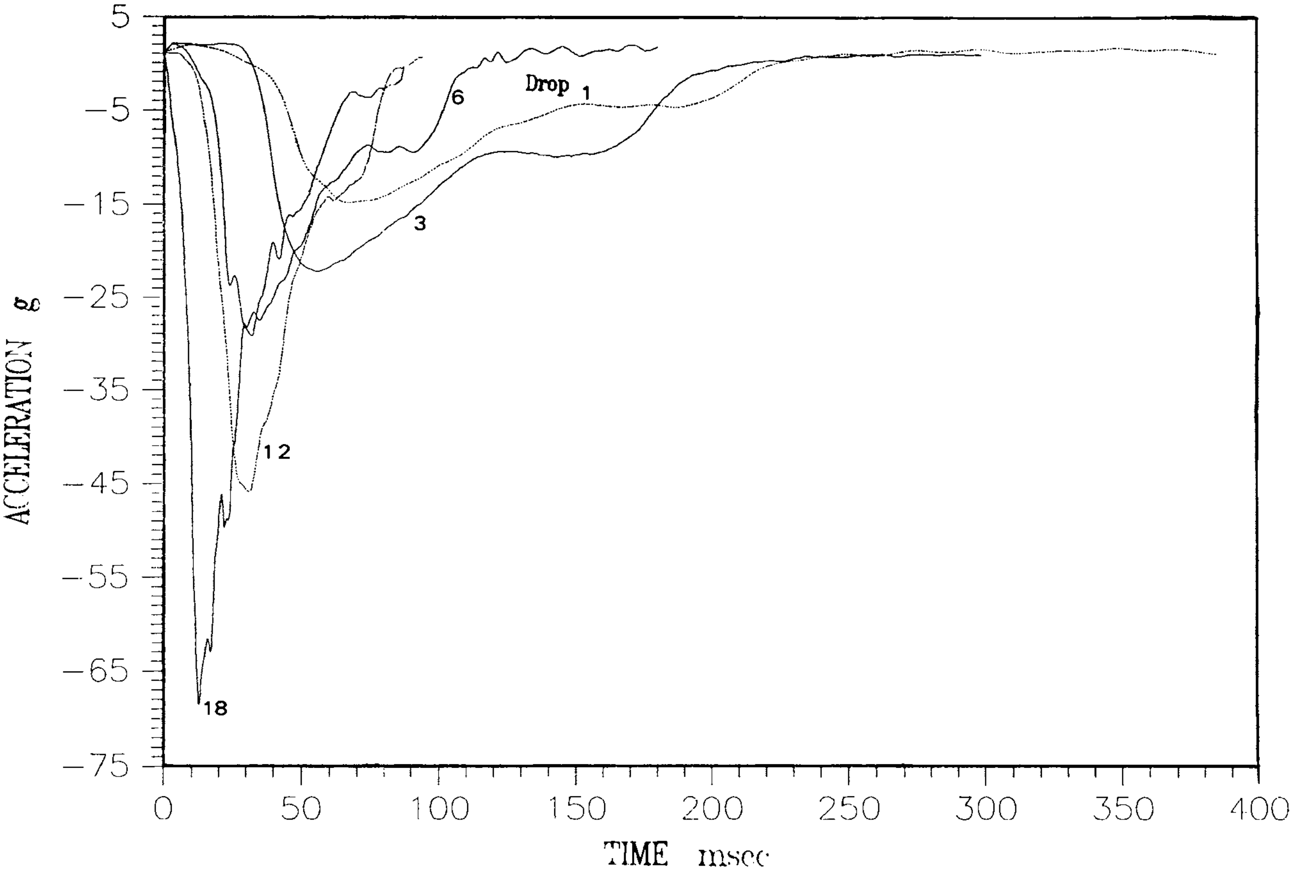

Figure 2 - Impact Acceleration vs Time, Test 21.

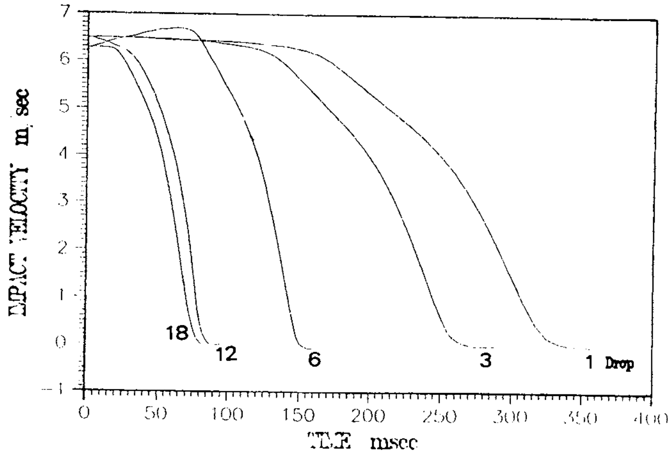

Figure 3 - Impact Velocities vs Time, Test 21.

Adjusted d_t curves are shown in Figure 4, where C_d was determined based on the actual "at rest" incremental pounder displacement for each drop, i.e., C_d was calculated by equating the computed pounder displacement value, d_t, at the end of each impact record to the measured, net incremental pounder displacement for that drop.

The impact stress, p_t, applied by the pounder over the duration of the impact was then determined for the digitized acceleration record as:

$$p_t = \frac{ma_t}{A} \tag{3}$$

where m and A where the mass and contact area of the pounder, respectively. Then, the adjusted dynamic displacement record of the pounder, d_t, was plotted versus the corresponding impact stress, p_t. The DSM was defined as the slope of the tangent of the loading portion of the impact stress-strain curve, as:

$$DSM = \frac{\Delta p_t}{\Delta\left(\frac{d_t}{D}\right)} \tag{4}$$

where the impact strain, ϵ_i, is defined as the pounder displacement, d_t, divided by pounder diameter, D. The DSM value was then determined by the computer processing of the dynamic loading slope data ($dDSM/d\varepsilon_1$), as graphically shown in Figure 5. This data processing was very rapid.

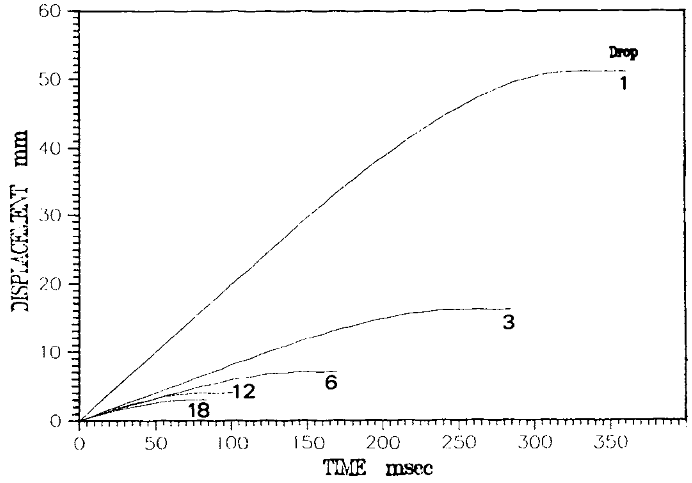

Figure 4 - Pounder Displacement vs Time

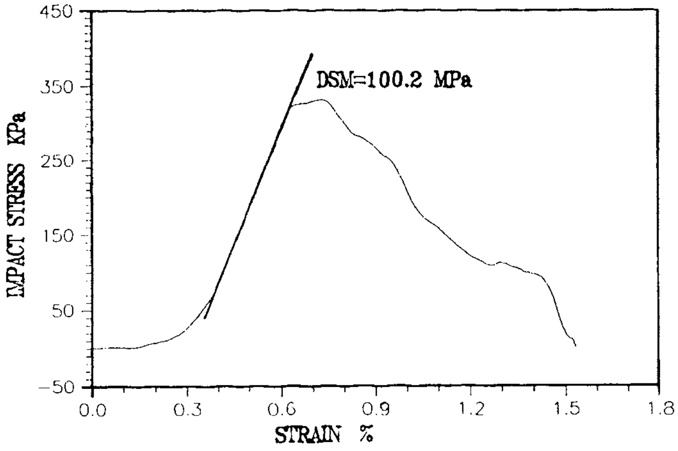

Figure 5 - Impact Stress vs Strain, Test 21, Drop 12.

Finally, the DSM values were plotted as a function of pounder drops, as shown in Figure 6. Generally, the rate of DSM increase was significantly reduced from the 12th drop on. This rate was found to be generally proportional to the rate of densification (density increase as a function of number of drops) as shown in Figure 6, where results of accumulated, net crater depth are also plotted versus number of pounder drops. As shown in the Figure, the DC was more effective in the first seven pounder drops, whereas drop 12 and its successive drops have relatively small effect.

CORRELATIONS TO ELASTIC PROPERTIES

Heh (1990) has shown that DSM values may be correlated with the elastic moduli for this sand as it was compacted from loose to dense state. Figure 7 shows a typical impact induced compaction after 18 pounder drops corresponding to the same test as in previous figures. Heh concluded from static triaxial and oedometer test results that the range of elastic properties for this sand is as indicated in Table 2.

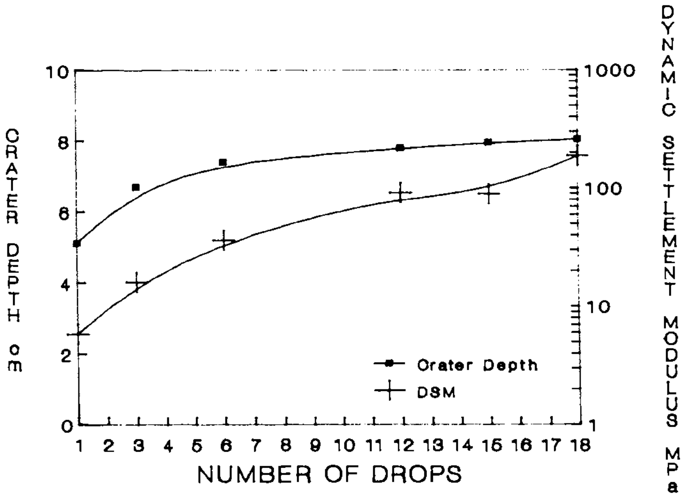

Figure 6 - Crater Depth and DSM vs Number of Drops.

In order to compare the DSM to the tangent Young's modulus it is first necessary to look at an equivalent static system where the stiffness of a circularly loaded area with a diameter D on an elastic half space is given by:

$$K = E\,D\left(\frac{1+\mu}{1-\mu}\right) \qquad (5)$$

where K is the system stiffness in terms of force/displacement, and μ is the Poisson's ratio. The equivalent form of Equation 5 may be expressed for a dynamic load as DSM_{EE}. Using this approach Equation 5 becomes:

$$DSM_{EE} = \left[\frac{\pi}{4}\left(\frac{1-\mu}{1+\mu}\right)\right]DSM \qquad (6)$$

where DSM is defined in Equation 4.

As shown in Table 2 DSM_{EE} correlates well with ranges for values of E from static test results and also corresponds well with the values reported in the literature with the exception of the dense sand where the ranges found in the literature, generally do not include the high end densities near Dr=100%.

CONCLUSIONS

The DSM concept which is based on the global dynamic response of the affected soil mass has been successfully applied to monitor DC of dry sand in laboratory model tests. DSM values may be correlated to the density and global elastic moduli of the sand and may be used to estimate elastic settlements. Ultimately, the DSM concept may be used to develop a field monitoring system

TABLE 2 - Correlation Between Elastic Properties from Static and DC Tests.

Sand Density	Estimated from Plate Bearing, Triaxial and Oedometer Tests		Estimated from Results of DC Test No. 21.		Range From Literature
	Poisson's Ratio	Estimated Tangent Young Modulus (MPa)	DSM (MPa)	DSM_{EE} (MPa)	Young Modulus (MPa)
Loose Dr≤35%	0.20	21	25	12	10 to 24
	0.25	19		12	
	0.30	17		11	
	0.35	14		10	
Medium Dense 35%≤Dr≤65%	0.25	37	70	33	17 to 27
	0.30	33		30	
	0.35	28		27	
	0.40	21		27	
Dense Dr>65%	0.30	82	215	90	35 to 55
	0.35	69		81	
	0.40	51		73	
	0.45	29		64	

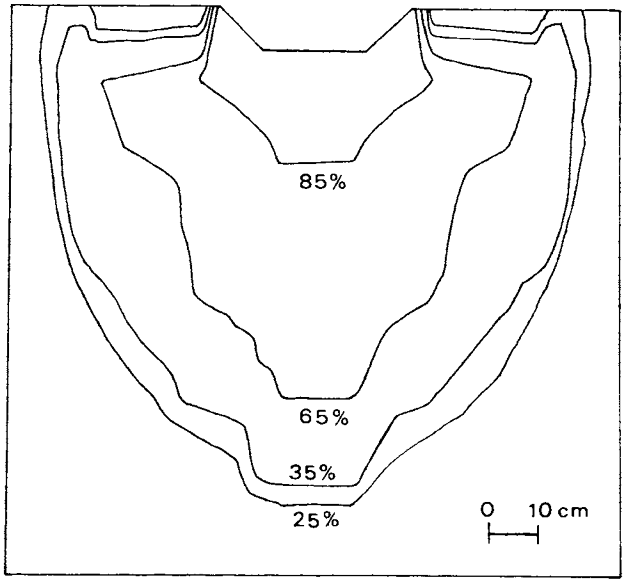

Figure 7 - Relative Density Contours After 18 Pounder Drops.

for DC. This system will be used as quality control to determine the pounder drop which results in sufficient compaction, without interrupting the compaction process at a certain grid point. When this will occur and the drop number will equal or exceed a minimum, initially specified number of drops, the DC process will be moved to the next grid point on the site. Obviously, this procedure must be developed and successfully demonstrated in a full scale field study.

ACKNOWLEDGEMENT

The results presented in this paper are from a study on Dynamic Compaction of Granular Soils funded by the National Science Foundation Award No. MSM8709280.

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