EFFECTIVE DEPTH OF DEEP DYNAMIC DENSIFICATION

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ABSTRACT:

This paper presents the laboratory study of dynamic densification on three distinct types of fill materials including clay, sand and flyash under both dry and saturated moisture conditions. Other variables include depth of overburden material, weight and contact area of pounder, height of drop and the number of drops. Effects of these variables relating to the densification energy and ground response are measured and examined. A comparison of ground response between theoretical and experimental results is made. The theoretical results are computed from Westergaard and Bousinesq Equations. Finally, a simple procedure for estimating the effective depth of densification based on the crater depth and radius and the degree of saturation is proposed for practical application.

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INTRODUCTION

Deep dynamic densification is a mechanical process to densify loose soil deposits at great depths. The process has been frequently used in large scale construction projects for densification of deep granular soils and more recently for the densification of soft clays (Qian, et al., 1980; Ramaswamy, et al., 1981).

The greatest concern in this process for the geotechnical engineer is the depth of influence due to the dynamic densification. The depth of influence is defined as how deep the pounder (weight), dropped freely from a certain height, will affect the fill material below the ground surface. Menard and Broise (1975) proposed that the effective depth or depth of influence is equal to:

\[ D_e = \sqrt{\frac{W \cdot h}{x^2}} \]  

(1)

Later, Leonards et al. (1980) modified as:

\[ D_e = 0.5 \sqrt{\frac{W \cdot h}{x^2}} \]  

(2)

and Lukas (1980) concluded that:

\[ D_e = (0.65 \text{ to } 0.80) \sqrt{\frac{W \cdot h}{x^2}} \]  

(3)

where \( D_e \) = Effective depth or depth of influence, m

\( W \) = Weight of pounder, metric tons

\( h \) = Height of free drop, m

Equations (1), (2), and (3) have been used for the in-situ ground improvement process and field control. The equations do not consider the type of fill
material, size of pounder or saturation of ground soil. These additional parameters are considered in the evaluation of the effective depth in the laboratory investigation.

To understand the densification process, it is necessary to examine the mechanism and mechanics of soil-pounder interaction. As shown in Fig. 1, when the pounder is applied to the soil mass, deformation will result from immediate elastic and inelastic deformation of the soil structure. Pore water drains from the soil resulting in reorientation of soil particles. This process depends upon the soil properties, drainage conditions, stress history and environmental conditions. The purpose of this paper is an attempt to answer or to clarify some of these questions including the effect of the pounder size and the various soil types and moisture conditions. From an analysis of these variables, a simple procedure to estimate the effective depth of the deep densification process is developed.
Figure 1 Schematic Diagram Illustrating the Soil-Pounder Interaction

(a) Reorientation of the soil particles
(b) Porewater dissipated
LABORATORY EXPERIMENTAL STUDY

Material

Three distinct types of fill materials are used in this study: clay, sand and flyash (silt) with two moisture conditions: dry and saturated.

Clay: Silty clay passed through a No. 10 sieve with a liquid limit equal to 29 and plasticity index equal to 5 was used. The unified classification of this soil is denoted as ML-CL.

Sand: Uniform clean fine sand was used. The gradation for the sand is about 50% passing the No. 40 sieve and less than 1.0% passing the No. 200 sieve.

Flyash (silt): The flyash material was supplied by the Pennsylvania Power and Light Company of Martins Creek, Pennsylvania, with 58.7 percent of the flyash passing the No. 200 sieve and the several larger bottom-ash particles removed.

Test Equipment and Instrumentation

The soil is contained in a metal drum 45.7 cm (18") in diameter and 57.6 cm (24") in height. Table 1 summarizes the experimental and measurable variables used in this study.

Pressure Cell: The standard pressure cell with strain gauge, wrapped in plastic to prevent soil interference of its motion, is used for measuring the ground response (R) due to the pounder. The strain gauge measures the deflection of the cell which is recorded on an oscillograph.
<table>
<thead>
<tr>
<th>Experimental Variables</th>
<th>Given or Measured Parameters</th>
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<tbody>
<tr>
<td>1. Type of Fill Materials</td>
<td>Clay; Sand; and Flyash (Dry &amp; Saturated)</td>
</tr>
<tr>
<td>2. Pounder Weight, (W_x)</td>
<td>469.9 gr.; 248.6 gr.; 379.4 gr.; 208.4 gr.</td>
</tr>
<tr>
<td>3. Pounder Diameter, (d_x)</td>
<td>10 cm; 6.58 cm; 5.10 cm 3.21 cm</td>
</tr>
<tr>
<td>4. Pounder Contact Area, (A_x)</td>
<td>78.5 (cm^2); 34.0 (cm^2); 20.4 (cm^2); and 8.07 (cm^2)</td>
</tr>
<tr>
<td>5. Height of Drop, (h_x)</td>
<td>34.0 cm; 64.3 cm; 42.1 cm; 76.6 cm.</td>
</tr>
<tr>
<td>6. Overburden Depth, (t_x)</td>
<td>40mm; 60mm; 80mm; 100mm; 120mm; 140mm; &amp; 160mm</td>
</tr>
<tr>
<td>7. Number of Drops, (n)</td>
<td>6 drops</td>
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<tr>
<th>Measurable Parameters</th>
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<tbody>
<tr>
<td>1. Radius of Crater, (r)</td>
<td>Direct measurements by scale</td>
</tr>
<tr>
<td>2. Cross-Section of Crater, (\delta)</td>
<td>Direct measurement from scale</td>
</tr>
<tr>
<td>3. Ground Response ((R))</td>
<td>Measured from Pressure cell</td>
</tr>
</tbody>
</table>
**Drop Weight (Pounder):** The weights used for this study were made from hard steel plate. The plate is thick enough to resist bending during the test. The weight of the pounder is denoted as $w$ and the diameter is denoted as $d$. The characteristics of the four pounders used are given in Table 1. To control the drop of the pounder, an electromagnet system is used.

**Test Procedure**

*Control of Drop Weight (Pounder):* An electromagnetic system is connected with the pounder. To release the weight, the switch to the electromagnet is turned off. At the same time the oscillograph is turned on to measure the ground response by measuring the force from the strain gauge on the pressure cell. After the weight has dropped, the oscillograph is turned off and the pounder is carefully removed from the crater. This process is repeated six times. After the sixth reading, the oscillograph deflections are measured from the strip charts.

*Crater Profile Measurements:* A depression crater is caused by the densification process. It is varied by the pounder area, densification energy, material types and moisture conditions. The overall picture of a crater profile after each weight is dropped is shown in Fig. 1. Typical profiles of clay, sand, and flyash for the dry condition are shown in Figs. 4 and 5.

The profiles are measured for each drop with each pounder size and material type. Before the weight is dropped, the surface material is leveled...
and the elevation measured at 2 cm intervals across the expected crater area. After each of the six drops, the distance from the datum to the surface of the crater profile is measured. Also, the horizontal points at the crater's edge and the horizontal location and depth of the deepest point of the crater are recorded.

**Density of Fill:** Before the fill is added, the surface elevation is measured at eight (8) random points on the clay foundation. After the fill is added and several trials are run, the surface is leveled and the elevation at the same eight points measured. Subtracting the values gives the fill depth. The average depth is calculated and with the diameter of the metal drum, the volume of fill can be computed. Dividing the mass of fill added by the volume of fill added yields the unit weight of the fill material. Detailed test procedures and instrumentation are described in a separate report (Fang and Ellis, 1983).

**SUMMARY OF TEST RESULTS AND DISCUSSION.**

**Thickness of Fill and Pounder Area**

Thickness of fill versus ground response with various pounder areas and constant densification energy is summarized for all three fill materials in Fig. 2. The thickness, \( t_x \), varies from 20 mm to 175 mm. Four pounder areas are used varying from 8.07 cm\(^2\) to 78.5 cm\(^2\). The ground response is the force acting on the pressure cell in Newtons. It is obvious that for a thin layer deposit the ground response is higher, and this is true for all pounder sizes.
Figure 2 Effect of Overburden Depth and Pounder Area on Ground Response

Ground Response, R, Newtons

- ○ Sand A = 78.5 cm²
- □ Clay A = 78.5 cm²
- △ Flyash A = 78.5 cm²
- ● Sand A = 8.07 cm²
- ■ Clay A = 8.07 cm²
- ▲ Flyash A = 8.07 cm²

Overburden Depth of Fill Material, tₓ, mm

Ground Response, R, Newtons
In comparing the response of the three types of soils, the flyash clearly has a greater response at shallow depths. This effect is magnified for the smaller pounders. The shapes of the ground response curves show a similarity between the flyash and sand when compared with the response of the clay. Both the flyash and sand have high ground responses at shallow depths followed by a rapid reduction in the response with depth. The clay response, however, is less at shallow depths but reduces more gradually allowing for more response at greater depths.

Fig. 3 is interpreted from Fig. 2 showing that for the thin deposit (say $t_x = 60$ mm), the pounder size has significant effect on ground response. This is particularly true of flyash where for each overburden depth the ground response increases rapidly at a critical pounder size. However, for the thicker layer ($t_x = 120$ mm), the pounder size has little effect on the ground response. Also indicated in these figures, the larger the pounder area, the less the effect on the ground response for all three fill materials, clay, sand and flyash.
Figure 3  
Ground Response versus Pounder Area with Various Depths of Sand, Clay and Flyash
Crater Profiles

A depression crater is caused by the densification process. The shape of the crater is influenced by the pounder area, number of drops, fill material types, moisture condition and densification energy. Figures 4 and 5 present the typical crater profiles for various fill materials in the dry condition with two pounder areas, \(A = 8.07\, \text{cm}^2\) and \(A = 78.5\, \text{cm}^2\). Number of drops, \(n\), varied from 1 to 6 with drop 6 indicated in the figures. Fig. 4 shows that for the smaller pounder, the surface area of the clay fill is small, but the depth is great. However, for the flyash the surface area is greater but the depth is less. Fig. 5 shows that for the larger pounder area, the flyash crater has the greatest surface area and depth. The profiles for the large and small pounders show entirely different shapes. For small pounder areas the crater can be approximated by an inverted cone while for large pounder areas the profile can be approximated by a trapezoid. Also, for sand it is shown that heave occurs at the edge of the crater. No heave is recorded for both clay and flyash fills.

Crater Area and Volume

Based on the data from Figs. 4 and 5, the surface area of the craters and volume of the craters are plotted versus pounder areas with constant densification energy for various fill materials as shown in Figs. 6 & 7. The crater volume is computed based on a conical shape. For larger pounder sizes the crater volume calculated by this equation is less than the actual value because the crater shape is no longer conical.

It is indicated clearly that the flyash (Chaney, et al. 1983) gives greater crater surface areas and volumes than sand and clay. For the smaller pounder, the crater area is small, and the crater area increases as the
Figure 4. Effect of Fill Types on the Shape of Crater Cross-Section for Pounder Area = 8.07 cm². After 6 Drops.

\[ W_x h_x = \text{constant} = 1.57 \, J \]

Pounder Area = 8.07 cm²

Dry Condition

Vertical & Horizontal Scale: 2 divisions = 1" = 2.54 cm
\[ W_h x = \text{constant} = 1.57 \text{ J} \]

Pounder Area = 78.5 cm\(^2\)

**Figure 5.** Effect of Fill Types on the Shape of Crater Cross-Section for Pounder Area = 78.5 cm\(^2\). After 6 Drops.
Figure 6  Crater Surface Area versus Pounder Area
Crater Volume = \( \frac{1}{3} \delta r^2 \)

![Graph showing Crater Volume versus Pounder Area]

Figure 7  Crater Volume versus Pounder Area
pounder area increases. However, after the pounder area reaches a certain size \((A = 34.0 \text{ cm}^2)\), the crater creates the side-slip phenomena after the pounder is removed. For the sand, the side-slip phenomena is greater in comparison with flyash and clay.

**Number of Drops, \(n\)**

Further plotting of crater radius and deformation-height of drop ratios versus the number of drops, \(n\), is presented in Figs. 8 and 9. Figure 8 shows the crater depth-height of drop ratio increases as the number of drops, \(n\), increases for all three fill materials. The ratio is much higher for flyash than it is for sand and clay. The rate of increase for the clay and flyash is greater than sand. The ratio of crater radius-height of drop versus number of drops is presented in Fig. 9. The ratio is higher for flyash and sand than it is for clay. The increase in the ratio for both flyash and clay with the number of drops is greater than the increase for sand because of the side-slip phenomena as previously discussed. In both Figs. 8 and 9, the rate of increase of the ratios decrease with the number of drops. Also, in comparing Figs. 8 and 9, a similarity can be found in the shape of the curves for flyash and clay. In both Figures, the slope of the flyash ratio is approximately constant up to about 4 drops when it decreases. The slope of the clay ratio shows the opposite behavior decreasing for small number of drops to an approximately constant value.

The deformation-height of drop ratio versus number of drops, \(n\), indicates that the flyash is more greatly affected by the number of drops than sand and clay. The \(d/D\) ratio is kept constant at 0.110 for Figs. 8 and 9 where \(d\) = diameter of pounder and \(D\) is the diameter of the metal drum.
Figure 8  Crater Depth-Height of Drop Ratio versus Number of Drops
Figure 9  Crater Radius-Height of Drop Ratio versus Number of Drops
Various d/D conditions have been tested; however, d/D = 0.110 yields the maximum r/h and δ/h ratios.

**Dynamic Densification for Saturated Deposit**

For the saturated condition, pounders (weights) from known heights were again dropped into fills as described previously for the dry condition. The crater dimensions, δ and r, were again measured. The craters formed were quite different in shape (see Fig. 10) from craters formed under dry conditions (Figs. 4 and 5). The depths, δ, were much greater for the saturated condition, while the crater diameter was only slightly larger than the diameter of the pounder.

**Vertical Stress vs. Depth**

Comparisons between theoretical results and experimental data are shown in Fig. 11. Both Westergaard and Bousinesq equations (Perloff, 1975) are used for the vertical stress versus depth. The Bousinesq curve was calculated for uniform circular loading and the Westergaard curve was calculated for uniform square loading. The initial loading was taken as the response of the best-fit curve at zero overburden depth (t₀ = 0). The pounder area used for the calculation is A = 34.0 cm². Similar trends between theoretical and experimental data are found with the Westergaard curve forming the lower bound and the Bousinesq curve forming the upper bound for the ground response.
Figure 10  Effect of Saturation on Crater Profile (a) Laboratory Condition (b) In-situ Condition (Photo courtesy of Z. Qian)
Figure 11  Comparison of Overburden Depth versus Ground Response

Ground Response, Newtons

Stress, (Pa)

Overburden Depth, $t_x$, mm

- Clay —
- Sand ○
- Flyash △

Westergaard Equation

Boussinesq Equation

Pounder Area = 34 cm²
EFFECTIVE DEPTH

As discussed previously, the effective depth or depth of influence is defined as how deep the pounder (weight), dropped freely from a certain height, will affect the fill material below the ground surface. Eqs. (1), (2) and (3) are frequently used for field applications. However, the depth of influence is related to the type of fill material and pounder characteristics. A further modification of Eq. (1) including these factors is proposed as:

\[ D_e = \Psi \sqrt{\frac{W}{x}} \]

where \( \Psi \) is the coefficient of effective depth. Other terms are the same as described previously. The \( \Psi \) value is a function of the fill material type, pounder size and degree of saturation of the fill material.
Figure 12 Procedure for Estimation of Coefficient of Effective Depth, $\psi$.

\[
t_x \text{ (at 2 Newtons)} = D_e
\]

\[
D_e = \psi \sqrt{Wh} \quad \text{(Eq. 4)}
\]

\[
\psi = \frac{t_x}{\sqrt{Wh}}
\]

$W$ = Weight of pounder

$h$ = Height of drop

$D_e$ = Effective depth
Figure 13. Various Parameters versus Coefficient of Effective Depth Under Dry Condition

da = Diameter of pounder, mm
r = Radius of crater, mm
δ = Maximum deformation of crater, after 6 drops, mm
Figure 14 Crater Depth versus Crater Radius
Development of the Coefficient of Effective Depth, $\psi$, Chart

For the laboratory dry condition, the effective depth, $D_e$, is found as shown in Fig. 12 as the depth of fill at the critical ground response. The critical response is defined as the ground response in which a decrease in value will result in values of $D_e$ with little difference for pounders of various sizes while an increase in value will result in overly conservative values for $D_e$. For the densification energy used in this study the critical response was found to be 2 Newtons. With $D_e$, $W_x$, and $h_x$ known, Eq. 4 can be solved for $\psi$ and the results plotted versus $r/\delta$ as shown in Fig. 13a and 15. Other combinations were also tried including plotting $\psi$ versus $d/\delta$, $d/2r$ and $r$. However, plotting $\psi$ versus $r/\delta$ was found to have the best correlation for all types of soil with the best fit curve.

For the laboratory saturated condition, the effective depth, $D_e$, is measured as the maximum depth reached by the pounder. Because of the large amount of energy used in forming the deep craters and the effect of the porewater pressure in decreasing the energy transferred for ground improvement, assuming the effective depth, $D_e$, equal to the maximum depth of the crater, $\delta$, is considered to be a reasonable approximation. With $D_e$, $W_x$, and $h_x$ known for the saturated condition, Eq. 4 can again be solved for $\psi$ and the results plotted versus $r/\delta$ as shown in Fig. 15. In Fig. 15 parallel lines are drawn at equal intervals between the dry and saturated conditions to approximate the effect of various degrees of saturation.
Figure 15  Coefficient of Effective Depth versus Radius/Depth of Crater Ratio
Use of the Coefficient of Effective Depth, $\psi$, Chart

In the field the value of $\psi$ is found by first measuring the radius of the crater formed, $r$, and the depth of the crater, $\delta$, after 3 or more drops and also the initial degree of saturation of the fill material, $S$. Requiring 3 or more drops was chosen because after 3 drops the ground improvement was found to be small or decreasing in rate as evidenced in Figs. 8 and 9. From these values $\psi$ can be found by using the chart in Fig. 15. With $W_x$ and $h_x$ known, Eq. (4) can then be solved for $D_e$. The $r/\delta$ ratio is a measure of the ground material type and the pounder size. The degree of saturation is a measure of the moisture condition of the ground.

Discussion of the Coefficient of Effective Depth, $\psi$, Chart

Measuring the effective depth of densification by use of the $\psi$ chart in most cases yields values of $D_e$ greater than those calculated by Eqs. (1), (2) or (3). One of the reasons for this is the measurement and definition of effective depth. Eqs. (1), (2) and (3) were developed from field studies in which the ground improvement was typically measured by cone penetration resistance. In the laboratory study the ground improvement was measured by the pressure cell. Also, the definition of what constitutes significant ground improvement is subjective.

Because the $\psi$ chart accounts for more variables than previously considered, the worst case condition for soil type, ground saturation and pounder size does not have to be assumed. For instance, this study has shown that the effective depth of densification for flyash is clearly greater than that for sand. Also, a dry soil can be densified to greater depths than a saturated soil.
Additionally, the r/δ ratio allows for a comparison of the effect of various pounder sizes. For example, in one case a pounder of small diameter might be used to increase the depth of densification, while densifying a smaller area. In another case, a pounder with a greater diameter, but of equal weight, might be used to densify a larger area at the cost of reducing the effective depth of densification. In both cases the same amount of densification energy is used, but the pounder shape is tailored to meet the individual site requirements.

The conditions in which the ψ chart was developed must be recognized to understand the limitations of its use. First, the crane drop used in the field practice is less efficient than the free drop for the laboratory study, thus resulting in a reduced value of De. Second, the laboratory study used a homogeneous soil layer on top of a stiff clay foundation. In the field the ground will probably consist of a variety of soil types. A foundation of soft clay or peat will decrease the densification of the fill layer above it because of a damping effect.

SUMMARY AND CONCLUSIONS

1. In all cases, for a thin layer deposit the ground response is higher. For the smaller pounder area, the effects on ground response with depth are greater in comparison with larger pounder areas. The pounder size has significant effect on ground response. However, for the thicker layer, the pounder size has little effect.

2. For the smaller pounder area, the crater area is small and the crater area increases as the pounder area increases. However, when the pounder area reaches a certain size, the crater creates the side-slip phenomena after the pounder is removed.
3. For the sand, the side-slip phenomena has greater effect in comparison with clay and flyash. In all cases, the crater area or volume of the flyash is greater than the sand and clay deposits.

4. For the sand, it is shown that heave occurs at the edge of the crater. No heave is recorded for both clay and flyash fills.

5. In all cases, increasing the number of drops increases the deformation-height of drop ratio. Clay, sand and flyash yield the same trends; however, for flyash the effects are more pronounced than for the clay and sand deposits.

6. In all cases, increasing the number of drops increases the radius of crater-height of drop ratio. However, the rate of increase for the flyash is more significant than the clay and sand deposits.

7. For the saturated case the craters formed are deeper than the dry case with a diameter only slightly larger than the diameter of the pounder.

8. For the same initial loading the Westergaard equation forms the lower bound on the ground response and the Bousinesq equation forms the upper bound.

9. A simple procedure for estimating the effective depth of densification based on the crater depth and radius and degree of saturation has been developed for practical application.

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Lehigh University


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