May 6th, 12:00 AM

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Recommended Citation
John F. O’Brien and Charles P. Gupton, "In situ stabilization of two industrial sites by dynamic compaction" (May 6, 1984).
International Conference on Case Histories in Geotechnical Engineering. Paper 29.
http://scholarsmine.mst.edu/icchge/1icchge/1icchge-theme9/29

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In Situ Stabilization of Two Industrial Sites by Dynamic Compaction

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SYNOPSIS: The authors directed selection and control of two large-scale dynamic compaction projects on largely cohesionless soils in Bangladesh and Spain. Both projects included intensive in-situ quality control testing. The findings of the control work is discussed. Based on this work and comparison with published data guidelines for estimating the effectiveness of dynamic compaction are presented.

INTRODUCTION

In 1970 a French engineer, Louis Menard, introduced a process he called "dynamic consolidation" for improvement of soils for engineering purposes. Also known as "heavy tamping," "pounding," and "dynamic compaction," Menard's technique has quickly gained acceptance as a cost effective, time-saving means of improving soils. As the effect of the Menard technique on soils is more like compaction than consolidation, it is generally referred to as "dynamic compaction."

The process of dynamic compaction involves repeated dropping a heavy weight from great height across the soil surface, resulting in high energy impacts that compact the underlying soils. However, despite numerous successful applications of dynamic compaction, there are no established means to predict and measure its effectiveness for various projects. Performance claims and counter-claims by contractors and engineers further complicate the application of dynamic compaction.

The authors directed selection and control of dynamic compaction at two of its larger applications undertaken to date: stabilization of a 40-acre site for a $400 million ammonia/urea plant on alluvial and hydraulic fill soils in central Bangladesh; and densification of a 30-acre site for a $240 million automobile parts plant on estuarine and fill soils in southwestern Spain. These projects involved work with a variety of soil types. This article will present the results of these experiences and offer recommendations for achieving soil improvement by dynamic compaction.

THE PROCESS OF DYNAMIC COMPACTION

As has been noted, dynamic compaction is a fundamentally simple process: it involves repeated drops of a heavy weight from great height in a regular pattern across a site. The technique is principally applied to granular soils, improving strength by densification. It has also been used to preconsolidate highly organic soils as well as various types of refuse and some clays. In saturated granular soils, the impact of the pounder generates high pore water pressures that then decay at rates dependent upon the soils' permeability and hydraulic gradient. Densification is achieved by partial liquefaction coupled with shear strain from the pounding.

If complete liquefaction occurs due to excessive pore pressures, the craters formed by the high energy impacts will deepen, but no further significant compaction will occur, due to soil heave. Hence, it is necessary that the successive pounding be staged such that excess pore pressures generated by the previous pounding have essentially dissipated prior to onset of the succeeding pounding.

Conventionally, compaction is not accomplished in a single pass across a site, but rather in multiple passes across an established pattern, with each pass spaced several days apart. This pattern is varied to meet the required depth and degree of improvement. For purposes of this discussion, these terms will be defined as follows:

- A "drop" describes a single lifting and dropping of the weight.
- A "print" is the grid location of the drop point. Commonly 10 to 45 drops are made at a single print location, creating a conical-shaped crater.
- A "pass" denotes coverage of an area by completing a pattern of prints over the area.
- The "energy" imparted to the soil is the average theoretical kinetic energy, equal to the potential energy of the weight (or pounder) times the number of drops per print area. For example, 18 tonnes dropped from 25 meters, 40 times per print on a 10-meter by 10-meter grid spacing imparts a densification energy of

\[
(18 \text{ tonnes} \times 25 \text{ meters} \times 40 \text{ drops})
/
(10 \text{ meters} \times 10 \text{ meters})
= 180 \text{ ton-meters per square meter.}
\]
PROJECT DESCRIPTIONS

Fertilizer Plant Site in Ashuganj, Bangladesh

Hydraulic filling of a 40-acre site for a 1600-metric ton per day ammonia/urea fertilizer plant and associated personnel housing was undertaken in mid-1975. Five to eight meters of fine sand were dredged from the adjacent Meghna River to build what is in effect an "island" site in the floodplain of that river. The naturally occurring soils at the site were typically well-sorted, silty fine sands. However, fine-grained soils (that is, silts and clayey silts) were encountered. Figure 1 presents a generalized profile of the soils encountered at the Ashuganj site.

When the foundation investigation for the 30-acre Cadiz site was performed in late 1979, it was determined that the strict criteria for soil improvement could not be met without either soil improvement or deep foundations. Most significantly, machinery requirements dictated that post-construction angular distortion due to differential settlement be virtually eliminated. As incompressible soils occurred below a depth of about 10 meters, it was intended that dynamic compaction effect improvement to that depth and the plant be constructed on shallow foundations.

The dynamic compaction/shallow foundation scheme used at the Cadiz site was estimated to cost $10 million less and to require three months less time than a piling scheme (18,000 piles, each 15 meters long) which was considered as the first foundation alternative.

DENSIFICATION PROGRAMS

Densification at the Bangladesh and Spain sites proceeded similarly. Initially the contractor
Heavy tamping, achieved with these 15- and 40-metric ton weights, tends to loosen the upper one to two meters of soil due to heave around the print crater and regrading of the surface between passes. Consequently, a last pass is designed to recompact this upper, loosened zone. The last pass also serves to provide more uniform density in the near-surface region. This recompaction is often called the "ironing" pass. At the Spain site, it was accomplished by dropping the weights from 10 to 25 meters height, one to two drops per print at contiguous prints to provide complete coverage.

**TABLE 1**

**SUMMARY OF COMPACTION CONTROL DATA**

<table>
<thead>
<tr>
<th>Site</th>
<th>Intended Depth of Improvement (meters)</th>
<th>Applied Impact Energy (ton-meters)</th>
<th>Number of Passes</th>
<th>Total Applied Energy (ton-meters per square meter)</th>
<th>Average Maximum Cone Penetration Resistance (kilograms per square centimeter)</th>
<th>Total Enforced Settlement (centimeters)</th>
<th>Effective Depth of Improvement (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangladesh</td>
<td>10</td>
<td>420</td>
<td>4-6</td>
<td>300-400</td>
<td>260</td>
<td>39-46</td>
<td>10</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>20</td>
<td>1,000</td>
<td>5-8</td>
<td>350-400</td>
<td>360</td>
<td>50-57</td>
<td>15</td>
</tr>
<tr>
<td>Spain</td>
<td>10</td>
<td>450</td>
<td>3-5</td>
<td>200-400</td>
<td>170</td>
<td>40-53</td>
<td>10</td>
</tr>
</tbody>
</table>

**FIELD CONTROL**

At both the Bangladesh and Spain sites, control testing was undertaken using the following techniques:

- Ground-surface settlement, or subsidence, induced by the compaction was evaluated to assess densification.
- In situ testing was used to evaluate the general soil strengths. Static cone penetrometer (CPT), standard penetrates (SPT), and Menard pressuremeter (MPT) testing were undertaken before, during, and following compaction.
- The rise and decay of pore water pressures were monitored with standpipe-type piezometers and pore pressure cells.
- Ground instrumentation was also used to monitor the increase in horizontal effective stress as a measure of densification and an over-consolidation effect due to pounding.

At both sites control testing was intensive. It is estimated that the cost of such control represented about 10 percent of the total compaction costs.

**RESULTS OF COMPACTION**

Comparison of careful pre-compaction soils testing with testing completed during and after compaction gives an indication of the degree of improvement achieved by the pounding as well as additional indications of the over-consolidation effect due to pounding.

**Bangladesh Site**

Figure 4 presents a summary of soil improvement to the intended 20 meters depth, measured in terms of average cone penetration resistance. As shown in this figure, no considerable improvement was achieved beyond a depth of about 16 meters, using a 40-metric ton weight dropped from 25 meters height and a total applied energy of 350 to 450 ton-meters per square meter. For these projects, "improvement" was considered to be a 10 percent or greater increase in situ measured parameters of cone penetration point resistance, or the Menard pressuremeter pressure limit. However, pounding often effected spectacular improvement in the upper 10 meters, particularly in the hydraulic fill.
Within the upper silts (that is, the soils at five to seven meters depth), improvement was measured both as an increase in pressure limit and minimum measured cone penetration resistance and a reduction in the apparent thickness of this often plastic soil. Figure 5 presents a demonstration of the impact of the 40-metric ton pounder on the upper silts, indicating a reduction in the apparent thickness of the cohesive layer and some increase in minimum measured values of cone penetration resistance.

Within the zones of 10 meters intended improvement, compaction was generally achieved per plan. Figure 6 presents results of improvement measured by static cone penetration. It is significant to note that the lighter impact energy of the 15-metric ton weight falling 28 meters had little effect in improving minimum measured values of static cone penetration resistance in the somewhat cohesive upper silts, though some reduction in the apparent thickness of the strata was observed. Also note in the example shown in Figure 6 that more than trebling the applied energy at that location did little to affect the depth of improvement, but rather only increased values of maximum cone penetration resistance near the ground surface.

Comparison of in situ testing with measurements of impact energy, the total applied energy and the resultant settlements also provides some interesting insight. As shown in Table 1, measurements show that the site grade has been lowered by 39 to 57 centimeters. It is apparent that the induced subsidence is not proportional to applied energy nor to the number of passes. The greatest settlement occurred in the area to be compacted to 20 meters depth where the heaviest pounders were used. In this area the impact per drop was greater and intended to provide greater energy transfer to the lower regions with consequent deeper seated compaction. Thus, the affected soil column is greater.

**FIGURE 4**

**FIGURE 5**

**FIGURE 6**
in 20-meter zones than in the 10-meter compaction zones, indicating that the heavier impact per drop is more effective in compaction at depth. Comparison of the enforced settlements with the effective depth of compaction shows volume changes of about four percent in both the 20-meter zones and the 10-meter zones.

Spain Site

The compaction experience in Spain was similar to that in Bangladesh. Figure 7 presents typical pre- and post-compaction soundings at the Cadiz site, indicating, as in Bangladesh, the greatest improvement was achieved in sands and silty sands. No considerable improvement in pressure limit or cone resistance was measured in the clayey zone at 9 meters depth. Again, some reduction in the apparent thickness of the fine-grained soil strata was observed and attributed to densification of sand around the clayey strata. Overall, improvement in the soil profile was observed to depths of 10 to 11 meters.

Comparison of in situ testing with measurements of impact energy, total applied energy and enforced settlements shows results similar to the Bangladesh case for these somewhat similar soils. Impact energy is certainly a criterion in achieving densification at depth, while application of the unit total applied energy again led to higher values of maximum cone penetration resistance.

Menard (1975) originally estimated the effective depth of densification as a function of impact energy, as follows:

\[ D = \sqrt{Wh} \]  \hspace{1cm} \text{(1)}

where

\[ D = \text{depth of influence, in meters.} \]
\[ W = \text{falling weight, in metric tons.} \]
\[ h = \text{height of drop, in meters.} \]

Leonards (1980) compared the findings of a compaction project undertaken in Indianapolis, Indiana along with the findings of other dynamic compaction projects. Figure 8 presents a summary of these cases and those in Bangladesh and Spain, showing that the effective depth of compaction may be expressed as:

\[ D = \frac{1}{2}\sqrt{Wh} \]  \hspace{1cm} \text{(2)}

As has been noted, this relationship is sensitive to soil type. It seems reasonable to assume that while the Bangladesh data well fit Equation 2, the presence of the soft upper silt layer may have absorbed compaction energy which would have achieved greater densification at depth.

The degree of compaction achievable, as measured by peak values of soil strength parameters such as cone penetration resistance, seems related to the total applied energy. Figure 9 presents a summary of project data developed by Leonards. Comparing this information with that obtained in Bangladesh and Spain, it appears that for a wide range of compaction effort, the degree of improvement is reasonably predictable. It appears from Figure 9 that an upper limit of achievable densification, as measured by the static cone penetrometer, is about 400 kilograms per square centimeter.
CONCLUSIONS

This article has attempted to describe the measured success of in situ improvement of soils by dynamic compaction. The discussion herein is by no means a description of all aspects of dynamic compaction, but hopefully will serve as a guide to the reader for use on future projects.

Significant findings in the Bangladesh and Spain projects, as well as comparison of the data with published data, indicate:

- The depth of effective compaction appears directly related to impact energy (that is, a function of the weight of the hammer and the height of fall). The relationship proposed by Leonards (1980) appears to be a reasonable first estimate for compaction projects:
  \[ D = \frac{1}{2} \sqrt{\frac{Wh}{}} \]  

- Both the Bangladesh and Spain projects were completed largely on fine-grained, normally consolidated silty sands, with lenses and layers of silts and clays. Shortening at the soil column effected by compaction was on the order of four percent and might be considered in future estimates of ground loss due to compaction of sands.

- The degree of compaction achievable appears to be a function of impact energy and the total applied energy. As shown in Figure 9, project data collected to date suggest a reasonably predictable degree of compaction up to about 300 kilograms per square centimeter. A measured static cone penetration resistance of about 400 kilograms per square centimeter may represent a limit of practically achievable densification. These values are achieved within a few meters of the ground surface in cohesionless soils.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support in these studies of the Ashuganj Fertilizer and Chemicals Company and General Motors Espana, in particular, the support (and inspiring skepticism) of Mr. A.R. Barber of General Motors.

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