GROUND IMPROVEMENT:
A 2017 DISCUSSION ON DYNAMIC COMPACTION

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Abstract

Founded by Louis Menard in France during the early 1970s, dynamic compaction has become one of the most versatile and cost-effective methods of ground improvement in the world. Primarily applicable to granular soils, dynamic compaction has been proven to be equally as successful at improving urban fill materials, mine spoils, liquefiable sands, and collapsible soils. In specialized instances, such as mine spoil and karst topography sites, dynamic compaction has also proven to be highly effective, even considering the high amount of fine-grained soils generally present at these types of sites.

While not reinventing the wheel, the following paper provides a basic outline to the successful design and implementation of a dynamic compaction program, with commentary on recent advancements where applicable. A general discussion of the dynamic compaction process, along with presentation of pertinent design features, methods of post-improvement assessment, and construction-related issues such as vibrations are discussed herein.

1. INTRODUCTION

Ground improvement, as a concept, generally dates back to the early 1900s. Since that time, the field of geotechnical engineering and specifically ground improvement has continually been advancing, with new methods constantly being invented, and existing methods being improved and further developed. Dating to the early 1970s when it was first developed by Louis Menard in France, dynamic compaction is a relatively economical ground improvement method that is predominantly applicable to granular soils. More recently, specific applications in fine-grained soils have also been successfully developed and implemented. This paper is intended to serve as a basic guide to approaching dynamic compaction program, based on the current state of practice and the author's experience. A brief discussion on the background of dynamic compaction, as well as the pertinent design components to a successful program, suitable methods of post-improvement evaluation, and how to address construction issues such as vibrations are discussed herein.

2. WHAT IS DYNAMIC COMPACTION?

Dynamic compaction consists of the introduction of multiple passes of high energy impacts at the ground surface by repeatedly dropping steel pounders generally ranging from 6 to 20 tonnes from drop heights ranging from 12 to 22 meters. The high energy impact creates a shock wave that densifies the soil at depth and reduces the void ratio; thus improving the consistency and overall engineering properties of the soil mass. As a result, shallow foundation systems and slab-on-grade construction are able to be used, due to reduced total and differential settlements that result from the dynamic compaction operation. Additionally, the need for off-site removal of the existing soils for replacement with compacted granular fill can be eliminated, which can provide substantial cost savings on a project.

In addition to strengthening and compacting the existing fill or loose natural soils, dynamic compaction is similar to proof-rolling in that it exposes pockets of softer material or materials that are unsuitable to provide foundation support or to construct finished hardscape features upon. These areas, when identified during compaction, can be remediated in one of two ways; either additional pounding can be carried out until the soils are adequately densified, or granular soil can be used as backfill before conducting additional drops – this is often referred to as "dynamic replacement."

The pounder used in the dynamic compaction process generally results in craters on the order of two meters in diameter and ranging in depth from 0.5 to 2 meters. Typically, following each pass, the craters are backfilled. If suitable, surrounding material can be pushed into the craters, resulting in an overall lowering of the site grade. If not, then imported granular material must be used to backfill the craters in between passes. In some instances, where the ground response is favorable and shallow groundwater is not present, both passes can be completed simultaneously, providing benefit to the project schedule.

Dynamic compaction is typically performed over a predetermined grid pattern (see Figure 1), with multiple passes being implemented on offsetting grids. The grid spacing, number of drops per impact point, drop height, and total number of passes is dependent on the site-specific soil conditions, the observed ground response, and the dissipation of pore water pressure subsequent to pounding. On projects where settlement tolerances are extremely tight, additional passes at the foundation locations are also conducted.

Figure 1 – Typical Dynamic Compaction Grid Pattern

Comprehensive monitoring of ground response during the process is needed to control the work, and allow for modification to the program on a real-time basis. The applied energy, impact grid, and the sequence and timing of the drops can all be adjusted, as needed, to achieve the desired results. Many times, simply by adjusting the program in the field to match the conditions being observed, a successful outcome can be anticipated the first time, as opposed to having to perform additional remedial work.

3. DESIGN OF A DYNAMIC COMPACTION PROGRAM

The degree and depth of soil improvement achieved with dynamic compaction depends upon the total amount of energy applied to the soil; i.e., the more energy imparted to the soil, the greater the degree and depth of improvement. A discussion of the three main design components to a dynamic compaction program is provided below.

3.1 Depth of Improvement

The first design consideration, depth of improvement, is a function of the amount of weight being dropped and the drop height, as well as the type of material being improved. This is generally the most important aspect from a cost perspective, as the size of the weight to be used will determine the size of crane required, and mobilization costs for different-sized cranes can vary substantially. Utilizing commercially available equipment, target improvement depths for dynamic compaction programs are generally on the order of 10 meters or less, with the majority of improvement occurring in the upper 6 meters of soil. The conventional depth of influence formula for dynamic compaction (Lukas, 1995) is as follows:

(Eq. 1) $D = n\sqrt{WH}$ where:

D = depth of influence (m)
n = empirical coefficient
W = weight of tamper (Megagrams)
H = drop height (m)

The empirical coefficient "n" is based on the soil type being improved. The general ranges that are used in practice today for a given soil type are provided in Table 1.

Table 1 – Typical "n" Values Used to Evaluate Depth of Improvement

Soil Type	Range of "n" Values
Pervious Soils (Zone 1)	0.5 to 0.6
Semi-Pervious Soils (Zones 2 and 3)	0.35 to 0.5
Impervious Materials	0.35 to 0.4
Landfill Deposits	0.35 to 0.45

3.2 Applied Energy

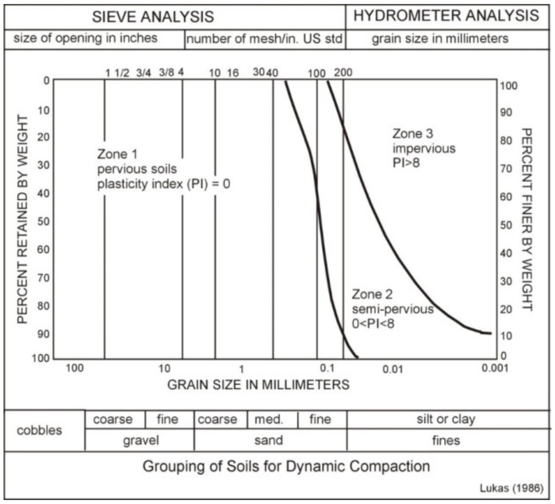
The second design consideration of a successful dynamic compaction program is the amount of energy to be applied to soil, or simply, the applied energy. Applied energy is the energy per unit volume (kJ/m^3 most typically), calculated as shown below (Lukas, 1995).

(Eq. 2) $$\text{Applied Energy} = \frac{(Pounder\ Weight)*(Pounder\ Height)*(\#\ of\ Drops)*(\#\ of\ Passes)}{(Grid\ Spacing)*(Grid\ Spacing)*(Depth\ of\ Improvement)}$$

The amount of applied energy is a function of several things, including the drop height, drop weight, number of drops, grid spacing, and the anticipated depth of improvement from Eq. 1. The applied energy required of a program can vary significantly depending on the soil type being targeted for improvement. Figure 2 shows the three general zones that are considered when it comes to the applicability and required energy for ground improvement. For example, a clean beach sand with a relatively deep water table will transfer energy very cleanly, and as such, will not require as much energy to achieve a suitable level of improvement as say, a municipal solid waste (MSW) landfill material, which is full of voids. Table 2 provides the industry standard ranges for targeted applied energy based on these soil types (Lukas (1995), Zekkos et al (2012), and Woods et al (2016)).

3.3 Pounder Specifications

A third main component in designing a successful dynamic compaction program, based on the author's experience, is the dimensioning, and more importantly, contact pressure of the pounder(s) to be used. Although none of the formulas outlined above contain a mechanism for accounting for this empirically, experience shows that the choice of pounder can be vitally important to the success of a program. On sites where deep penetration is required to effect improvement, such as sandy sites or MSW sites, high contact-pressure pounders that will punch into the subgrade are ideal. Generally, a good target pressure for this application would be on the order of 50 to 75 kilopascals (kPa). Alternatively, on softer sites that perhaps contain a higher level of fine-grained soils or a shallow groundwater table, where punching into the subgrade will result in the weight driving through the softer material and becoming stuck, a lower contact pressure pounder, say 35 to 50 kPa, would be preferable. In these instances, the overall approach to the program would be more of a uniform compression of the soil mass being improved, using more passes of less drops, and lowering the overall grade of the site gradually.



Lukas (1986)

Figure 2 – Grain Size Plot Showing Various Zones of Soil Types

Table 2 – Typical Applied Energy Ranges for a Given Soil Type

Soil Type	Range of Applied Energy (kJ/m^3)
Pervious Soils (Zone 1)	200 to 250
Semi-Pervious Soils (Zones 2 and 3)	250 to 350
Landfill Material	600 to 1,100
Coal Mine Spoil Material	150 to 350

4. VERIFICATION OF A DYNAMIC COMPACTION PROGRAM

One of the biggest challenges in geotechnical engineering is ensuring that a sufficient amount of data has been collected before, during, and after construction, so that all parties involved can agree that project objectives have been met. Most sites will have pre-improvement data, obtained during the design phase. However, these data are usually limited to discrete boring or test pit locations across the site, and represent a significantly small portion of the overall site area. During execution of the dynamic compaction program, visual data is collected in the field, which helps assess whether or not soft areas or voids were encountered and subsequently remediated.

For most dynamic compaction programs, visual observation of ground response is the most certain method of providing a first-pass evaluation of the effectiveness of the dynamic compaction program. One of the main benefits of such a program is that the tamper is essentially probing the entire site, at each of the drop points. At each location, the response of the ground can be evaluated. This information can then be combined with further intrusive testing methods such as borings, cone penetrometers, or other regionally-used methods to provide a strong overall picture of the improved subgrade conditions. The type of post-improvement program to be implemented is generally specified by the Geotechnical Engineer, based on the conditions expected to be encountered, as well as the regional preference. Geophysical evaluation of ground improvement is an emerging approach as well; however, given the author's mixed results with this approach, further study into the applicability of such methods appears to be warranted.

5. VIBRATIONS AND DYNAMIC COMPACTION

As one might imagine, one of the biggest hurdles to overcome when implementing a dynamic compaction program is managing the vibrations that are induced by the process. Generally speaking, the vibrations associated with dynamic compaction are low-frequency waves that have relatively high velocities at close proximity to the drop point. On vibration-sensitive sites, it is commonplace to assess the anticipated levels ahead of time, using a Scaled Energy Factor plot, as seen in Figure 3, which is based on the soil type, the size of the weight, and the drop height. The anticipate peak particle velocity (PPV) can then be assessed for various distances from a given drop point, based on the distance to nearby structures at a given site.

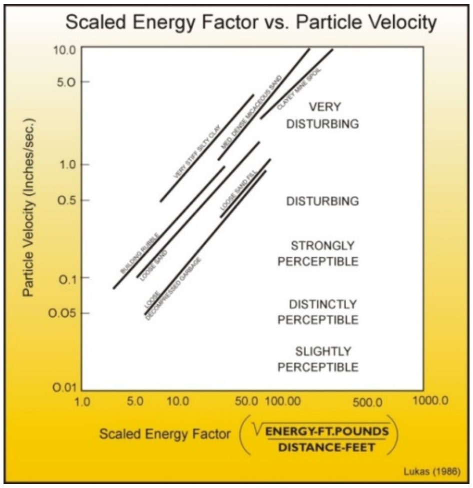


Figure 3 – Scaled Energy Factor Plot (Lukas, 1986)

Once construction has begun, real-time monitoring can then be conducted using portable seismographs, placed between the work area and the closest structure of concern. In some instances, threshold vibration levels during the dynamic compaction operation are determined by the local jurisdiction; most commonly, however, the United States Bureau of Mines safe levels of blasting vibration for houses (see Figure 4) is used as the limiting criteria for vibration and frequency on a job site.

The data is generally collected and stored on a daily basis to verify that vibration levels were maintained within the predetermined limits; alternatively, the program can use the data to alter the program accordingly to achieve the desired limits. There are several approaches that can be taken towards minimizing vibrations at a site. Most often, a seismic cutoff trench can be installed between the drop point and the structure of concern to provide a break in the medium through which the waves are traveling. This can also be combined with a modification of the program, i.e. lower drop height and more drops.

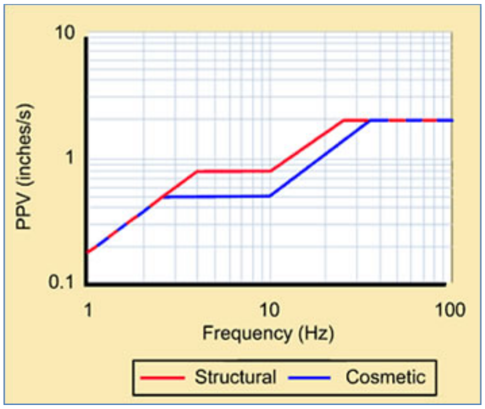


Figure 4 – Bureau of Mines Safe Blasting Criteria (Siskind, 1980)

6. SUMMARY

During the past several decades, dynamic compaction has grown to become a common-place method of ground improvement that is used all over the world. Successful applications can be anticipated for several different soil types, provided that the program is implemented and phase properly. Key points relative to a successful dynamic compaction program, in no particular order, are:

- The amount of applied energy needs to be carefully considered based on the soil medium being improved.
- The choice of pounder (shape, contact pressure, etc.) can be vitally important to the success of a project.
- There are several ways to evaluate the post-improvement condition of a soil, and understanding the soils present and the most suitable methods of testing can make a tremendous difference on a project.
- Vibration levels associated with dynamic compaction can be high, but can also be monitored and managed properly, making dynamic compaction a viable option on many different types of site.

REFERENCES

1 Drumheller, J.C., and Shaffer, R.A., (1997). “Dynamic Compaction”. In proceedings for the Conference on Ground Improvement, Ground Reinforcement, and Ground Treatment, (Geotechnical Special Publication No. 69), ASCE, Logan, Utah, July 17-19, 1997.

2 Lukas, R.G., (1986). Dynamic Compaction for Highway Construction, Volume 1: Design & Construction Guidelines, FHA Report FHWA/RD-86/133, July.

3 Lukas, R.G., (1995). Geotechnical Circular No. 1 – DYNAMIC COMPACTION, Federal Highway Administration Report FHWA-SA-95-037, March.

4 Siskind, D.E. et al, (1980). “Structure Response and Damage Produced by Ground Vibrations from Surface Mine Blasting”, Bureau of Mines, Department of Investigation, RI 8507.

5 Woods, C. B., Drumheller, J.C., and Huber, K.A., (2013). “Building the Devil’s Playground: How a Ground Improvement Program Eliminated the Need for Pile Foundations”, 38th Annual Conference on Deep Foundations, Phoenix, AZ, September 25-28.

6 Woods, C. B. (2012) “Urban Fills; How Ground Improvement Can Eliminate the Need for a Costly Deep Foundation System”, Structure Magazine, December.

7 Woods, C.B., Drumheller, J.C., and Drumheller, S. (2016) “Ground Improvement on Strip-Mined Sites: Using Dynamic Compaction to Remediate Mine Spoil Sites”

8 Zekkos, D., Kabalan, M., and Flanagan, M. (2012). "Lessons Learned from Case Histories of Dynamic Compaction at Municipal Solid Waste Sites." Journal of Geotechnical and Geoenvironmental Engineering, August 2012.