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Comparison of Energies Required to Densify Liquefiable Soil

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Fifth International Conference on
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COMPARISON OF ENERGIES REQUIRED TO DENSIFY LIQUEFIABLE SOIL

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ABSTRACT

The objective of the study presented herein is to compare the energy required to densify loose, liquefiable sand by various techniques and the energy required to liquefy the soil by earthquake shaking. The states-of-practice for performing remedial ground densification and evaluating earthquake liquefaction potential of loose saturated sands have evolved relatively independently of each other. This is in spite of the fact that the inducement of liquefaction is typically requisite for remedial ground densification of sands. Using the energy required to induce liquefaction as a common metric, simple calculations are presented for estimating the mechanical energy required to densify a unit volume of clean, loose, saturated sand using deep dynamic compaction, vibrocompaction, and explosive compaction. These computed energies are compared with that required to induce liquefaction during an earthquake per the Green-Mitchell energy based liquefaction evaluation procedure. The comparison highlights the importance of the efficiency of the process by which the energy is imparted to the soil and the importance of the mode of dissipation of the imparted energy (e.g., breaking down of initial soil structure, ramming soil particles into denser packing, and/or radiating away from the treatment zone). Additionally, the comparison lays the groundwork for incorporating the vast knowledge from fundamental studies on earthquake induced liquefaction into design procedures for remedial ground densification.

INTRODUCTION

The objective of the study presented herein is to compare the energies required to remedially densify loose, saturated sand by three different methods to the energy required to liquefy the soil by earthquake shaking. Various techniques have been developed to mitigate the risk from liquefaction of cohesionless soils, including ground densification by deep dynamic compaction, vibrocompaction, and explosive compaction. The first step in the densification process for all of these techniques involves imparting energy into the soil to breakdown the initial structure. When applied to saturated sand, a controlled liquefaction is induced, thus allowing the particles to rearrange into a denser packing concurrent with the dissipation of excess pore pressures. In addition to increasing the relative density, deep dynamic compaction and vibrocompaction may significantly increase the lateral effective confining stress in the treated soil, which further reduces liquefaction susceptibility.

The bases of the design procedures for deep dynamic compaction, vibrocompaction, and explosive compaction are largely empirical and involve indices that are related to the energy imparted to the soil (e.g., for explosive compaction: the weight of the explosive charge per unit volume of densified soil). For comparison, simple calculations are presented for estimating the mechanical energy required to densify a unit volume of loose, saturated, clean sand using deep dynamic compaction, vibrocompaction, and explosive compaction. The term “mechanical energy” refers to the energy that is available to do mechanical work, as opposed to energy expended in other forms (e.g., heat). The distinction between the energies can be understood by considering deep dynamic compaction. The total energy expended during deep dynamic compaction could be quantified in terms of the fuel consumed by the crane that lifts the tamper. However, to avoid need for considering such things as the efficiency of the crane’s combustion engine, the potential energy of the tamper at its drop height is used to approximate the (mechanical) energy per drop imparted to the soil.

Similar to the design procedures for soil improvement techniques, liquefaction evaluation procedures have been developed that quantify the earthquake load imposed on the soil in terms of energy indices. The predicted requisite energy for the inducement of liquefaction in loose, saturated, clean sand during an earthquake using the Green-Mitchell energy based liquefaction evaluation procedure (Green, 2001) is compared with the mechanical energy required to densify a unit volume of the same soil using deep dynamic compaction, vibrocompaction, and explosive compaction. The premise of the comparison is that the physical process of liquefaction is the same, irrespective of whether the input energy is from earthquake shaking or remedial ground densification

In this paper the remedial densification techniques are discussed first. This is followed by a presentation of the energy based liquefaction procedure. Finally, a comparison and discussion of the energies is given. This paper is a revised, updated and extended consideration of this topic from a prior paper on the subject (Green and Mitchell, 2004).

REMEDIAL DENSIFICATION TECHNIQUES

Explosive Compaction

Similar to earthquake induced liquefaction, explosive compaction breaks down the soil structure by imparting energy into the ground, with subsequent densification occurring concurrently with the dissipation of excess pore pressures (e.g., Narin van Court and Mitchell, 1994a, 1994b). A typical blasting program consists of the detonation of charges placed in a grid pattern spaced 3 to 8 m apart in developed areas and 8 to 15 m or more apart in remote areas, with charge weights between 2 and 15 kg, although larger charges have been used on some projects, e.g., Solymar (1984), where charge weights of up to 30 kg were used. For soil layers less than 10 m thick, the charges are usually placed at a depth between one-half and three-quarters the thickness of the layer being treated, with a depth of two-thirds the layer thickness being common.

The quantity of explosive required to densify a unit volume of soil by deep explosive compaction, the "Powder Factor (PF)", is given by Van Impe and Madhav (1995) as ranging from 15 to 35 g/m^3. Similarly, the case histories listed in Ivanov (1967), indicate a range of 8 to 28 g/m^3. Although somewhat less direct than the ranges stated by Van Impe and Madhav (1995) and Ivanov (1967), Narin van Court (1997) developed the following relationship between vertical strain resulting from explosive compaction and amount of explosives per volume of soil treated in terms of the powder factor:

$$\frac{\Delta H}{H}(\%) = 3.96 \cdot \log(PF) - 1.02 \tag{1}$$

where, PF has units of g/m^3. For a vertical strain ranging from ~3 to 6%, which is typical of the range attained on many explosive compaction projects, Equation (1) predicts that the quantity of explosive required to densify a unit volume of soil ranges from ~10 to 60 g/m^3.

From calorimeter measurements, the energy density of TNT is approximately 4560 J/g. However, upon detonation, only about 67% of this energy is transformed into mechanical energy (Kennedy 1996). Accordingly, the mechanical energy available for densification of a unit volume of soil by explosive compaction likely ranges from ~22 to 180 kJ/m^3.

Deep Dynamic Compaction

Deep dynamic compaction consists of the repeated dropping of heavy weights (or tampers) on the ground being densified. Although the origin of this technique dates back to the Romans, it became formalized as an approach for ground densification in the late 1960's and has been referred to in the literature as heavy tamping, dynamic consolidation, and deep dynamic compaction (Elias et al. 1999). The mass of the tamper generally ranges from 5 to 27 Mg, and the drop height ranges from 12 to 30 m (Lukas 1995). The heaviest tamper that can be lifted with conventional equipment is about 16 Mg with drop heights of 23 to 28 m. Maximum improvement depths are limited to about 11 m.

Figure 1 shows the range of grain-size distributions suitable for densification by deep dynamic compaction. Zone 1 soils (i.e., clean sands) are the most suitable for treatment, and Zone 3 soils are the least suitable. General guidelines for estimating the amount of energy required for densifying various soils by deep dynamic compaction are given in Table 1.

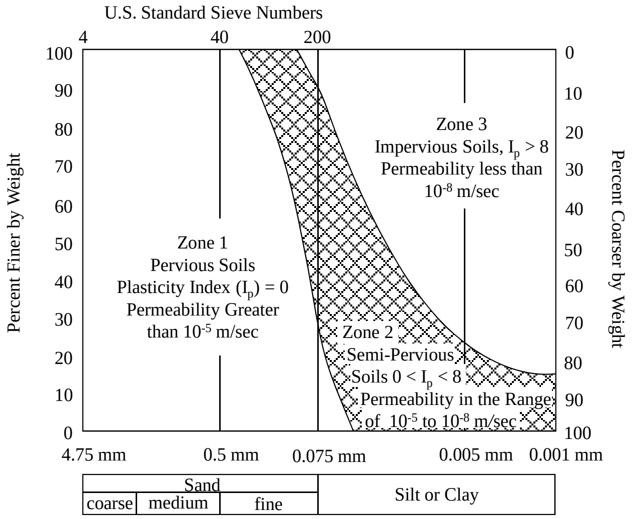

Fig. 1. Grouping of soils for dynamic compaction. Zone 1 soils are most suitable. (Adapted from Lukas 1986).

The cumulative potential energy of the drops applied per unit area of the site is given by the following expression:

$$AE = \frac{N \cdot M \cdot g \cdot H \cdot P}{A_{cp}} \tag{2}$$

In this expression, AE = applied energy (kJ/m^2); M = mass of tamper (tonnes: 1 tonne = 1 Mg); H = drop height (m); P = number of passes; N = number of drops per pass; g = acceleration due to gravity (9.81m/sec^2); A_{cp} = tributary area per compaction point (m^2). A "pass" is the dropping of the tamper at designated grid points for a predetermined number of times. From Table 1, the mechanical energy required to densify Zone 1 soil ranges from 200 to 250 kJ/m^3. Improvement by deep dynamic compaction includes both an increase in the density of the treated zone, as well as a considerable increase in lateral effective confining stress. The latter can be inferred from the lateral displacements shown in Figure 2 that are the result of the cratering and displacements caused by the impacting weight.

Table 1. Applied energy guidelines for densifying various soils (See Figure 1 for definitions of the soil Zones). (Adapted from Lukas 1986)

Type of Deposit	Applied Energy per Volume (kJ/m^3)	Percent Standard Proctor Energy
Pervious coarse-grained soil (Zone 1)	200 - 250	33 - 41
Semi-pervious fine-grained soils (Zone 2) and Clay fills above the water table (Zone 3)	250 - 350	41 - 60
Landfills	600 - 1100	100 - 180
Note: Standard Proctor energy equals 600 kJ/m^3		

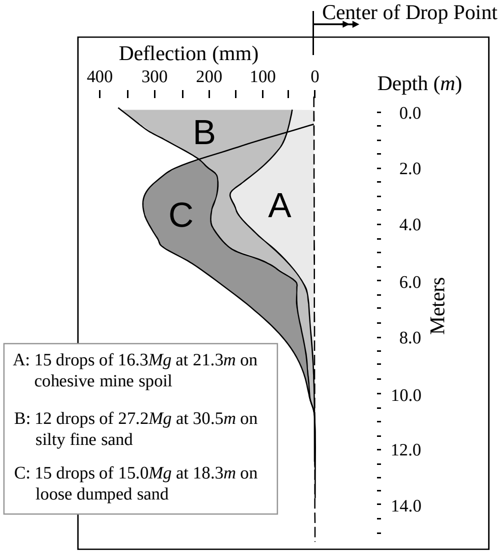

Fig. 2. Lateral movements 3 m from the centerline of the drop points. (Adapted from Lukas 1986).

Vibrocompaction

Vibrocompaction is a general term for densification techniques characterized by the insertion of long probes into the ground followed by probe vibration during withdrawal that compacts the surrounding soil. The probes are typically hung from cranes or masts and are advanced to the desired treatment depth using vibratory methods, often supplemented by water jets at the tip (Mitchell 1981). The location of the vibrator on the probe, the direction of the induced vibrations (e.g., vertical, horizontal, torsional), and whether backfill is used distinguish various vibrocompaction techniques. The equipment configuration in which the vibrator is located inside the probe (vibroflot) and induces lateral and torsional vibrations is most common. In some applications a granular backfill is added from the ground surface (top feed) or through a tube extending to the bottom of the probe (bottom feed) during the compaction process.

As described in Brown (1977) and D'Appolonia (1953), for electrically driven motors the current draw of the vibrator can be used as an indicator of the compaction process effectiveness: the current draw increases as the soil densifies. When the current draw "peaks", the vibroflot is raised to the next location, at which point, the current draw drops and compaction begins again. This process is illustrated in the current log shown in Figure 3, which was adapted from a figure given in Section 4.4.1 in Degen and Hussin (2001). As may be observed from this figure, the vibroflot rapidly penetrates the soil profile to the desired treatment depth of 8 m, with one up-down flushing of the machine after reaching 4 m (lower portion of right plot in Figure 3). The penetration time was just over one minute. After reaching 8 m depth, the compaction process begins and is designated in this figure as $t = 0$ min. The probe is raised in 0.5 m intervals and held at each position for about 45 sec.

The average rate of work (i.e., power) done in a soil by a vibroflot with a 3-phase electric motor can be estimated as (e.g., Puchstein et al. 1954):

$$P = I \cdot E \cdot pf \cdot eff \cdot \frac{\sqrt{3}}{1000} \tag{3}$$

In this expression, P = average rate of work performed by the vibroflot (i.e., power) (*kW*, *kJ/sec*); I = average line current (*amps*); E = phase-to-phase voltage requirement of vibrator (*volts*); pf = average power factor (≈ 0.8); eff = efficiency of electric motor (i.e., portion of the electrical power consumed by the motor that is available to do mechanical work, ≈ 0.9).

Based on the average current draw and the amplitude of the peaks (left plot in Figure 3), the profile may be considered as consisting of two layers: one 2.5–5.5 m thick and the other 5.5–8 m thick. The average current draws for the top and bottom layers are estimated to be about 140 amps and 115 amps, respectively. Using the specifications of the vibrator employed (i.e., Vibro V23 vibrator: 440 volts) in conjunction with Eq. (3), the rates of work (P) performed by the vibroflot in the top and bottom layers are estimated to be about 77 and 63 kW, respectively.

Knowing the rate of probe withdrawal, the rate of work performed, and the tributary area per compaction point, the mechanical energy required to densify a unit volume of soil can be determined. From Figure 3, the withdrawal rate is estimated to be about 0.37 m/min; i.e., (8–2.5 m)/15 min (the probe was rapidly withdrawn from the ground once it had been raised to 2.5 m below the ground surface). This withdrawal rate is in reasonable agreement with the typical rate of 0.3 m/min given in Mitchell (1981). For the project under consideration, the tributary area per compaction point is estimated to be about 7.5 m^2 (≈ 80 ft^2). Finally, the range in the mechanical energy expended to treat a unit volume of soil in the profile corresponding to the current log shown in Figure 3 is:

$$(63\ to\ 77\,kW)\cdot\left(\frac{\min}{0.37\,m}\cdot\frac{60\sec}{\min}\right)\cdot\frac{1}{7.5\,m^2}=1362\ to\ 1665\,kJ/m^3$$

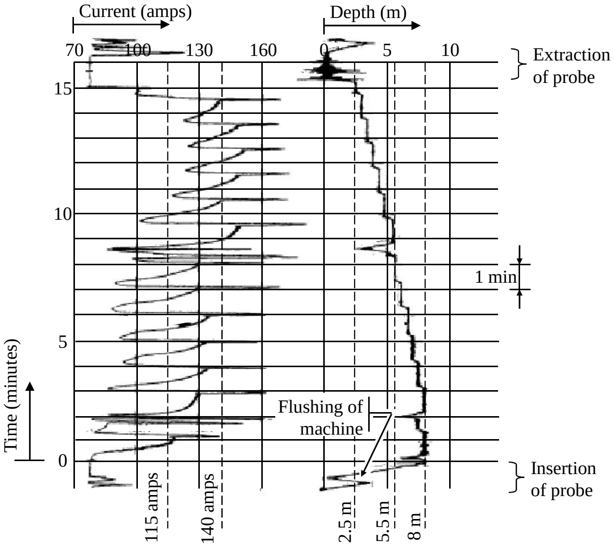

Fig. 3. Current log recorded during vibrocompaction. (Adapted from Degen and Hussin 2001).

The improvement of soil by vibrocompaction results from both densification and significant increase in lateral confining stress. The increase in effective lateral stress is potentially greater than that resulting from deep dynamic compaction because of the longer time of energy input, continuous infilling of additional backfill around the vibroflot, and direct application of lateral forces to the adjacent soil.

EARTHQUAKE INDUCED LIQUEFACTION

Several energy based liquefaction evaluation procedures have been proposed that quantify the seismic load imposed on the soil in terms of an energy index. One such procedure is the Green-Mitchell energy based liquefaction evaluation procedure (Green 2001). In this procedure, the earthquake load and the ability of a soil to resist liquefaction are quantified in terms of dissipated energy per unit volume. Green and Mitchell quantify the energy required to induce liquefaction by integrating the stress-strain hysteresis loops up to initial liquefaction, defined as 5% double amplitude axial strain in cyclic triaxial specimens and the manifestation of surface liquefaction features in the field.

To develop a correlation relating the dissipated energy per unit volume needed to induce liquefaction during earthquake shaking to penetration resistance, Green (2001) analyzed 126 liquefaction/non-liquefaction earthquake case histories. For each case, the normalized energy demand (NED) was plotted versus the corrected standard penetration test N-values $(N_1)_{60cs}$ (Figure 4), where NED is the dissipated energy per unit volume of soil divided by the initial mean effective confining stress. The boundary giving a reasonable separation of liquefaction and non-liquefaction cases (i.e., the "capacity curve") can be used to determine the amount of dissipated energy per unit volume of soil that is required to induce liquefaction during earthquake shaking as a function of SPT penetration resistance. Using the correlation shown in Figure 4, the dissipated energy required to induce liquefaction in a clean sand confined at a mean effective pressure of 100 kPa and having $N_{1,60}$ from 5 to 15 blows/ft ranges from 0.03 to 0.192 kJ/m^3; i.e., (0.0003 to 0.00192) × 100 kPa = 0.03 to 0.192 kJ/m^3.

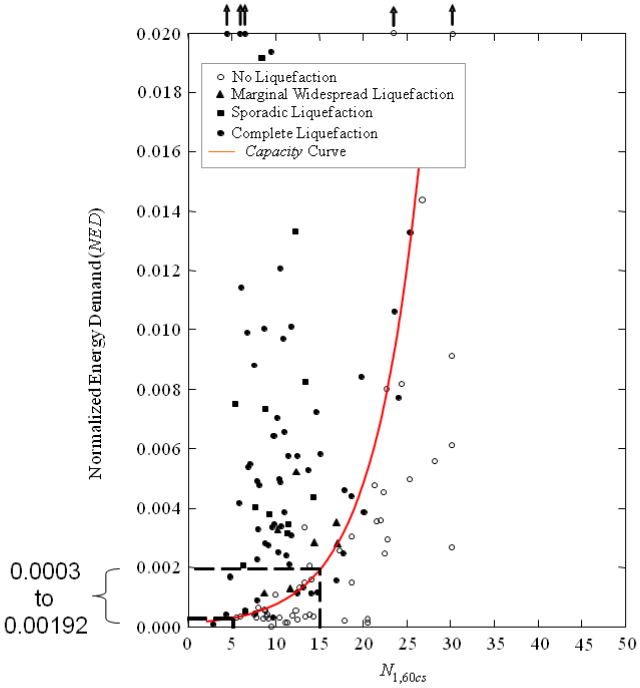

Fig. 4. Energy based liquefaction evaluation curve. (Adapted from Green 2001).

DISCUSSION

A summary of the ranges of input energies per unit volume typically used to densify clean sand by the three remedial ground densification techniques discussed above and the range of energy per unit volume required to induce liquefaction in clean sand by earthquake shaking is given below.

Explosive Compaction:	22 to 180 kJ/m^3
Deep Dynamic Compaction:	200 to 250 kJ/m^3
Vibrocompaction:	1362 to 1665 kJ/m^3
Earthquake Liquefaction:	0.03 to 0.192 kJ/m^3

It is very evident that densification imparts orders of magnitude more energy into the ground than is required simply for soil structure breakdown and liquefaction. For this and other reasons a *direct* comparison of these energy ranges is not appropriate. First the Green-Mitchell energy based liquefaction evaluation procedure quantifies the ability of a soil to resist liquefaction in terms of energy dissipated primarily through frictional mechanisms resulting from inter-particle slippage (Green 2001), but *total* mechanical energy inputs are listed for the densification techniques. While, ultimately, all the mechanical energy imparted to the soil by the densification techniques "dissipates," much of the energy dissipates by radiating away from the immediate zone being treated (i.e., radiation damping). The radiated energy does not contribute to breaking down the initial soil structure in the treated zone. The second reason a direct comparison is not appropriate is that both deep dynamic compaction and vibrocompaction involve imparting energy into the soil beyond that which is required simply to induce liquefaction. A large portion of this additional energy is expended "ramming" the soil particles into a denser packing, which ultimately results also in increased lateral confining stress. Although direct, unambiguous measurements of the increase in lateral pressure appear not to have been reported, Schmertmann (1978) noted that measured increases in cone penetration resistance post-treatment by vibrocompaction could not be explained solely by increases in the soil's relative density. Deformations of the type shown in Fig. 2 developed during deep dynamic compaction would also lead to increased lateral pressure in the treated ground.

Although a *direct* comparison of the energy ranges listed about is not appropriate, insights can be gained from a *relative* comparison of these ranges. First, the relative magnitudes of the energies listed for explosive compaction, deep dynamic compaction, and vibrocompaction are in accord with the expected improvement that can be achieved with each technique for a given soil; i.e., vibrocompaction imparts the greatest amount of energy and generally results in the greatest amount of improvement, whereas, explosive compaction imparts the least energy and results in the smallest increase in density.

Second, the initial breakdown of the soil structure and subsequent densification of the soil concurrent with the dissipation of excess pore pressures is similar for earthquake liquefaction and explosive compaction. The range of energy listed for earthquake liquefaction should be viewed as that required to induce initial liquefaction if almost all the mechanical energy imparted to the soil contributes to the breakdown of the soil structure, irrespective of whether the energy is imparted by earthquake shaking or by detonation of an explosive. The significantly larger range of energies used for explosive compaction, relative to that imparted to the ground for earthquake liquefaction, is related to the wave types that transmit the mechanical energy. S-waves transmit the majority of the energy in earthquake motions of engineering interest, while P-waves transmit the majority of the blasting energy. A large portion of the P-wave energy propagates through the pore fluid and radiates away from the immediate zone being treated. On the contrary, S-waves can only be transmitted in the soil skeleton, which, if of sufficient amplitude, results in slippage between and rearrangement of soil particles.

For deep dynamic compaction, a large portion of the energy is carried by surface waves (e.g., Rayleigh waves) and P-waves (e.g., Richart et al. 1970). As stated above, P-waves propagate through the pore fluid, and radiate away from the immediate zone being treated. Rayleigh waves significantly decrease in amplitude with depth in the profile (i.e., Rayleigh wave energy is carried near the surface and may not reach the soil being treated). Furthermore, it is believed that a significant portion of the energy imparted to the soil by deep dynamic compaction is expended ramming soil particles into denser packing, rather than just inducing liquefaction.

Analogous to deep dynamic compaction is explosive compaction wherein the charge is placed at the surface of the soil profile, as opposed to being buried deep within the profile. From the case histories listed in Ivanov (1967), the quantity of explosives required to densify a unit volume of soil by surface blasting is approximately five to ten times greater than required for deep blasting. Accordingly, the energy range to densify soil by surface blasting is comparable to that required for deep dynamic compaction.

Finally, in vibrocompaction, the energy is imparted over a relatively long time span, during which the properties of the soil are continually changing. When liquefaction is induced in the soil immediately surrounding the probe, little energy is transferred from the probe to the outer, non-liquefied soil, during which time the majority of the imparted energy is expended inducing vibrations in the already liquefied soil. Furthermore, as with deep dynamic compaction, vibrocompaction improves the ground by both densifying the soil and increasing the lateral confining pressure. The latter improvement largely results from the lateral compaction of backfill. Accordingly, the energy range listed above reflects both the energy required to induce liquefaction in the virgin profile and the energy expended to laterally compact the backfill material.

CONCLUSIONS

The mechanics and dynamics of cohesionless soil densification by explosive compaction, deep dynamic compaction, and vibrocompaction have been examined. Ranges of input energies expended for ground improvement using these methods have been estimated and compared with estimates of energy input required to cause liquefaction by earthquake ground motions.

The three ground improvement methods as currently used require far more input energy for effective densification than is needed to simply breakdown the initial soil structure and produce liquefaction. Reasons for this are given, as are reasons for why, for a given soil, the amount of improvement that can be obtained is usually in the increasing order of explosive compaction, deep dynamic compaction, and vibrocompaction. Increases in lateral confining pressure are considered significant contributors to the greater improvement, as measured by penetration resistance increases, by deep dynamic compaction and vibrocompaction.

Evaluation and comparison of the ranges of energy highlight the significance of both the efficiency of the method in which the energy is transmitted to and within the soil and the mode in which the energy is dissipated/expended in the soil. This finding is important for proper incorporation of the knowledge from fundamental studies on earthquake liquefaction into energy-based design procedures for remedial ground densification techniques and lays groundwork for unifying two important sub-disciplines of geotechnical engineering.

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