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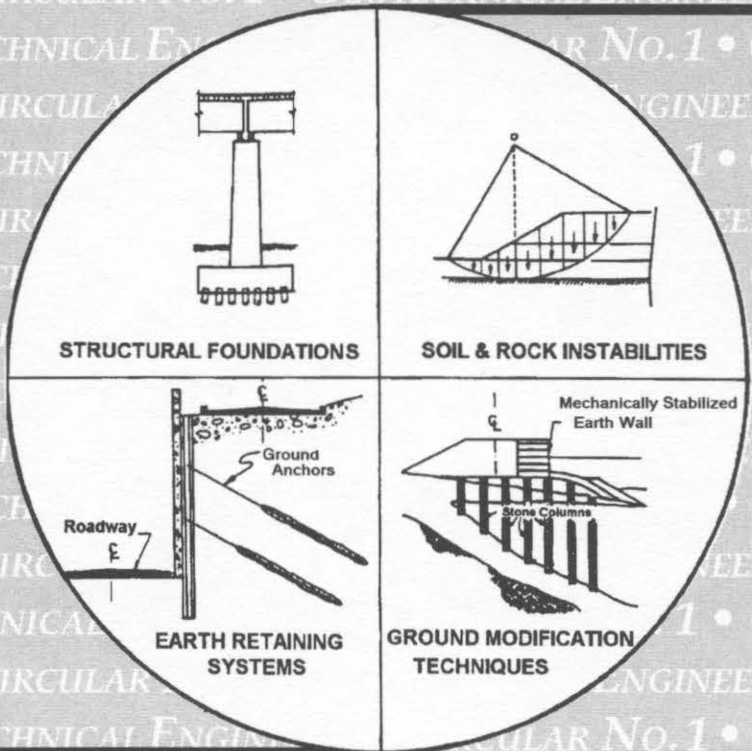
GEOTECHNICAL ENGINEERING CIRCULAR NO. 1

DYNAMIC COMPACTION



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16. Abstract

This manual provides state-of-the-practice methods and techniques to assist the highway engineer in the planning, design, and construction monitoring of dynamic compaction to improve the load supporting capacity of weak foundation soils. Guidelines are presented for:

* completing a preliminary evaluation to determine if dynamic compaction is appropriate for the site and subsurface conditions
* detailed design for site improvement
* preparation of a specification
* construction monitoring

Two case histories of actual projects are presented to demonstrate the use of the guidelines.

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DYNAMIC COMPACTION CIRCULAR
ABBREVIATIONS AND SYMBOLS

AE = Applied energy

CPT = Cone penetration test

D = Depth of improvement in meters

g = Acceleration due to gravity

H = Height of tamper drop in meters

n = An empirical coefficient used in the depth of improvement prediction

PMT = Pressuremeter test

SPT = Standard penetration test

W = Mass of tamper

V = Velocity of tamper

SI CONVERSION UNITS

1 t (metric ton) = 1 Mg (Megagram)
1 tm (ton meter) = 9.807 kN/m = 9.807 kJ (kiloJoule)
1 tm/m^2 (ton meter/meter^2) = 9.807 kJ/m^2 (kiloJoule/meter squared)

Approximate conversion:

100tm/m^2 = 1 MJ/m^2

CHAPTER 1
INTRODUCTION

PURPOSE

This document provides guidelines for evaluation, design and contracting procedures for the use of dynamic compaction to produce ground improvement in unstable or compressible soil deposits. Although guidelines are useful in planning and implementing dynamic compaction, it cannot replace good judgment. Frequently during site densification, adjustments must be made to the planned program based on how the ground responds to impact. The design engineer must always use good judgment to supplement or alter the guidelines.

BACKGROUND

Highways and interchanges are frequently required to be constructed on land with poor support conditions. This is particularly true in or near urban areas where land with good ground support conditions has already been developed for commercial or other purposes, and the remaining space is undeveloped land due to deficient subsoils.

In the past, poor support areas have been avoided or structures with deep foundations such as a bridge supported roadway have been constructed over the top of the loose deposits. Many types of site improvement techniques are now available that allow embankments and interchanges to be constructed directly on densified ground. One form of site improvement is dynamic compaction.

Dynamic compaction consists of using a heavy tamper that is repeatedly raised and dropped with a single cable from varying heights to impact the ground. The mass of the tampers generally ranges from 5.4 to 27.2 Mg, and drop heights range from 12.2 to 30.5 m. The energy is generally applied in phases on a grid pattern over the entire area using either single or multiple passes. Following each pass, the craters are either levelled with a dozer or filled with granular fill material before the next pass of energy is applied.

All of the energy is applied from existing grade and the degree of improvement is a function of the energy applied: i.e., the mass of the tamper, the drop height, the grid spacing, and the number of drops at each grid point location. Lighter tampers and smaller drop heights result in depths of improvement on the order of 3.0 to 4.6 m. Heavier tampers and greater drop heights result in improvements on the order of 6.1 to 9.1 m. Figures 1 to 3 illustrate the dynamic compaction process and the equipment that has been used on a regular basis. References 7, 26, 32, 35, 38, 39, 46, 54, and 60 describe the dynamic compaction procedure.

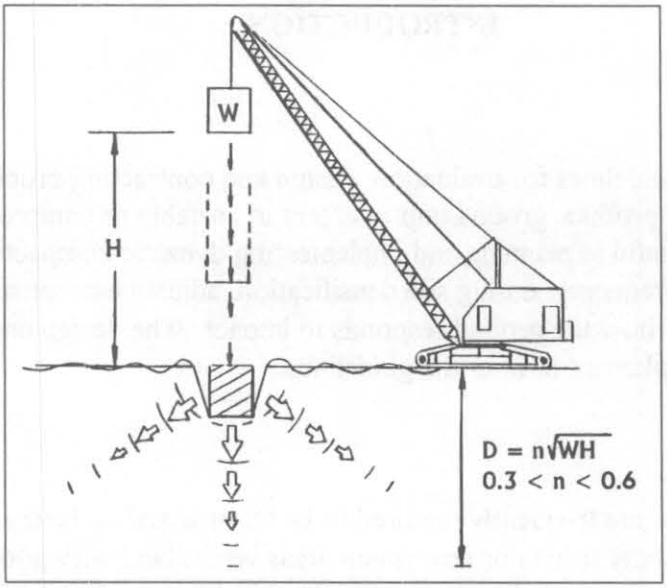


Figure 1. Dynamic compaction.

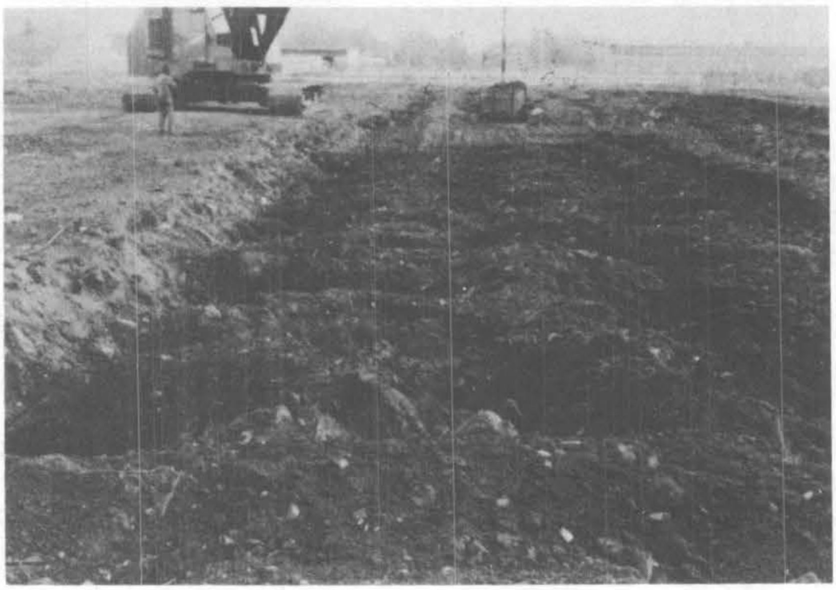


Figure 2. Typical dynamic compaction grid pattern with 13.6 Mg tamper in background.

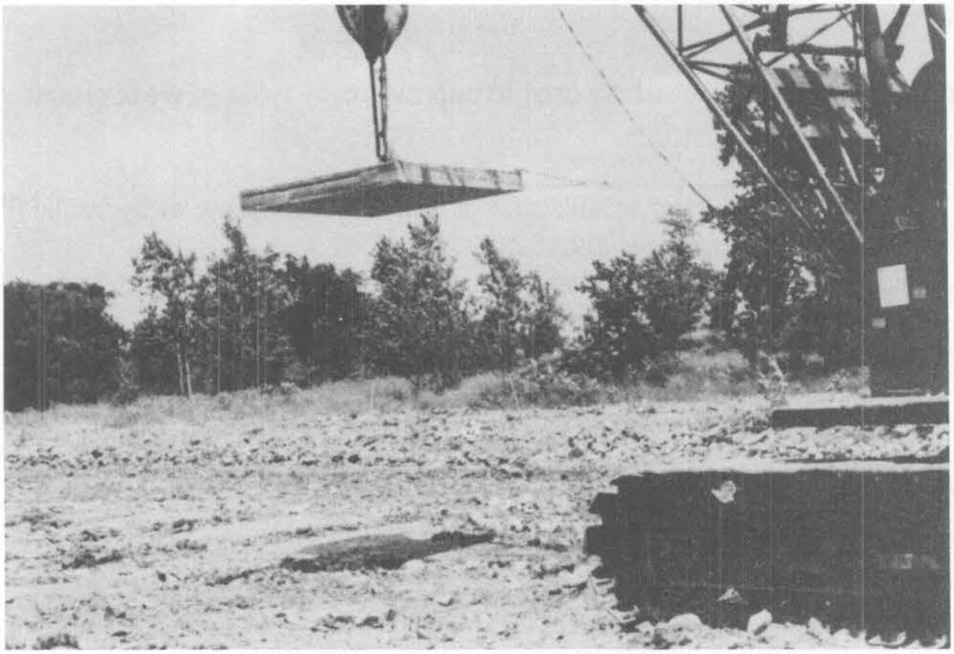


Figure 3. Square tamper with low contact pressure used for ironing pass.

ORGANIZATION

The chapters are presented in the sequence that is normally followed in the planning process for dynamic compaction projects.

Chapter 2 covers preliminary considerations including the design constraints such as sensitivity of the new embankment or facility relative to settlement and bearing capacity. The types of deposits at the site also need to be evaluated to determine if dynamic compaction is appropriate. Finally, the cost for dynamic compaction versus the cost of other alternatives needs to be evaluated. If an alternate form of ground improvement is more attractive, then this option could be pursued.

Chapter 3 presents guidelines for the specific use of dynamic compaction. This includes selections of the tamper size and drop height, the amount of energy to apply, the drop pattern, and the number of passes. This information can then be used to refine the cost estimate.

Chapter 4 discusses contracting methods and specifications.

Chapter 5 discusses field monitoring, which is normally undertaken during the dynamic compaction operations. This includes the observations of ground displacements during the site improvement as well as borings and in situ testing after completion of the work.

Possible adjustments during dynamic compaction are discussed in chapter 6. Case histories and design examples are presented in chapter 7.

APPLICATIONS

Dynamic compaction has been successfully used to improve many types of weak ground deposits including:

- Loose naturally occurring soils such as alluvial, flood plain, or hydraulic fill deposits. (See references 2,9,10,20,37,47,55,61.)
- Landfill deposits both recent and old. (See references 5,17,25,33,34.)
- Building rubble and construction debris deposits.[31]
- Strip mine spoil. [3,56]
- Partially saturated clay fill deposits that are elevated above the water table.[42]
- Collapsible soils including loess. (See references 4,36,48,49,50,53.)
- Formations where large voids are present such as karst topography or sinkholes that are located close to grade.
- Loose sands and silts to reduce liquefaction potential. (See references 8,12,15,21,58.)
- Special wastes. (See references 27 to 30.)

An estimated 500 dynamic compaction projects have been completed in the U.S. Most were for commercial purposes. The actual number may be much greater because many projects are not reported in the literature.

A list of highway-related dynamic compaction projects completed in the U.S. was compiled in 1992.[13] Twenty-five projects were identified where dynamic compaction was used on at least a part of the project site. Figure 4 indicates where these projects are located and the type of deposit that was densified.

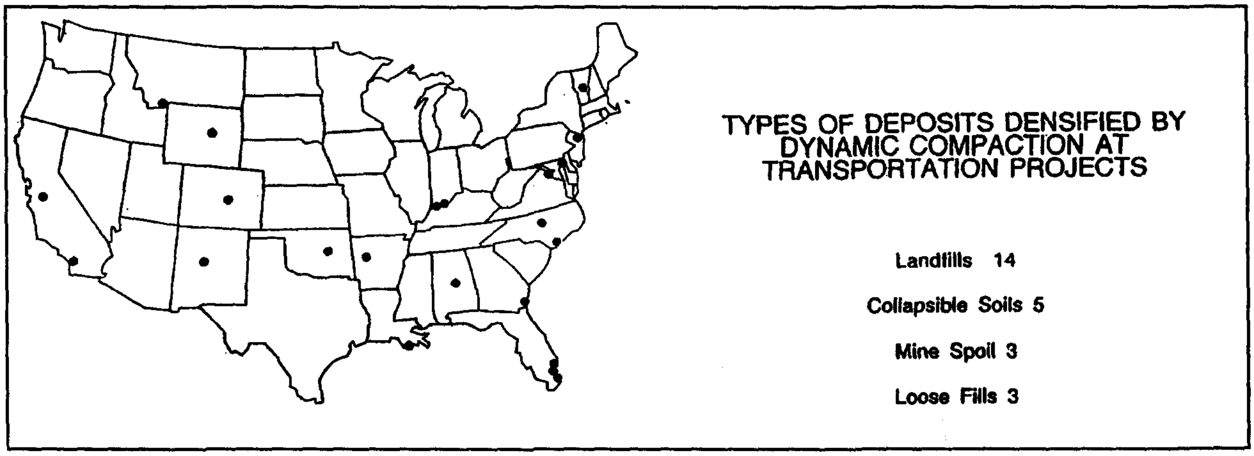


Figure 4. U.S. highway dynamic compaction projects. [13]

The greatest use of dynamic compaction has been to stabilize former landfills. This is attributed to the need for routing highways through or adjacent to urban sites where the land is at a premium and frequently the only spaces available are sites such as former landfills that have been bypassed for commercial development.

Dynamic compaction has been frequently used to densify collapsible soils present in the western part of the United States. The purpose of densification is to reduce settlement of the pavements that occurs as the soils become wetted after the highways are constructed.

Mine spoil deposits consisting of reworked shales and sandstones plus soil overburden have also been densified by dynamic compaction. The soil and rock mixture is usually in a medium-dense condition, but often there are pockets of very loose deposits within an otherwise more stable formation. Dynamic compaction has been found to be effective in making the subgrade more uniform.

CHAPTER 2
PRELIMINARY EVALUATION

PRELIMINARY EVALUATION STEPS

The following steps are suggested for conducting a preliminary evaluation to determine the suitability of using dynamic compaction at a specific project site. These steps are listed in the order in which they should be evaluated. However, some steps may be eliminated while other steps may require additional information or be expanded for a more thorough evaluation depending upon the site and soil conditions.

1. **Categorize soil type**: The properties, thicknesses, and extent of the weak ground must be known. This is usually determined by soil borings with Standard Penetration Tests (SPT), Cone Penetrometer Tests (CPT), or Pressuremeter tests (PMT).[32,62] Other tests such as the dilatometer, Becker Hammer, geophysical measurements, or deceleration measurements have also been used. (See references 6,11,18,45.) The site history such as when fill deposits were placed or the geologic origin of natural soils is also important. Test pits might be necessary to further explore erratic deposits.

   Based upon the types of soils that are in need of improvement at the site, the deposits can be rated as favorable, unfavorable, or intermediate for dynamic compaction.

2. **Assess site restraints** The project site should be examined to determine if the ground vibrations or lateral ground displacement could have an effect on adjacent properties. This would be especially important in urban areas where roadways or buildings might be situated in very close proximity to the area to be densified.

3. **Determine design requirements** If reduction in settlement is desired, a settlement estimate should be made before and after dynamic compaction and then compared with the requirements of the new embankment or facility. If the settlement is still larger than the new facility can tolerate, an alternate form of site improvement or support should be considered. Fortunately, roadway embankments can tolerate settlements of 0.3 to 0.6 m.[44] A properly designed dynamic compaction procedure usually results in settlement predictions less than this amount.

4. **Estimate costs** A preliminary estimate of costs for dynamic compaction should be made. The cost estimate can be refined later, but a quick cost estimate is necessary to compare with alternate site improvement techniques.

Table 1 lists parameters for rating each of these factors. This table can be used as a decision tree.If an unfavorable rating is obtained for any of the evaluation steps, other forms of site improvement should be considered. To permit the use of dynamic compaction, alterations or adjustments can sometimes be made to the item that produced an unfavorable rating. In this case, the additional cost for these adjustments or alterations needs to be considered. The next sections discuss the evaluation steps in more detail.

Table 1. Preliminary evaluation guidelines.

Steps	Favorable for Dynamic Compaction	Favorable with Restrictions*	Unfavorable for Dynamic Compaction
1. Categorize Soil Type			
Zone 1: Pervious	Best deposit for dynamic compaction	---------------	---------------
Zone 2: Semipervious	---------------	Apply energy in phases to allow for dissipation of	---------------
Zone 3: Impervious	---------------	Partially saturated impervious soils with deep water	Saturated or nearly saturated impervious soils
2. Assess Site Restraints			
Vibrations	Adjacent to: modern construction , < 19 mm per	19 to 51mm per sec allowable if adjacent to	Adjacent to: modern construction , > 19 mm per
Lateral Ground Displacements	Dynamic compaction > 7.6 m from buried utilities	Most buried utilities can tolerate 76 to 127 mm per	Immediately adjacent to easily damaged
Water Table	> 2 m below grade	< 2 m below grade, with drainage provided to lower	< 2 m below grade
Presence of Hard or Energy-Absorbing Layer	No hard or soft layers	1. Hard surface layer: loosen prior to dynamic compaction 2. Energy-absorbing surface layer: remove or stabilize with aggregate	Energy absorbing layer that limits depth of improvement, such as Zone 3 soil of 1m or more in thickness at a depth that is impractical to
3. Determine Design Requirements			
Settlement	< 0.3 to 0.6 m for embankments	> 0.3 to 0.6 m if site conditions preclude large	Settlement > design engineer can tolerate
Minimum Soil Property	Can usually achieve relatively high SPT, CPT, and	May need wick drains in saturated Zone 2 soils to	---------------
Depth of Improvement Limitation	Deposit < 9 m thick	Special equipment required for deposits in range of	Soils cannot be significantly improved below
4. Estimate Costs			
Dynamic Compaction	Generally least expensive form of site improvement	Multiple phases could slightly increase cost	If costs exceed alternate forms of site
Surface Stabilization	Frequently not required	---------------	1m layer could cost more than dynamic

*Judgment must be used in assessing the applicability of dynamic compaction for these cases. For further explanation, see text. Also, consult a dynamic compaction specialist.

CATEGORIZE SOIL TYPE

Site Investigation

Before soils can be grouped into categories ranging from suitable to unsuitable for dynamic compaction, it will be necessary to evaluate the subsurface ground and water table conditions. Ordinarily this is accomplished by a site investigation consisting of borings with SPT, CPT, or PMT tests.

The type of field exploration undertaken is dependent upon the characteristics of the soil at the site as well as local practice. In formations containing large boulders or broken concrete CPT testing would not be appropriate because of the chance of not being able to penetrate these obstructions. The SPT results also can be affected in a deposit where a large obstruction that influences the driving record is encountered. If the proper size borehole can be formed, PMT testing is appropriate in these formations. In heterogeneous deposits that are smaller in size than gravel, CPT testing is appropriate because of the near continuous record of penetration resistance in the vertical direction. In addition, the speed of CPT testing allows a larger number of tests to be done and provides some additional information on lateral variation in properties.

The type of testing chosen will also depend on what is currently in use in the area, the availability of equipment, and the experience of the designer with that type of in situ testing.

Samples of the various soils should also be obtained for the performance of laboratory index tests consisting of water content, grain size distribution, and Atterberg limits. This is especially important for fine-grained soil deposits. Organic content tests may also be appropriate, depending on the soil deposit.

Extended water level readings should be obtained in all the boreholes. If necessary, an observation well can be installed to obtain variations in water levels with time. The position of the water table affects the dynamic compaction operations. Soils below the water table are considered fully saturated, and excessive pore water pressures developed during dynamic compaction could influence the grid spacing and number of drops that can be made at each specific drop point location. In addition, if the water table is close to the ground surface, dewatering wells might be required to temporarily lower the water table to at least 2 m below the working surface.

The site history at man-made fill sites is also important. The age of the fill and the source of the fill are important considerations in planning and designing dynamic compaction and for estimating settlements. Older fill deposits have usually consolidated under their own weight, while newer fill deposits can still have a significant amount of voids present.

In extremely variable deposits such as landfills, examination of soil samples from either SPT testing or auger cuttings can be misleading. For this reason, test pits are frequently dug to obtain a better understanding of the composition and relative state of packing of the landfill deposits. Some idea of the age of the landfill can be obtained from visual observations, methane gas readings, and ground temperature readings. In newer landfills, a significant amount of methane is generally emitted, and the ground temperature is generally elevated above the prevailing average ground temperature for the region.[32]

The site history can also be established by talking with adjacent land owners, reviewing permitting records at local government agencies, and reviewing topographic maps and air photos taken at different times. In natural soil deposits, the available geologic mapping should be reviewed to provide further insight into the origin of the soil deposits.

General Description of Soil Categories

During dynamic compaction, the soils are densified at the prevailing water content. At many sites, the soils being densified are fully saturated, being below the water table. For densification to be effective, the deposit should be relatively permeable so excess pore water pressures that develop during densification can dissipate relatively quickly thereby allowing the soil particles to move into a denser state of packing. Following this reasoning, the most favorable soil deposits for dynamic compaction would be those where the permeability of the soil mass is high and drainage is good. Likewise, deposits with a very low permeability and poor drainage would be unfavorable for dynamic compaction. Figure 5 shows the range of soil gradation over which dynamic compaction is appropriate.

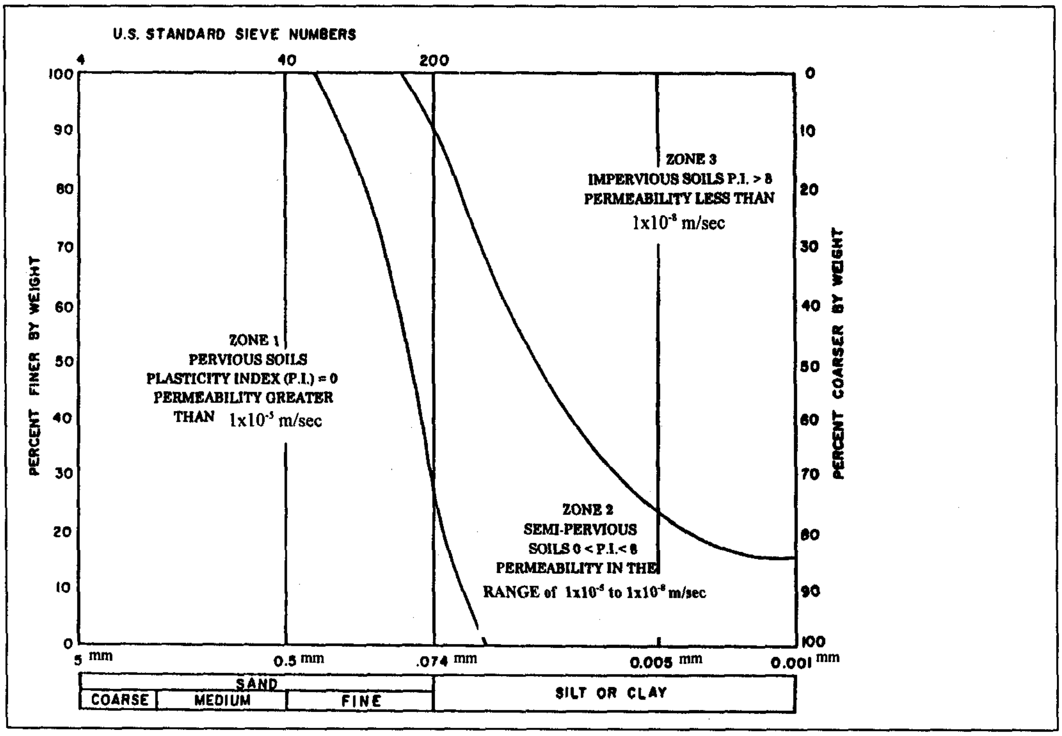


Figure 5. Grouping of soils for dynamic compaction.[32]

Most Favorable Soil Deposits - Zone 1

Dynamic compaction works best on deposits where the degree of saturation is low, the permeability of the soil mass is high, and drainage is good. Deposits considered most appropriate for dynamic compaction include pervious granular soils. If these deposits are situated above the water table, densification is immediate as the soil particles are forced into a denser state of packing. If these deposits are situated below the water table, the permeability is sufficiently high, excess pore water pressures generated by the impact of the tamper dissipate almost immediately, and densification is nearly immediate. Pervious granular deposits include not only natural sands and gravels but also fill deposits consisting of building rubble, some mine spoil, some industrial waste fill such as slag, and decomposed refuse deposits.

Dynamic compaction extends the range of compactable soils beyond that which is ordinarily undertaken by conventional compaction. Ordinary roller compaction would be very difficult on some of the coarser grained pervious deposits such as boulders and cobbles, building rubble, or slag deposits.

Unfavorable Soil Deposits - Zone 3

Deposits in which dynamic compaction is not appropriate would clayey soils, either natural or fill, that are saturated. In saturated deposits, improvements cannot occur unless the water content of the deposit is lowered. Generally, clayey soils have permeabilities of less than 10^{-8} to 10^{-9} m/s, so dissipation of excess pore water pressures generated during dynamic compaction cannot occur, except perhaps over a lengthy period of time. This makes dynamic compaction impractical for these deposits. Furthermore, the degree of improvement is generally minor.

Some improvements have been achieved in clayey fill deposits that are only partially saturated. This includes fills elevated well above the water level and with good surface drainage. In this case, improvement occurs as the particles are compacted before the deposits become fully saturated. After saturation occurs, no further improvement will be realized regardless of the amount of energy applied. Generally, the water content of the clayey soils prior to dynamic compaction should be less than the plastic limit of the deposit.

Intermediate Soil Deposits - Zone 2

There is a third zone of soils, labeled Zone 2 on figure 5, that is intermediate between the most favorable soils and the unfavorable soils for dynamic compaction. Silts, clayey silts, and sandy silts fall into this category. Normally, the soils in Zone 2 have a permeability on the order of 10^{-5} to 10^{-8} m/s. Dynamic compaction works in these deposits, but because of the lower than desired permeability, the energy must be applied using multiple phases or multiple passes. Sufficient time should be allowed between the phases or passes to allow excess pore water pressures to dissipate. Sometimes, the excess pore water pressure takes days to weeks to dissipate. On some projects, wick drains have been installed in these formations to facilitate drainage.(12,58)

ASSESS SITE RESTRAINTS

Site restraints may necessitate an alteration in the dynamic compaction procedure or supplemental construction activity to compensate for a site's deficiency. These site restraints should be evaluated in the preliminary study to determine what effect they might have on the project cost and timing.

Ground Vibrations

When a tamper strikes the ground, vibrations are transmitted off site. The vibrations are largest when heavier tampers and higher drop heights are used. If dynamic compaction is undertaken in a congested area, some off-site structures could be affected by the ground vibrations.

The U. S. Bureau of Mines[52] has studied the effect of ground vibrations on structures and has established threshold particle velocities beyond which cracking in walls of homes may occur. These limits are shown in figure 6. Numerous measurements from dynamic compaction projects have indicated that the frequency of ground vibrations from dynamic compaction is in the range of 6 to 10 hz. At this frequency, the U. S. Bureau of Mines criteria indicates that the particle velocities should be less than 13 and 19 mm/sec for older and more modern construction to prevent cracks in the walls. Structural damage does not occur until the particle velocities exceed about 50 mm/sec, although the tolerance to vibrations depends upon the condition of the structure.

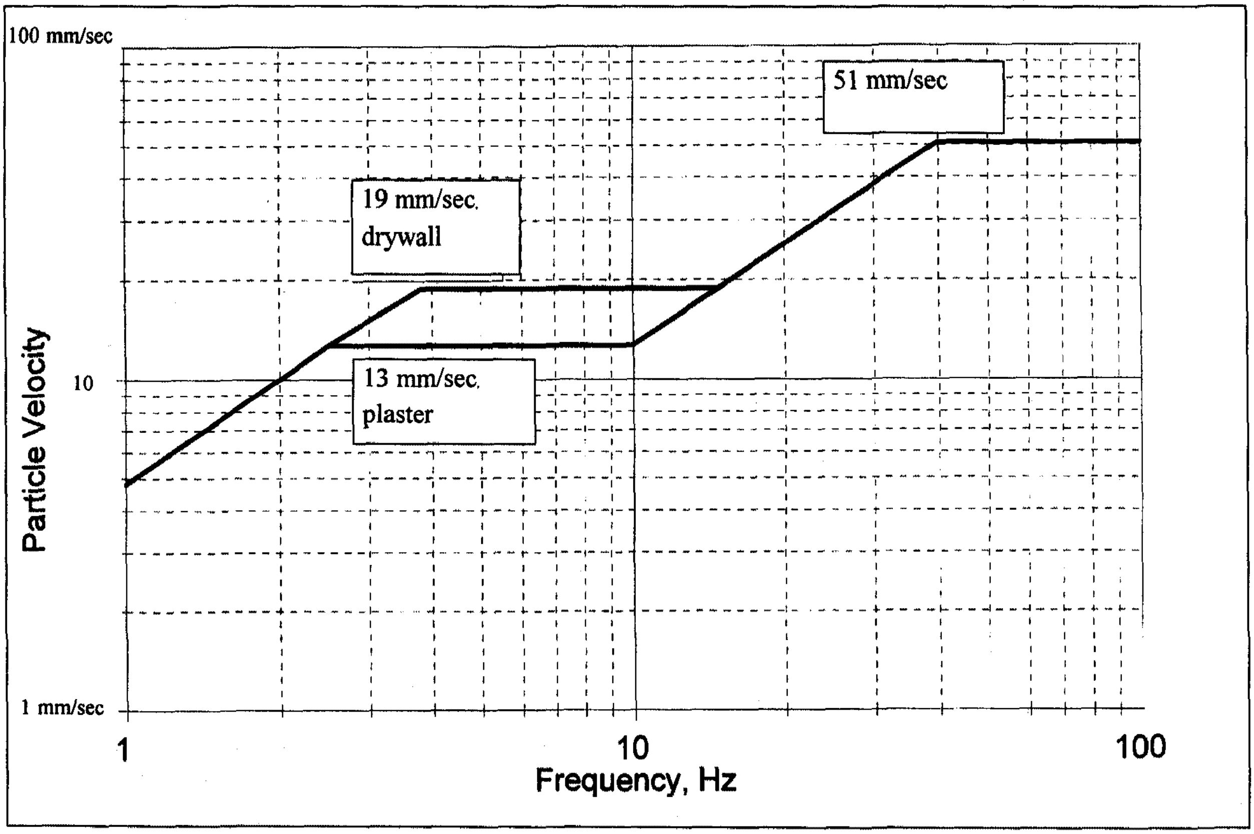


Figure 6. Bureau of Mines safe levels of blasting vibration for houses.[52]

Particle velocities can be measured with a portable field seismograph and compared with the criteria shown in figure 6. Readings should be taken on the ground adjacent to the concerned facility.

The particle velocities that will develop as a result of dynamic compaction should be predicted in advance of construction to determine if threshold vibration levels will be exceeded. Figure 7 has been developed from measurements taken on numerous projects and can be used to predict particle velocities.(32) The scaled energy factor incorporates the energy imparted into the ground from a single drop plus the distance from the point of impact to the point of concern. The chart is entered with the calculated scaled energy factor and a line projected vertically to the most appropriate soil type. A horizontal line is then extended laterally and the predicted particle velocity read off the vertical axis. This chart is based on records taken from many sites and provides a good estimation of ground vibration levels for planning purposes.

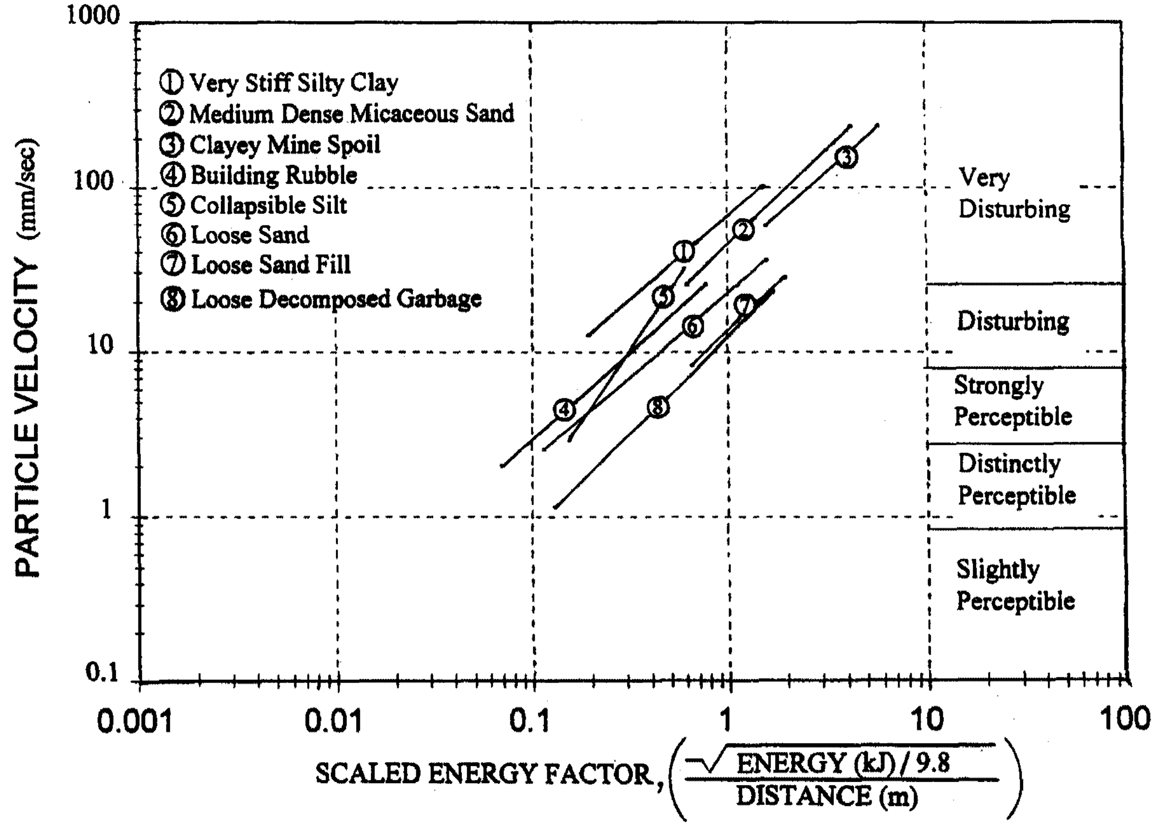


Figure 7. Scaled energy factor versus particle velocity.(32)

If dynamic compaction must be performed near an existing facility and the ground vibrations need to be minimized, some success has been obtained with digging a trench to a depth of approximately 3.0 m between the point of impact and the structure of concern. The trench should be installed at a location where it will not undermine the foundations of the structure or lateral support of a buried utility. An open trench is the most effective in reducing vibrations. However, open trenches which could cause undermining or other concerns should be filled with some loosely placed soil or compressible material. The purpose of the trench is to cut off the Rayleigh wave, which is a surface wave that travels off site from the point of impact. At some sites, off-site ground vibrations have been reduced by reducing the thickness of the loose deposit by excavation and then using a lighter tamper and smaller drop height to densify the remaining soils. Afterwards, the upper portion of the excavated soil can be replaced and densified in a similar manner.

Lateral Ground Displacements

Some lateral displacements occur in the ground following the impact. Unfortunately an established procedure has not been developed to predict lateral ground movements. Reliance is placed on experience and measured data reported in the literature. As part of the FHWA study on dynamic compaction(32), three project sites were instrumented with inclinometers located at distances of 3.0 m and 6.1 m from the point of impact. Lateral ground displacements were measured at both of these locations, and the results are shown in figures 8 and 9. At a distance of 3.0 m from the point of impact, lateral displacements ranging from 152 to 318 mm were measured within the zone of 6.1 m below grade. At 6.1 m from the point of impact, the lateral ground displacements were only on the order of 19 to 76 mm within the upper 6.1 m of the soil mass. Less displacement would occur for sites where a smaller tamper and reduced drop height were used.

If there are roadways or buried utilities located close to the point of impact, the likelihood of permanent ground displacements should be considered. Field measurements of lateral displacement or ground vibrations can be used to assess potential damage at structure locations.

Particle velocity measurements have been made with a seismograph on the ground over buried utilities.(63) Particle velocities of 76 mm/sec have not damaged pipes and mains. Pressure pipelines have withstood 250 to 500 mm/sec without distress.

High Water Table

Water table levels within approximately 2 m below the level of dynamic compaction often cause problems. During impacting, crater depths are frequently on the order of 0.6 to 1.2 m, and high pore water pressures generated in the soil mass generally cause the ground water table to rise. This could result in water filling into the craters. Additional drops could cause intermixing of the soil and water with subsequent softening of the upper portion of the soil mass.

If the water table is within 2 m of ground surface, consider:

- Lowering the ground water table by dewatering ditches or dewatering wells.
- Raising the ground surface by placing fill.

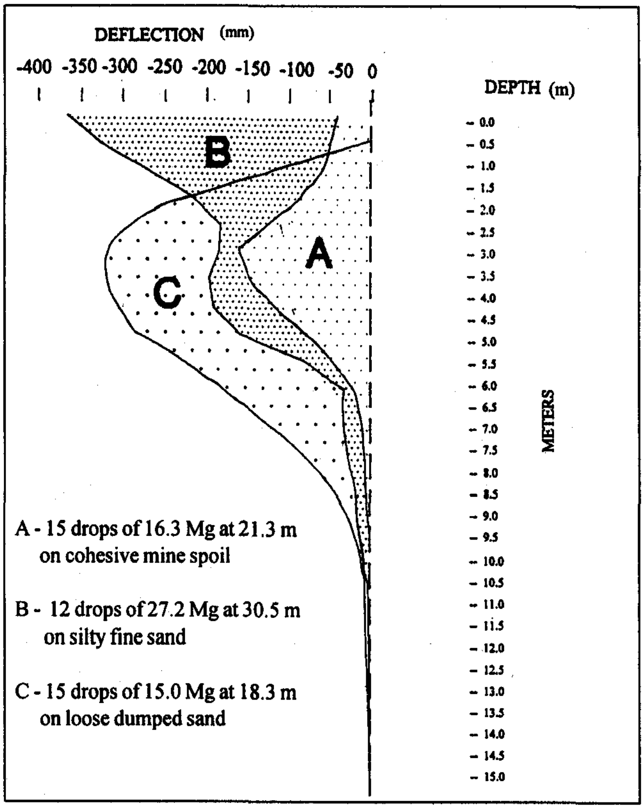


Figure 8. Lateral movements 3 m from drop point.(32)

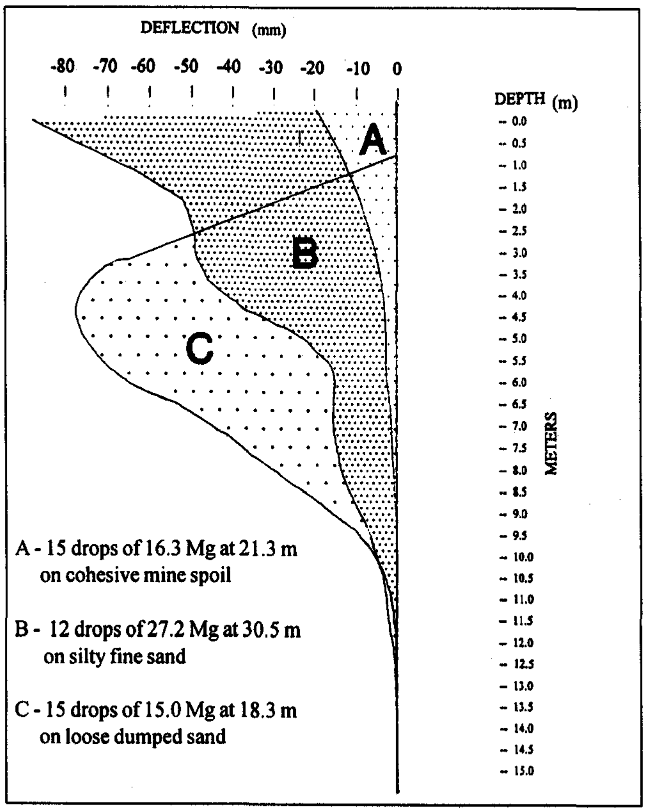


Figure 9. Lateral movements 6 m from drop point.(32)

Presence of Hard or Soft Layers

The depth of improvement from dynamic compaction can be affected by the presence of a hard surface layer overlying a weak deposit or the presence of a soft and compressible layer within an otherwise stiffer deposit.

Hard surface layers can form as a result of aging, cementation, or compaction from surface traffic. If this hardened layer is relatively thick (1 to 2 m), the energy from impact can be distributed throughout this layer and transmitted at a much lower intensity to the underlying weak deposits thereby resulting in less depth and degree of improvement. Thick hardened layers either have been removed or loosened prior to dynamic compaction so that the energy is transmitted to the deeper formations.

If this hardened layer is relatively thin the tamper will likely penetrate through the hardened crust and still deliver the proper energy to the underlying layers.

Soft energy absorbing soils at grade can be excavated or stabilized by adding granular soil that is driven into the soft soil during impact. Soft clays or organic deposits at depth within the formations can absorb the energy from dynamic compaction. In this case, very little energy will be transmitted below these layers so the lower lying layers will not be improved as much as desired. The effect that the soft layer will have on the densification is dependent to a large extent upon the thickness of the layer and its position below the ground surface. Test sections will be required to evaluate the depth and degree of improvement that can be attained.

EVALUATE DESIGN REQUIREMENTS

Tolerable Settlement

When planning a new embankment or other facility, the settlement under new loading should be estimated. This includes:

- Settlement prediction under loading without site improvement. This helps to justify the need for the site improvement.

- The estimated settlement under loading after dynamic compaction.

- Establishing the tolerable settlement of the embankment or other facility.

Predicting settlement before and after dynamic compaction can be done using the test results of conventional procedures such as the SPT, CPT, or PMT tests. In very loose deposits such as recent landfills, SPT, CPT, or PMT test procedures for estimating settlement can be misleadingly low. Settlement predictions in recent and mid-age landfills based upon SPT and PMT tests have been found to underestimate the settlement that was measured by actual load tests on landfills before dynamic compaction.[24] Large objects within the loose fill matrix cause misleadingly high SPT values that result in low settlement predictions. The pressuremeter is inappropriate in deposits that are still consolidating under their own weight. Except for these recent-age landfills, conventional settlement predictions made for other sites provide reasonable estimates of settlement and differential settlement.

The value of making a settlement prediction in advance of site improvement is to compare the estimated movement with the tolerable movement. Excessive movement is justification for site improvement.

The amount of tolerable movement depends on the sensitivity of the new facility to total and differential settlement. Post-construction settlements during the economic life of a roadway of as much as 0.3 to 0.6 m are generally considered tolerable provided:(44)

- The settlements are reasonably uniform.
- The settlements do not occur adjacent to a pile-supported structure.
- The settlements occur slowly over a long period of time.

If a building, bridge, or more sensitive facility is to be constructed on the loose deposit, other guidelines have been presented.(43,59)

The amount of settlement following dynamic compaction is difficult to predict in advance of the actual work since the improvement depends to a large degree upon the amount of energy applied. Table 2 shows the maximum amount of improvement that can generally be achieved following dynamic compaction in terms of SPT, CPT, and PMT tests.

Table 2. Upper bound test values after dynamic compaction.(32)

	Maximum Test Value		
Soil Type	**Standard Penetration Resistance (blows / 300 mm)**	**Static Cone Tip Resistance (MPa)**	**Pressuremeter Limit Pressure (MPa)**
Pervious coarse-grained soil:			
sands & gravels	40 - 50	19 - 29	1.9 - 2.4
Semipervious soil:			
sandy silts	34 - 45	13 - 17	1.4 - 1.9
silts & clayey silts	25 - 35	10 - 13	1.0 - 1.4
Partially saturated impervious deposits:			
clay fill & mine spoil	30 - 40*	N/A	1.4 - 1.9
Landfills	20 - 40*	N/A	0.5 - 1.0

*Higher test values may occur due to large particles in the soil mass.

The average improvement will be less than the maximum amount. The maximum improvement generally occurs at a depth of 1/2 to 1/3 of the maximum depth of improvement as shown in figure 10. Figures 11 to 14 also show typical SPT, CPT, and PMT values that were measured following dynamic compaction as related to soil type and applied energy.

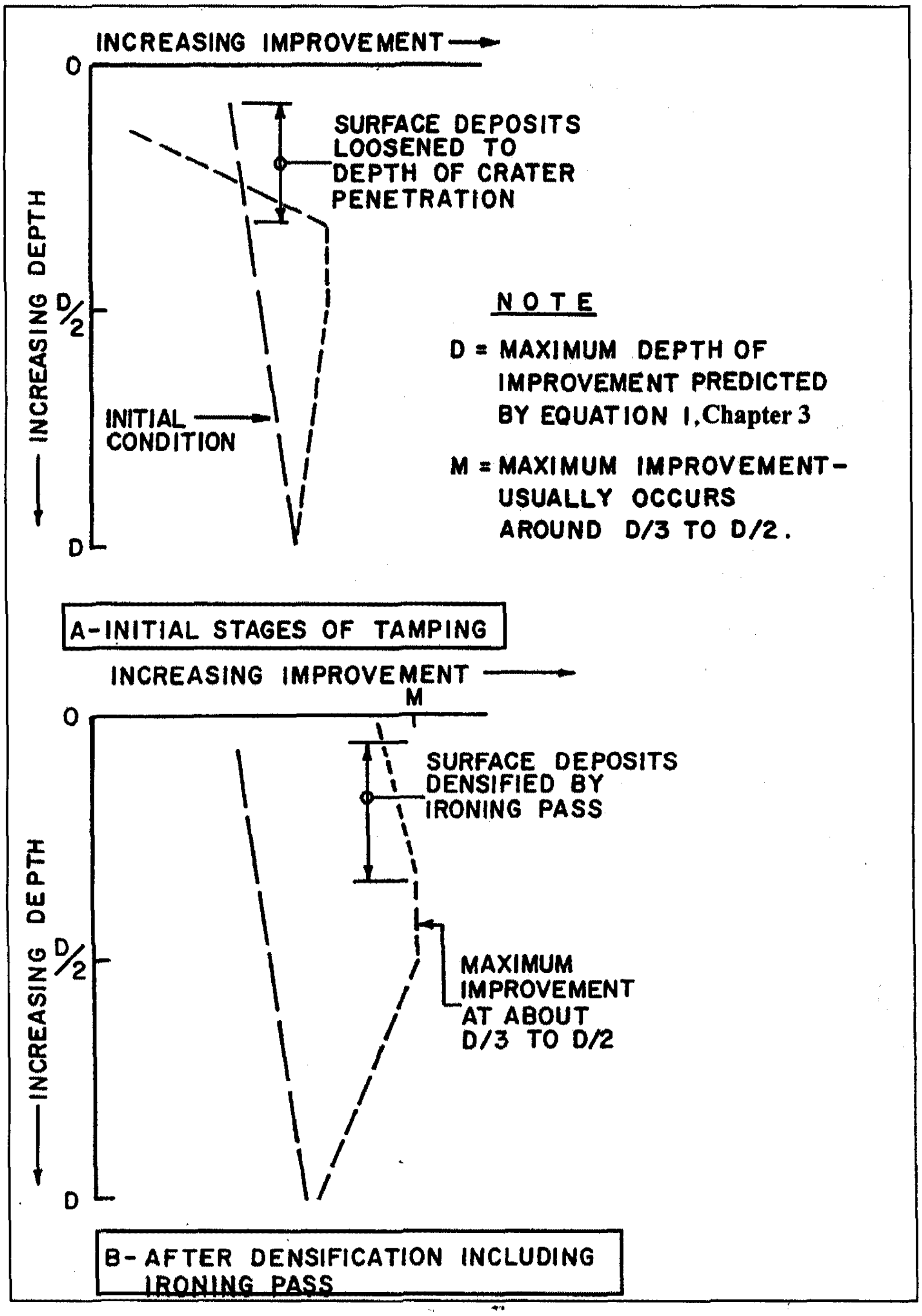


Figure 10. Variations in improvements with depth during dynamic compaction.[32]

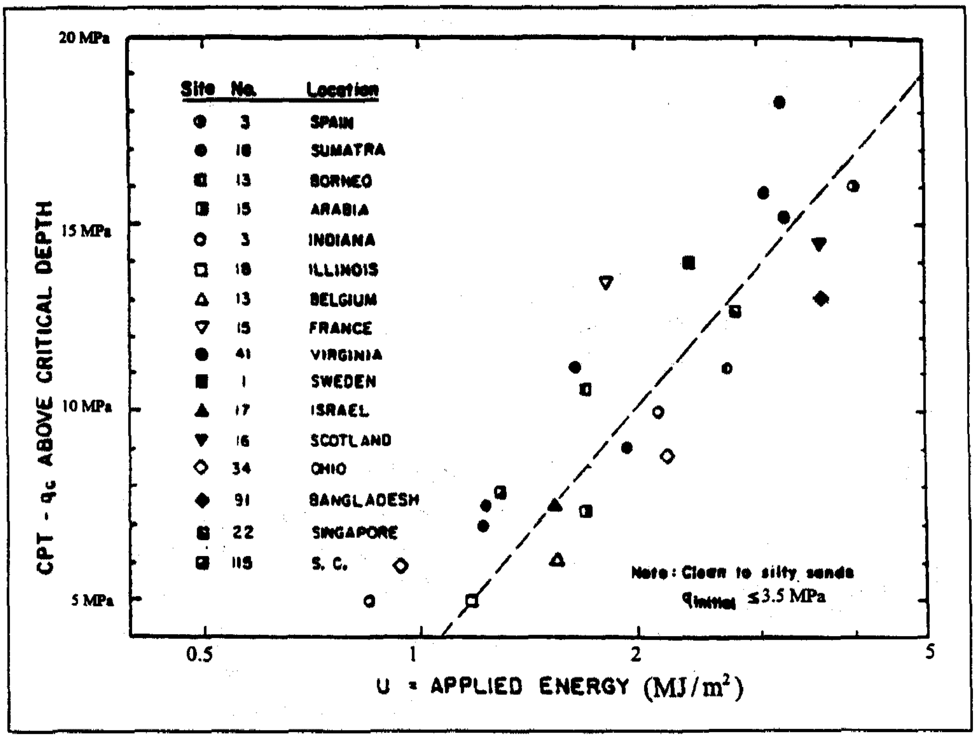


Figure 11. Increase in cone resistance in granular soils with applied energy.[38]

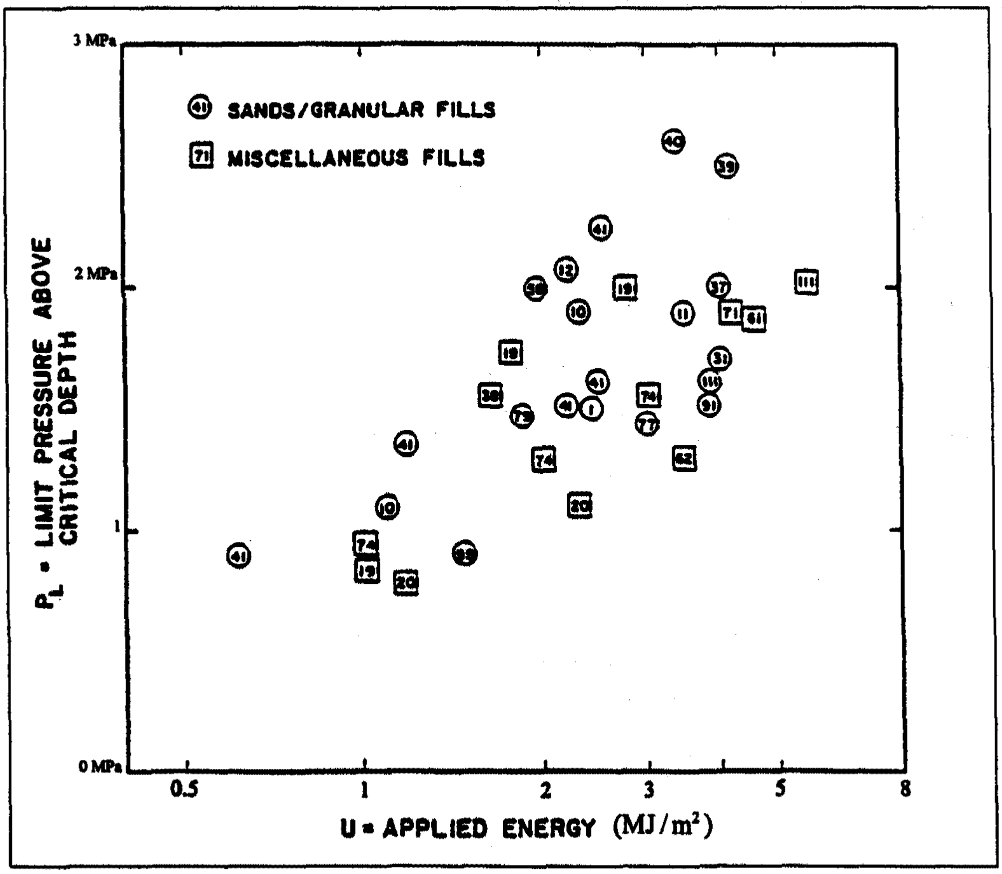


Figure 12. Observed trend between limit pressure and applied energy for granular soils.[38]
(See reference 38 for details of the numbers included in this figure.)

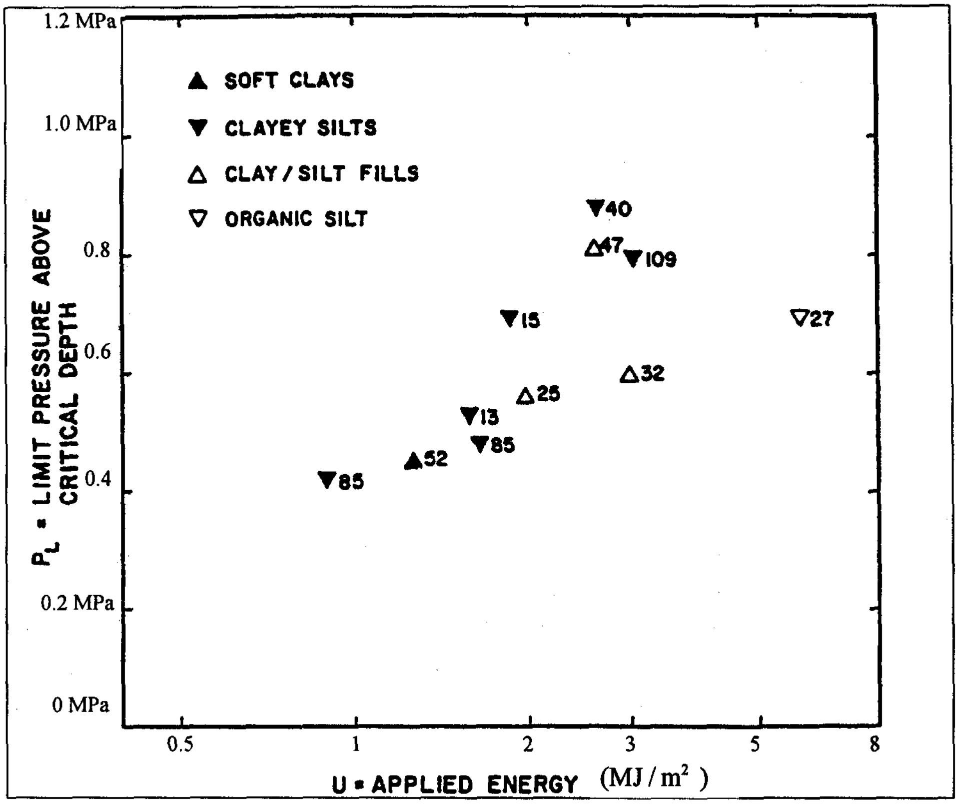


Figure 13. Observed trend between limit pressure and applied energy for cohesive soils.[38] (See reference 38 for details of the numbers included in this figure.)

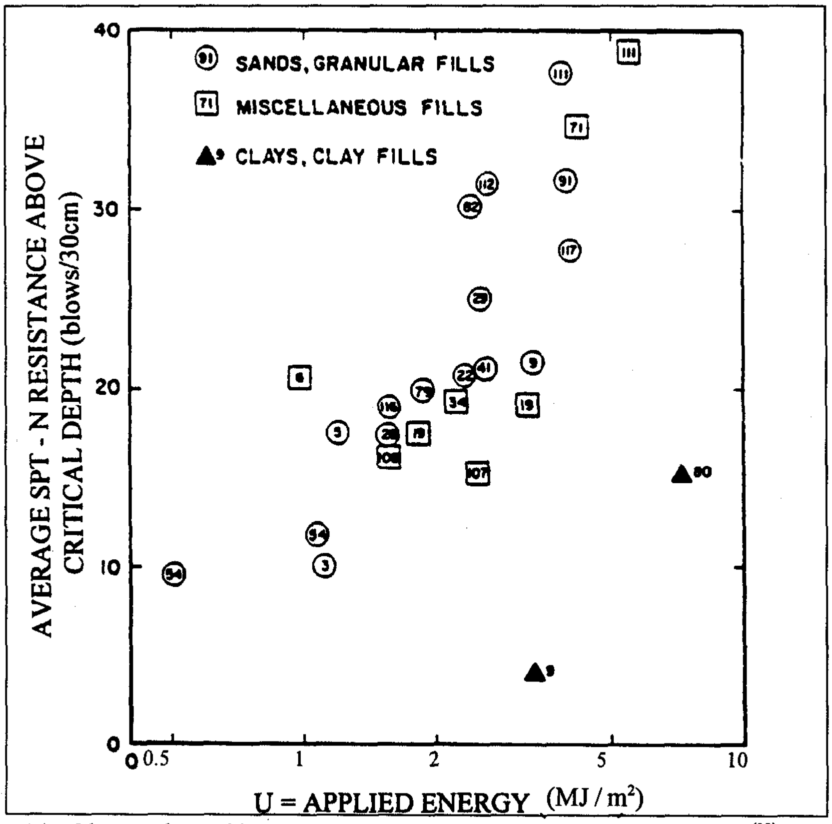


Figure 14. Observed trend between SPT-N Value and applied energy level.[38] (See reference 38 for details of the numbers included in this figure.)

The estimated post-densification settlement can be made using table 2 and figures 11 to 14 as a guide. Some judgement is required.

In landfill deposits secondary compression should be estimated.[24] In young-age landfills, secondary compression will be large but may still be tolerable provided higher than normal maintenance with periodic overlays is provided in the budget.

Borings with SPT, CPT, or PMT tests should be completed when dynamic compaction is underway and after completion to determine if the required properties of the soils are being met as a result of the site densification. If the desired improvement has not been achieved, additional energy could be applied to result in greater ground improvement.

In most deposits, the engineering properties of the soil improve with additional time following dissipation of the excess pore water pressures. (See references 31,32,40,51.) Figure 15 illustrates the gain in PMT values with time in a fill deposit consisting of a mixture of clay, shale, limestone, ash, sand, and pottery fragments. Figure 16 illustrates the gain in strength in CPT tests in a sandy soil deposit. Thus, borings with tests made immediately after dynamic compaction should take into account that the soils will gain in strength with time, so something less than the desired SPT, CPT, or PMT test results could suffice if the borings are made shortly after dynamic compaction is completed in that area.

Minimum Soil Property

In some cases, the goal of densification is to reach a minimum soil property that will satisfy a criteria other than settlement. An example would be a site where earthquakes could cause liquefaction of the soil deposit. An initial engineering analysis must be undertaken to determine what minimum value of SPT would be required to render the soils nonliquefiable for a design magnitude earthquake. Dynamic compaction would then be planned to impart enough energy to reach this minimum desired SPT value.

In areas where loessial soils are present, the goal of densification might be to achieve a minimum in place unit weight that renders the soil noncollapsible. Figure 17 shows the relationship between the collapse potential and unit weight for loess deposits.[19] Sufficient energy should be applied during dynamic compaction to achieve the minimum desired unit weight.

In collapsible alluvial soils, the single oedemeter-collapse test is the primary method for characterizing the collapse potential of these deposits.[4] Other index tests such as changes in void ratio and unit weight as a result of dynamic compaction have also been proposed to evaluate the effectiveness of stabilizing these deposits.[36]

Depth Of Improvement Limitation

The depth of improvement is primarily a function of the mass of the tamper and the drop height. Other factors which enter into the predicted depth of improvement are discussed in more detail in

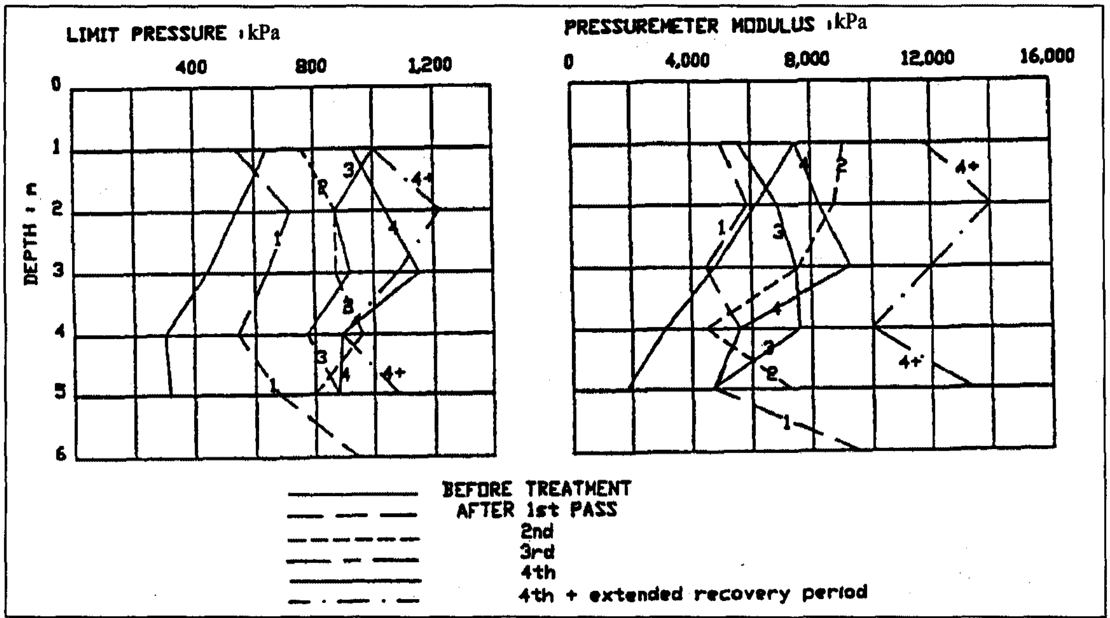


Figure 15. Housing development; comparison of improvements in a fill consisting of clay, shale, limestone, ash, sand, and pottery fragments. [42]

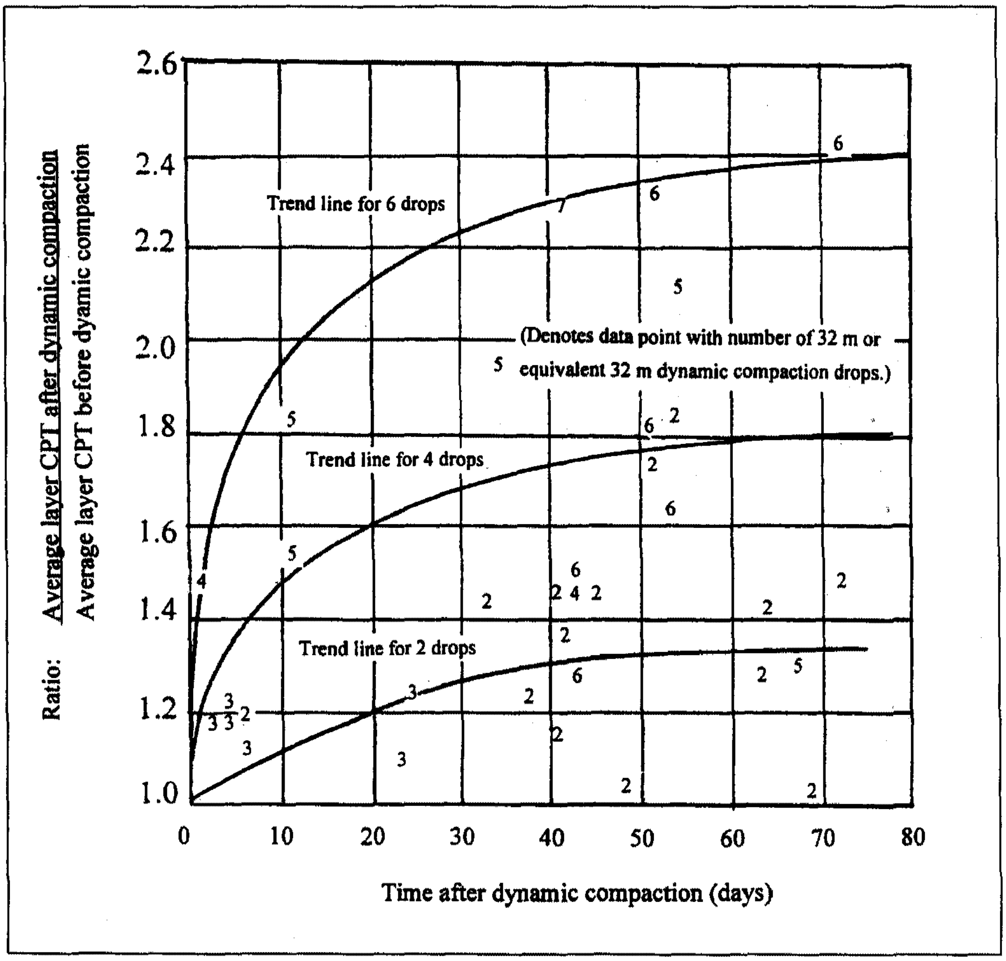


Figure 16. Effects of time on the relative improvements in CPT test values in sandy soil in depth range of 2 to 8 m. [51]

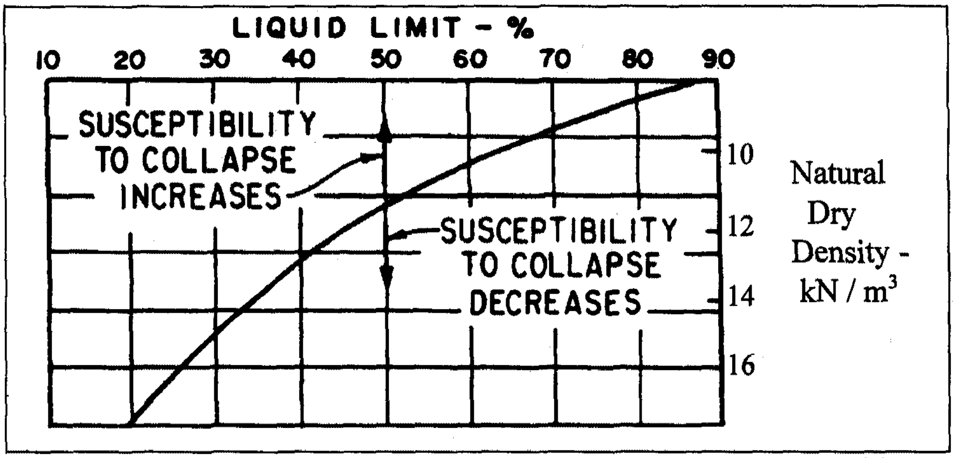


Figure 17. Criteria for evaluating looseness and probability of soil collapse. (19)

chapter 3. Using tampers in the range of 18.1 to 22.7 Mg and drop heights on the order of 22.9 to 30.5 m, the maximum predicted depth of improvement would range from about 9.1 to 12.2 m. For most projects, this is an adequate depth of improvement. Even if loose deposits extend below these levels, the pressure increase relative to the existing overburden pressure is generally very small, so the contribution of settlement from these deeper unimproved deposits may not be large.

If ground improvement must be attained at depths greater than 9.1 to 12.2 m, dynamic compaction in combination with other systems is discussed in the next section.

CONSIDER COSTS AND ALTERNATIVES

Dynamic Compaction Costs

The costs for dynamic compaction depend upon the type of equipment required to complete the work. Lighter tampers and smaller drop heights require a smaller crane size, and dynamic compaction can be done at a lower cost per unit area than for the heavier tampers that require a much larger crane. Equipment requirements for different size tampers are listed in table 3.

Table 3. Equipment requirements for different size tampers.(32)

Tamper Mass (Mg)	Crawler Crane Size (Mg)	Cable Size (mm)
5.4 - 7.3	36.3 - 45.4	19 - 22
7.3 - 12.7	45.4 - 90.7	22 - 25
12.7 - 16.3	90.7 - 113.4	25 - 29
16.3 - 22.7	136.1 - 158.8	32 - 38

For projects where a method specification (see chapter 4) is used, an estimate of costs for dynamic compaction can be obtained by using table 4 and equation 1 of chapter 3. For preliminary cost estimates a value of $n = 0.5$ should be used in equation 1. The prices include mobilization but do not include:

- A cost for the owner's quality assurance. For projects using a method specification, the owner is responsible for providing the monitoring during construction plus any borings or tests taken after dynamic compaction.

- A cost for granular fill, if required, to fill craters or provide a surface stabilizing layer. At sites where there is a weak surface layer such as a landfill, granular fill is imported to construct a working platform to allow for travel of the equipment across the site and to fill craters. The aggregate particle size generally ranges from 10 to 150 mm and the thickness ranges from 0.3 to 1.0 m. Local aggregate prices should be obtained to estimate costs.

Table 4. Dynamic compaction costs.[32]

Size of Tamper Required (Mg)	**Unit Cost Dollars / m^2**
4 to 7	5.50 to 8.00
7 to 15	8.00 to 10.75
15 to 23	10.75 to 16.25
23 to 32	16.25 to 32.25
32 to 91	Negotiated for each job.

Note: Prices based on projects undertaken during 1985 to 1993

At sites where stable materials are present at grade, granular materials are not needed. At these sites the ground is levelled following dynamic compaction by blading the soil from between the centers into the crater depressions. The loosened surface layer is then compacted with either normal compaction equipment or an ironing pass.

For projects undertaken using a performance specification (see chapter 4), the contractor will plan and engineer the job, provide field control, and assume more risk. The cost for dynamic compaction will increase depending upon the complexity of the job and the risk level. High-risk jobs will include projects where the specifications require a performance that is difficult to achieve. An example would be an unrealistic maximum allowable deflection under load. A lower risk job would be one where the contractor only has to meet a reasonable minimum value of SPT, CPT or PMT. The additional costs will vary for each project depending upon the factors listed above. A dynamic compaction contractor could provide an estimate for a project after provided with project details.

The costs for dynamic compaction relative to other forms of site improvement are shown in table 5. As can be seen, the cost for dynamic compaction is generally significantly less than for other forms of site improvement.

Table 5. Comparative costs of ground improvement methods.

	Cost Basis		
Treatment Method	Volume of Treated Soil ($ / m^3)	Surface ($ / m^2)	Length ($ / m)
Dynamic compaction	0.7 - 3	4.3 - 22	
Vibro-replacement	4 - 12		30 - 52
Vibro-compaction	1 - 7		16 - 39
Excavate-replace	10 - 20		
Slurry grouting	40 - 80		
Chemical grouting	160 - 525		
Compaction grouting	30 - 200		
Jet grouting	100 - 400		82 - 325
Freezing	275 - 650	110 - 160*	

*Plus $2 to $10.75 per sq. meter/week to maintain frozen zones.

A more refined cost estimate can be prepared if dynamic compaction is selected as being suitable for the site and a dynamic compaction plan is developed based upon considerations given in chapters 3 and 4. The weekly or monthly rate for rental of equipment to repeatedly raise and drop the tamper selected for the project can be obtained from local suppliers.

In the case of the lighter tampers such as 3.6 to 9.1 Mg, the operator should be able to achieve 500 to 600 drops per day depending, of course, upon the number of moves or standby time involved. For the tampers in the range of 9.1 to 18.1 Mg, the tamper can be repeatedly raised and dropped approximately 300 to 400 times per day. Based upon an initial mobilization charge plus an estimated length of time for the project, a better idea of the costs for dynamic compaction can be obtained. If there are other costs such as earth moving equipment for leveling of the ground or for importation of granular materials, this would have to be added into the estimate. The costs for monitoring can be calculated based upon the estimated duration of dynamic compaction and the unit rate for the person.

Alternate Ground Improvement Techniques

Alternate methods of ground improvement could be considered either as a replacement for or in combination with dynamic compaction. This could include:

- Removal and replacement.
- Vibro-compaction, vibro-replacement (stone columns).
- Grouting.
- Surcharging with or without prefabricated vertical drains.

An overview describing various methods of site improvement except for surcharging is presented in summarized form in the AGC-ARTBA Joint Committee Task Force 27 report.(1) Dynamic compaction has been used in combination with some of these alternate methods of ground improvement. Dynamic compaction was used at a building site(20) to densify the upper soil deposits and compaction grouting used to improve the deep-seated deposits. A similar technique was used for an electric power plant.(51) Dynamic compaction in combination with stone columns was used to improve a loose clayey sand deposit beneath a dam.(8,41)

The removal of soft surface deposits and replacement with more suitable material has been undertaken either prior to or during dynamic compaction at numerous project sites. Unsuitable material generally consisted of soft clay or an organic deposit overlying a more favorable deposit for improvement by dynamic compaction.

Wick drains have been used in combination with dynamic compaction to allow for more rapid pore water pressure dissipation. (12,58) The wick drains were installed in silty soil deposits. If the wick drains had not been installed, a significantly longer period of time would have been required between successive passes for the pore water pressures to dissipate and ground improvement to occur.

A combination of wick drains and surcharge plus dynamic compaction have been used on some projects.(57)

Variations in the normal dynamic compaction procedures have been used with success for special situations. In fine-grained soils a process called "select fill displacement" was used to form short granular columns that penetrated 5 to 7 m into the loose deposits.(14) This was accomplished by imparting as many as 70 to 150 high energy drops at each drop point location using multiple phases and passes and filling the craters with a select granular material. The granular columns improved the transmission of energy to greater depths than would otherwise occur with conventional dynamic compaction. In silty deposits with a high water table, the granular columns aided in dissipation of excess pore water pressures.(15)

Granular columns have also been driven into soft saturated cohesive soils and organic deposits.(9,23) The term "Dynamic Replacement and Mixing" has been applied to this method of ground treatment.

CHAPTER 3
DESIGN CONSIDERATIONS

DEVELOPMENT OF DESIGN PLAN

If the preliminary evaluation discussed in chapter 2 indicates that dynamic compaction will be appropriate, a more detailed dynamic compaction plan must be prepared. Items that need to be addressed include:

1. Selection of the tamper mass and drop height to correspond to the required depth of improvement.
2. Determination of the applied energy to be used over the project site to result in the desired improvement.
3. Selection of the area to densify.
4. Determination of the grid spacing and number of phases.
5. Establishing the number of passes.
6. The need for a surface stabilizing layer.

These six steps should be addressed regardless of whether the project will be completed with a method or a performance specification (see chapter 4). If the project will be undertaken with a method specification, the design agency or their consultant will determine the dynamic compaction procedure incorporating an evaluation of these six items. If the project will be undertaken with a performance specification, the specialty contractor will address these items based upon the level of improvement required. However, the design agency or their consultant should review the specialty contractor's plan to determine if these items have been adequately considered.

The design evaluation process is summarized in table 6. A detailed discussion of each step is presented in the remainder of this chapter.

SELECTION OF TAMPER AND DROP HEIGHT

Usually the thickness of the loose deposit and hence the required depth of improvement is known from the subsurface exploration. The relationship between the depth of improvement and the tamper mass and drop height is as follows:

$$D = n\,(WH)^{1/2} \qquad (1)$$

Where:
D = depth of improvement in meters
W = mass of tamper in Megagrams
H = drop height in meters
n = empirical coefficient that is less than 1.0

Table 6. Design guidelines.

Parameters to be Determined	Evaluation Process
Step 1: Selection of tamper and drop height for required depth of improvement Equation 1: $D = n(WH)^{0.5}$	A. Determine thickness of loose deposit from subsurface exploration or the portion of the deposit that needs densification to satisfy design requirements. B. Use Equation 1 and select *n* value from Table 7 for soil type. C. Use Figure 21 as a guide in selecting tamper mass and drop height for dynamic compaction equipment currently in use.
Step 2: Determine applied energy to achieve required depth of improvement	A. Use Table 8 to select the unit energy for the proper deposit classification. B. Multiply the unit energy by the deposit thickness to obtain the average energy to apply at ground surface.
Step 3: Project area to densify	A. For level sites, use a grid spacing throughout the area in need of improvement plus a distance beyond the project boundaries equal to the depth of improvement. B. If slope stability is a concern, improvement over a wider plan area may be required. C. At load concentration areas, apply additional energy as needed.
Step 4: Grid spacing and drops Equation 2: $AE = \frac{N(W)(H)(P)}{(grid\ spacing)^2}$ Where: N = number of drops P = number of passes W = mass of tamper H = drop height	A. Select a grid spacing ranging from 1.5 to 2.5 times the diameter of the tamper. B. Enter *W* and *H* from step 1 and applied energy from step 2 into Equation 2. C. Use Equation 2 to calculate the product of *N* and *P*. Generally 7 to 15 drops are made at each grid point. If the calculations indicate significantly more than 15 or less than 7 drops, adjust the grid spacing.
Step 5: Multiple Passes Prediction of crater depths or ground heave in advance of dynamic compaction is difficult. The contract should provide for multiple passes where very loose deposits like landfills are present or where silty deposits are nearly saturated.	A. Crater depths should be limited to the height of the tamper plus 0.3 m. B. Energy application should stop if ground heave occurs. C. If items A or B occur before the required number of drops are applied, multiple passes should be used to: * permit ground leveling if item A occurs * allow pore pressure dissipation if item B occurs
Step 6: Surface stabilizing layer	A. Not needed for Zone 1 soils. May be required for Zone 2 soils if nearly saturated. Usually required for landfills. B. When surface stabilizing layer is used, the thickness generally ranges from 0.3 to 0.9 m.

The empirical coefficient *n* attempts to account for factors that affect the depth of improvement other than the mass of the tamper and the drop height. As shown in figure 18, *n* has been found at project sites to range from 0.3 to 0.8. The variation in *n* is attributed to the:

- Efficiency of the drop mechanism of the crane.
- Total amount of energy applied.
- Type of soil deposit being densified.
- Presence of energy absorbing layers.
- Presence of a hard layer above or below the deposit being densified.
- Contact pressure of the tamper.

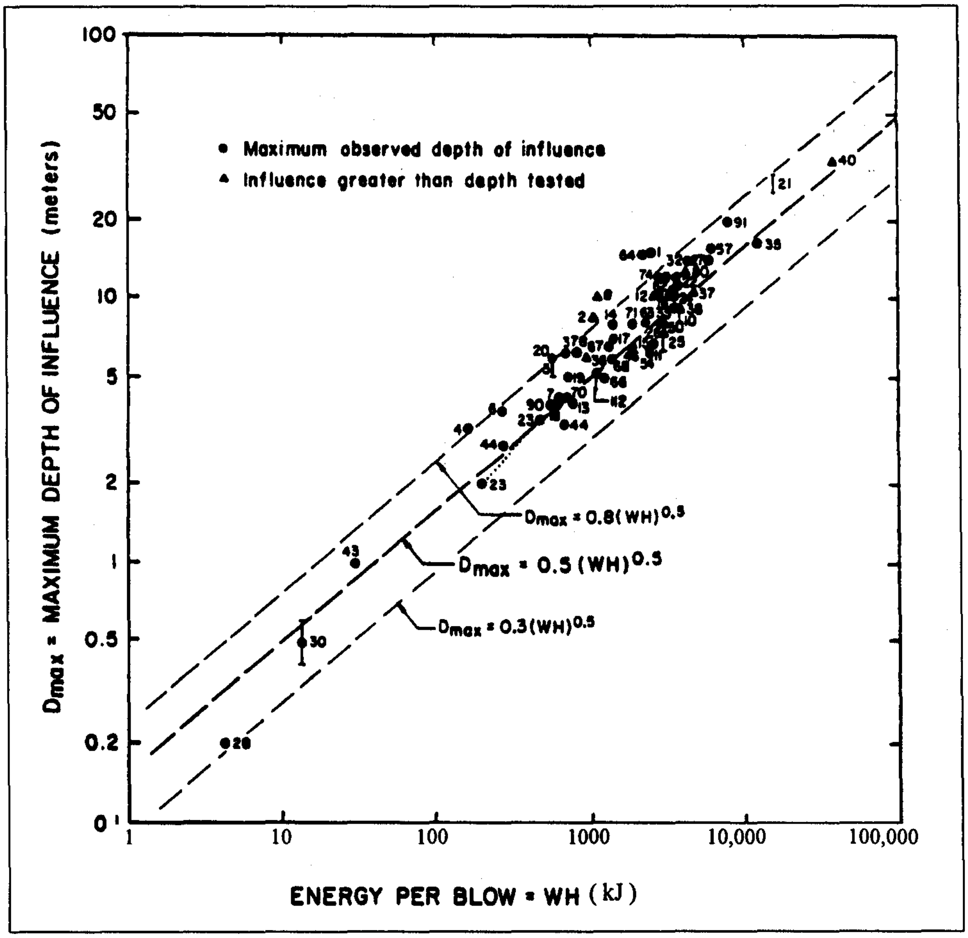


Figure 18. Trend between apparent maximum depth of influence and energy per blow.[38]
(See reference 38 for details of the numbers included in this figure.)

The first three variables listed above have been investigated previously[32] The efficiency of the drop mechanism using a single cable for lifting and dropping of the tamper was found to be approximately 80 percent of the maximum potential energy of the mass of the tamper times the drop height. This efficiency was found to be the same for different pieces of lifting equipment and for raising and dropping tampers in the range of 5.4 to 18.1 Mg. Thus, even though there is some energy loss in using the single cable for raising and dropping the tamper, the variable is approximately the same for different pieces of equipment thereby resulting in approximately the same percentage of energy delivered.

There is less energy loss when the tamper is raised and then allowed to free fall. However, the cycle time for 1 impact is approximately 5 to 10 times longer than for a tamper with a single cable attached. For this reason, the free fall method of dynamic compaction is rarely used.

The total amount of applied energy at a site has some influence on the depth of improvement. Figures 19 and 20 illustrate the measured depth of improvement for the number of drops of the tamper. In the case of the sandy deposits, approximately 90 percent of the maximum depth of improvement is achieved after only 2 to 4 drops at one location. In the case of the clayey soils, there is still an increasing depth of improvement even after 14 drops at one location. On most projects, the tamper is dropped on the order of 7 to 15 times at one specific grid point location. In the sandy soils, the maximum depth of improvement would be reached, but in the case of the clayey soils, some additional depth of improvement could occur with additional applied energy.

For the conditions where the energy is applied with a tamper that is raised and dropped with a single cable and where the average applied energy is in the range of 1 to 3 MJ/m^2, the coefficient, *n*, was found to be related to soil type as shown in table 7. These values can be used in equation 1 as a first step in estimating the depth of improvement. For most projects, this is all that is needed.

Table 7. Recommended *n* value for different soil types.

Soil Type	Degree of Saturation	Recommended *n* Value*
Pervious Soil Deposits - Granular soils	High	0.5
	Low	0.5 - 0.6
Semipervious Soil Deposits - Primarily silts with plasticity index of < 8	High	0.35 - 0.4
	Low	0.4 - 0.5
Impervious Deposits - Primarily clayey soils with plasiticity index of > 8	High	Not recommended
	Low	0.35 - 0.40 Soils should be at water content less than the plastic limit.

*For an applied energy of 1 to 3 MJ/m^2 and for a tamper drop using a single cable with a free spool drum.

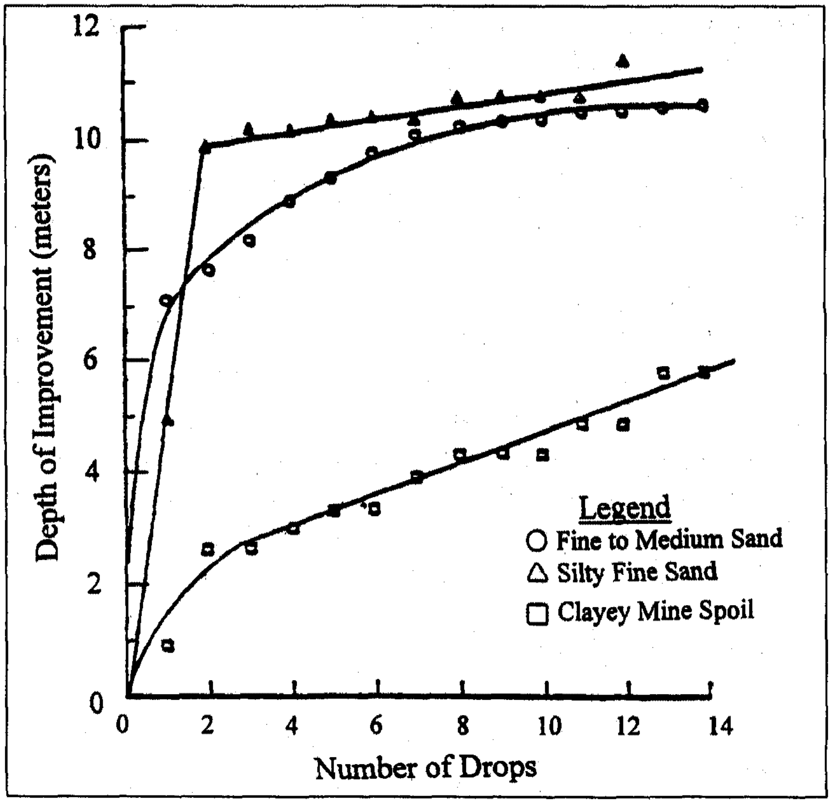


Figure 19. Depth of improvements as measured by lateral deflection obtained at inclinometer located 3.0 m from center of drop point.[32]

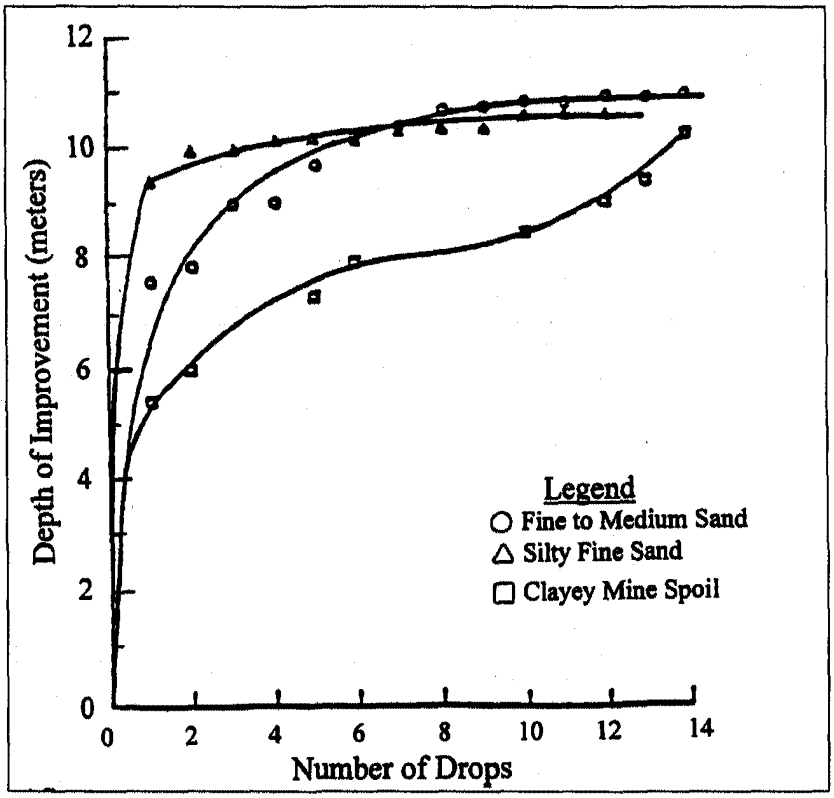


Figure 20. Depth of improvements as measured by lateral deflection obtained at inclinometer located 6.1 m from center of drop point.[32]

The other three variables previously listed could have an effect on the depth of improvement, but there is no quantitative method of taking these variables into account. Some judgment needs to be exercised on a case-by-case basis. This includes:

- If there is an energy absorbing layer such as a weaker saturated clay within the soil mass, the depth of improvement will be reduced to an extent that is dependent upon the thickness of the layer and the position within the soil deposit. If the energy absorbing layer is relatively thick and located within the center of the loose deposit, the depth of improvement will not extend below the depth of the weak layer. If the weak layer is near the surface of the deposit and is not very thick, it is possible that the tamper will penetrate through the layer and deliver the energy to the underlying loose deposits wherein equation 1 would be a relatively valid prediction of depth of improvement. Borings should be made after completion of dynamic compaction to determine the influence of the weak layer on the depth and degree of improvement.

- A hard layer present at ground surface could restrict the amount of energy transferred to the deeper layers. On projects where a thick crust of densified material is present, it will be necessary to loosen the surface layer to allow the energy to be transmitted to greater depths. A hard layer located below the loose deposit has a favorable effect in reflecting energy back upward into the deposit resulting in either a greater degree of improvement in the lower portion or a greater depth of improvement.

- Most tampers have a flat bottom with a contact pressure on the order of 40 to 75 kN/m^2. If the tamper falls within this range, there is no need to consider adjusting the depth of improvement by equation 1. However, it has been found by experience that if the contact pressure is significantly less than the lower bound value, the energy is distributed over too wide an area and a hard surface layer develops without the depth of improvement. Contact pressure significantly higher than the typical values could result in a tamper plunging into the ground.

After selecting the required depth of improvement and the most appropriate n value for the deposit, the product of WH is calculated from equation 1. Figure 21 shows the relationship between the tamper mass and drop height for various dynamic compaction equipment currently in use. This figure can be used to select values of W and H.

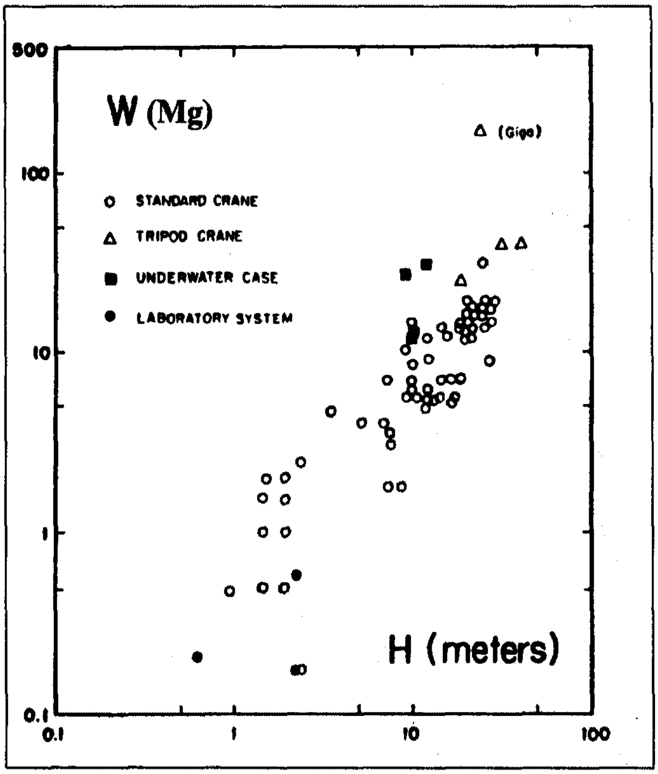


Figure 21. Relationship between size of tamper and drop height. [38]

APPLIED ENERGY REQUIREMENTS

A sufficient amount of energy must be applied during dynamic compaction to cause ground compression to result in property improvements that are necessary for design. The applied energy is generally given as the average energy applied over the entire area. It can be calculated as follows:

$$AE = \frac{(N)(W)(H)(P)}{(grid\ spacing)^2} \qquad (2)$$

where:

AE = applied energy
N = number of drops at each specific drop point location
W = tamper mass
H = drop height
P = number of passes

If different size tampers and drop heights are used, the total applied energy would be the sum of both levels of effort. The high level energy is applied first with a heavy tamper and a higher drop height. High energy application could result in craters of 1 to 1.5 m. After ground levelling this will result in a loosened surface layer. This loosened layer is densified, by an ironing pass using a smaller size tamper and a lesser drop height. The total applied energy would be the sum of the energy applied during the high energy pass plus the ironing pass. Where crater depths are shallow, the ironing pass can be omitted and surface densification is attained with conventional compaction equipment.

On typical projects, the average applied energy ranges from about 1 to 3 MJ/m^2. However, the amount of energy for any specific project should be varied taking into account the:

- Classification of the deposit being densified.
- Initial relative density of the deposit.
- Thickness of the deposit being densified.
- Required degree of improvement.

Table 8 can be used as a starting point to calculate the required average applied energy. This table takes into account the initial three factors listed above. The soil types are grouped into three broad categories in table 8. The range in applied energy accounts for the initial relative density of the deposit. More energy should be applied to the looser deposits and less to the denser deposits. The thickness of the deposit being densified is incorporated into table 8 by listing the applied energy in terms of a unit volume. The average energy to be applied at the surface of the deposit can be obtained by multiplying the suggested values by the thickness of the deposit being densified.

Table 8. Applied energy guidelines.[32]

Type of Deposit	**Unit Applied Energy (kJ/m^3)**	**Percent Standard Proctor Energy**
Pervious coarse-grained soil - Zone 1 of Figure 5	200- 250	33 - 41
Semipervious fine-grained soils - Zone 2 and clay fills above the water table - Zone 3 of Figure 5	250 - 350	41 - 60
Landfills	600 - 1100	100 - 180
Note: Standard Proctor energy equals 600 kJ/m^3 .		

In table 8, the recommended unit energies range from about one-third standard proctor energy for the pervious coarse grain soils to about one-half this energy for the semipervious fine grain soils and clay fills above the water table. Less than full proctor energy is sufficient to densify these deposits as long as they have been in place for more than 3 to 5 years. Older fills have experienced compression under their own weight and are at least normally consolidated. If these soils have just been recently placed, a higher unit applied energy would be appropriate.

Landfills are usually in an extremely loose condition because of the low unit weight of the debris at the time of placement plus the creation of additional void spaces due to decomposition of the organic components. These deposits are usually underconsolidated. Applied unit energies of 1 to 1.8 standard proctor are needed to densify these deposits.

To illustrate the use of table 8, consider the case of a building rubble fill deposit that is on the order of 4 m thick in one area and 8 m thick in another. This deposit has been in place for 10 years and it is considered to be in a medium dense condition. Building rubble would fall into the category of a pervious coarse grain soil. Because the deposit is in a medium dense condition and apparently consolidated under its own weight, the appropriate unit applied energy would be 200 kJ/m^3. For the 4 m thick deposit, this would require an average applied energy of 800 kJ/m^2, while the 8 m thick deposit would require an average applied energy of 1.6 MJ/m^2. If soil borings indicate the fill to be in a loose condition or if voids are present within the fill, the higher unit energy of 250 kJ/m^3 should be used for determining the energy application. In this case, the average applied energy at the ground surface would be on the order of 1MJ/m^2 for the 4 m thick deposit and 2 MJ/m^2 for the 8 m thick deposit.

The guidelines given in table 8 are to be used as a starting point and adjustments may be necessary in the field to attain the minimum desired property values. If densification is taking place to reduce liquefaction, the minimum SPT or CPT value will govern when sufficient energy has been applied. If densification is undertaken to reduce settlement, the design might call for a minimum pressuremeter modulus or minimum SPT value, and sufficient energy will need to be applied to reach these values. The manner in which the energy will be applied, whether in single or multiple passes, will be discussed in the following sections.

AREA TO DENSIFY

Dynamic compaction is generally completed over an area larger than the plan area of the embankment or the loaded area. This is to induce densification of the below ground area that will be subjected to stress increase due to the pressure distribution resulting from the new loading.

On many projects, dynamic compaction is undertaken beyond the edge of the loaded area for a distance equal to the depth of the weak deposit. This would include projects where heavy loads are applied near the edges of the plan area such as retaining walls or building footings. In the case of an embankment constructed over weak ground where slope stability is a concern, it might be necessary to densify the entire zone of soil beyond the toe that would lie within the predicted deep-seated failure zone.

GRID SPACING AND NUMBER OF DROPS

The energy is generally applied at a relatively tight grid spacing over the entire area to be densified. The high energy drop point locations do not have to be contiguous since some of the energy distributes laterally into the soil mass. A drop point spacing of 1½ to 2½ times the diameter or width of the tamper is common. In the fine grain soils where there is a concern with pore water pressures developing in the soil, the work plan should provide for two or more phases. The first phase would involve dropping the tamper at every second or third drop point location. After a period of time to allow dissipation of pore pressures, the intermediate drop point locations could be densified as part of the second or third phase.

The number of drops at each grid point location can be calculated using equation 2. The input includes:

- The applied energy calculated as per section 3.3.
- The tamper mass and drop height calculated as per section 3.2.
- A grid spacing ranging from 1.5 to 2.5 times the diameter of the tamper.
- An assumption that all the energy will be applied in one pass.

Normally, 7 to 15 drops of high level energy are applied at each drop point. If significantly less than 7 or more than 15 drops are calculated, consider adjusting the grid spacing.

If there are concentrated loads at isolated locations, such as from a retaining wall or building footing, an additional phase of energy could be applied at these locations.

The upper surface of the soil mass is generally loosened to a depth equal to the crater depth following the high energy level application. The loosened zone should be densified by a low level energy pass called an ironing pass. A square tamper, figure 3, with a low contact pressure is frequently used for this purpose. The area is densified on a contiguous or even overlapping grid. Generally a low drop height and only a few drops are needed to densify the surface soils. If the depth of craters is less than 0.5 m, the upper loosened soils could be densified by conventional compactors after levelling.

MULTIPLE PASSES

The number of drops that can be applied at a grid point location at one time could be limited by the depth of the crater. In extremely loose deposits, the initial drops may result in crater depths greater than the height of the tamper. This is undesirable for a number of reasons including:

- Extracting the tamper from a deep crater is difficult and could result in cable breakage. Sometimes a suction force develops as the tamper is lifted from the deep crater, and at other times loose debris falls in on top of the tamper, increasing the extraction force.

- After the tamper is extracted from a deep crater, the sides may cave into the crater, providing a cushioning effect for the next impact. In addition, the caving that occurs could cause the tamper to strike the base irregularly with some of the energy being absorbed as the tamper strikes the side walls of the crater.

- Applying the energy at a fairly deep level below ground surface could result in the tamper becoming closer to the ground water table and generating high pore water pressures.

- The loosened zone of soil above the base of the crater presents a problem for densifying the upper layer. A higher than normal level of energy may be required for the ironing pass to densify this relatively thick, loose deposit.

The crater depth should be limited to about the height of the tamper plus 0.3 m. If the full amount of energy has not been delivered at this time, either fill the craters with good material or level the ground and then apply the remaining energy during a subsequent pass.

The number of drops that can be applied at a grid point location at one time would also be limited if excess pore water pressures develop during impacting. In the finer grain deposits such as Zone 2 of figure 5, excess pore pressures may require days to weeks to dissipate following impact with the tamper. When high pore water pressures develop, the energy does not result in densification but rather in volumetric displacement of the soil mass. In this case, apply the energy in multiple passes to allow the excess pore water pressure to dissipate between passes. In the highly pervious deposits, pore water pressures generated in the soil mass as a result of tamping will dissipate between impacts. In this case, grain-to-grain contact is established very rapidly between the soil particles, and the energy can be applied all in one pass. In deposits consisting of building rubble, coarse sands, and gravels, or in some of the partially saturated deposits, the energy can usually be applied in one pass. It is more efficient for the contractor to apply the energy in one pass because there are fewer moves with the equipment.

If more than one pass is required to apply the energy, the number of drops per pass decreases proportionally. In equation 2, the product of number of drops and number of passes must remain the same. For example, if 12 drops are required at each grid point location (as per equation 2) but only 6 drops can be completed before the crater depth becomes excessive or excessive pore water pressures develop, two passes of 6 drops per pass will be required.

The required number of passes is very difficult to determine in advance of the actual site work. In fully saturated soils, more passes will be required than for partially saturated soils. Ideally, a pore water pressure measuring device should be installed in the ground at the start of construction to measure the rise and decay in pore water pressure following each drop of the tamper. The initial few drops might not cause a significant increase in pore water pressure, but repeated drops could result in very high values that could take a long time to dissipate. The information generated from the field readings would be helpful in planning both the proper number of drops at each location and the waiting period before additional energy can be applied. When writing the specification, it is preferable to specify multiple passes or phases for deposits classified as Zone 2 or Zone 3 soils. The contractor can then plan accordingly.

Ground heave measurements represent an indirect measurement of excess pore water pressure. Figure 22 illustrates ground heaving. Ground heaving is an indication that the soils are displacing plastically at no volume change rather than compacting. The energy is being transmitted through the pore water and, at this time, dynamic compaction is ineffective in

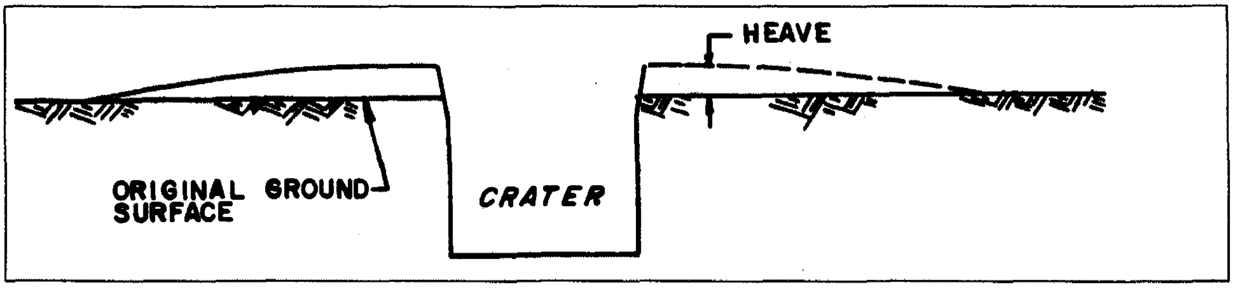


Figure 22. Ground heave pattern due to volumetric displacement.

causing densification. Ground heave measurements can be obtained at occasional drop point locations by installing settlement monitoring devices adjacent to the point of impact and measuring the change in elevation following each drop of the tamper. If enough observation points are established, the ground heave adjacent to the crater can be calculated. This can then be compared to the volumetric displacement within the crater itself, which is also determined from elevation readings. When the peripheral ground heave equals the change in crater volume, plastic deformation without densification is occurring. No additional energy should be applied if this condition occurs until there is a rest period to allow excess pore water pressures to dissipate.

SURFACE STABILIZING LAYER

At sites where the surface is in an extremely loose condition, such as an old landfill, it might be necessary to add a stabilizing surface material of granular soil to form a working mat. The purpose of the working mat is to provide a stable platform for the dynamic compaction equipment as well as to limit crater depth penetration. Working mats ranging from 0.3 to 1.2 m in thickness have been used at some project sites.

The most favorable type of material to use for a working mat is a coarse-grain granular deposit such as gravel, crushed rock, or building rubble.

In most cases, thick working mats should be avoided because a stiffened surface deposit tends to limit the energy penetration to greater depths. For very heavy tampers, working mats of 0.5 to 1m do not appear to be a limiting factor since there is so much energy applied that the tamper easily penetrates through these relatively thick deposits. However, if lighter tampers are used, the tamper may not penetrate the working mat and the depth of improvement is limited.

Unfortunately, the cost of importing a granular working mat adds significantly to the expense of dynamic compaction. For this reason, a granular stabilizing blanket may not be specified. However, granular material can be imported as dynamic compaction is underway to fill the craters.

CHAPTER 4
CONTRACTING PROCEDURES

INTRODUCTION

Two basic types of specifications are used for dynamic compaction projects: method specifications and performance specifications. The decision as to which type of specification to use will depend on the experience of the design agency and their consultants with dynamic compaction, the complexity of the job, the proximity of specialty and non-specialty contractors to the site, the time available for test sections, and experimentation plus the department or agency philosophy.

Table 9 highlights the differences between these two types of specifications. Details are provided in the next two sections.

METHOD SPECIFICATION

Preparation of a method specification requires knowledge of the various facets of dynamic compaction either within the design agency or by their consultants. In the method specification, the owner and/or their consultants do all of the engineering calculations regarding the size of tamper; drop height; energy that needs to be applied; area that is needed to be densified; number of passes to be made plus the delay time, if any, between passes; plus consideration of off-site vibration or displacement as a result of dynamic compaction. Basically, the owner or their consultant provides all the engineering services needed to obtain the desired improvement. Test sections completed just prior to or at the start of production work could be specified to adjust or confirm the proposed dynamic compaction procedure.

In this type of contract, the contractor assumes very little, if any, risk related to the improvement that occurs as a result of dynamic compaction. The contractor's primary duties under this type of contract include:

- Providing a tamper of the prescribed size and with the proper contact pressure at the base.
- Providing the proper equipment with a single cable to raise and drop the tamper on a repeated basis through the specified drop height.
- Providing sufficient cables, swivels, and other equipment to keep the operation progressing on a continuous operation.
- Maintaining safety at the job site including a safe working distance from the point of impact for working personnel; barriers, where necessary, to prevent debris from going off site; and maintenance of the swivels that connect the cable and the tamper.
- Keeping records of the number of drops, the number of passes, and any imported material that is required for a working mat.
- Maintaining production to meet the schedule assigned for the project.

Table 9. Contracting for dynamic compaction.

Method Specification	**Performance Specification**
Agency should have in-house experience or hire a consultant with experience to prepare detailed specifications for contractors. Specifications should include: - Tamper mass and size - Drop height - Grid spacing - Applied energy - Number of phases or passes - Site preparation requirements - Surface compaction after dynamic compaction - Drawings of work area	Owner or designer prepares specification outlining desired end product. This could include: - Minimum property values - Maximum permissible settlement - Other objectives of site improvement Owner provides initial subsurface data and lateral extent of project site.
Owner or designer provides: - Subsurface investigation data - Monitoring during construction - Borings and tests after dynamic compaction	The contractor is required to meet the minimum specified end product and is responsible for: - Proper equipment and work plan - Meeting project deadlines - Safety - Field monitoring - Additional subsurface exploration as required to properly prepare dynamic compaction plan - Verification of end product
Contractor is responsible for: - Providing adequate equipment to complete the work in a timely manner - Safety of personnel and equipment - Work plan subject to approval of designer	To obtain a quality work product, the designer should require: - Only experienced dynamic compaction contractors to bid - Submittal of work plan for review and comment - A method for adjusting differences of opinion between designer and contractor

In addition to preparing the specifications, the responsibility of the owner is to provide:

- Access to the site for the contractor.
- Information related to subsurface conditions including the soil borings and geotechnical report.
- Trained personnel at the site during dynamic compaction to make any adjustments in the field operations that are deemed necessary.
- Soil borings as a check on the degree and depth of improvement; monitoring load tests in the field; or measurement of pore water pressure.

With a method specification, different types of contractors can bid the work. Frequently, this work has been completed by earth moving contractors, wrecking contractors, or specialty contractors. The local contractors would have the advantage of lower mobilization and general knowledge of the area and can be very competitive. This is especially true for the tampers in the low to moderate range of generally less than 14 Mg and for moderate drop heights where conventional lifting equipment is not over-stressed. For the higher tamper weights or the large drop heights, specialty contractors have experience with strengthening of the lifting drums and using heavy-duty equipment to minimize field breakdowns.

The general requirements to be included in a method specification are listed as follows. Typical specifications are included in appendices A and B.

If a method specification is to be used, sufficient information must be provided within the specifications so that it is clear to the contractor exactly what must be provided. Some of the important considerations are:

- General Description - A general description of the new facility to be constructed along with a general description of dynamic compaction should be in the specifications to acquaint contractors with the project. All pertinent information including topographic mapping, surveys, soil boring logs, and geotechnical information should be provided.

- Work Area - The extent of the area to be improved by dynamic compaction should be outlined on a drawing or set of plans. This would include the plan dimensions of the embankment or building plus the additional area that is to be improved beyond the limits of the embankment or the building. Any utilities or other subsurface features should be shown on these drawings because they might affect the dynamic compaction operations. If some areas are designated for one type of tamper and drop height, these areas should be differentiated. The quantity of area to be dynamically compacted should be shown on the drawings.

- Equipment Required - The tamper mass and the drop height should be calculated in advance to match the depth of required improvement and the soil type and not left up to the contractor. The range in contact pressure of the tamper should be specified. It should also be pointed out that the tamper must be raised and dropped with a single cable with a free spool drum or by free fall methods.

In order to complete the job on a timely schedule, either the number of pieces of equipment should be specified or a starting and completion date should be given so that the contractor can plan the proper number of pieces of equipment to complete the work within the time frame.

- Energy Application - The amount of energy to apply at ground surface should be specified. If different energy levels are to be specified for different areas, these areas should be clearly delineated on the drawings.

  The grid spacing, number of drops at each grid point, and number of passes required should be specified. A maximum crater depth that can be tolerated for each pass should be specified. If this crater depth is reached before the desired number of blows is reached, either the crater must be filled before applying additional blows or an additional pass or passes are required after ground levelling, so that the specified applied energy is imparted.

  After the primary energy has been applied, the amount of energy to apply during the ironing pass to compact the surface of the deposit should be specified. If the surface is to be compacted with conventional compaction equipment instead of an ironing pass, this should also be specified.

- Backfill and Ground Leveling - If a backfill material is required to raise the grade or to provide a working mat on weak ground, the thickness and type of backfill should be specified. The specifications should state when additional fill is to be brought in to fill craters.

  On most projects fill is not required either in advance or during dynamic compaction. In this case, the contract should state that ground leveling be undertaken after each pass using a dozer to blade the ground from the high areas into the craters and to track roll the surface. This is necessary to form a smooth surface from which the equipment can work for the next pass as well as to obtain ground surface elevations.

- Required Testing - As the work is underway, certain tests should be performed to evaluate the effectiveness of dynamic compaction. These tests could include measuring crater depths, measuring heave adjacent to certain craters, determining ground losses from settlement readings following each pass, and borings with conventional soil testing. The specifications should state who will do this testing and how many tests will be performed. If the contractor is responsible for the soil borings, then the type of test and type of samples and sampling intervals should also be specified. If the owner is to perform some specialized testing within boreholes, such as pressuremeter testing, this should also be stated in the specifications, so the contractor can provide the proper equipment and money in the budget to compensate for time lost during this testing.

If dynamic compaction will take place adjacent to built-up areas, a seismograph should be used to measure the magnitude of ground vibrations being transmitted off site. The specifications should state who will be responsible for taking the readings, the frequency of readings and who will interpret the readings.

- Recordkeeping - Records should be kept of amounts of fill brought onto the site, the number of drops per day, the number of drops at each grid point, the number of passes completed to date, plus other general field records. The specification should point out who will keep these records and to whom they will be made available.

- Payment - An equitable form of payment for a method specification contract would be to have a lump sum for undertaking the dynamic compaction for the energies and area specified and then have unit rates for additional work. The additional work could consist of additional drops, where needed, or for undercutting and removing soil that will not compact properly and for replacement with new fill, where required. A separate bid item should be used for placement of granular fill as a working mat or to fill craters. These unit price items for work incidental to dynamic compaction will take some of the risk out of the total operation and allow the contractor to figure his budgets for the dynamic compaction work in the most economical fashion.

PERFORMANCE SPECIFICATION

If the design agency and/or their consultant do not have expertise in dynamic compaction, a performance type contract should be selected for the work. In this method, the design agency specifies the required degree and depth of improvement and the contractor selects the proper equipment to achieve this goal. The responsibility of the design agency in this case includes:

- Providing subsurface information including the geotechnical report to the bidders.
- Defining the extent of the area to be improved.
- Specifying the end product to be achieved. For instance, if the goal is to increase the SPT value, the minimum value at varying depths below grade should be specified.
- Listing the minimum prequalification requirements since the goal of this method of contracting is to obtain an experienced contractor to do the work.

The contractor assumes a greater risk with this type of a contract. If the equipment selected to do the work does not achieve the desired end product, the contractor must alter his field procedures and perhaps even use a heavier tamper or a larger drop height to achieve the goals. Normally, this work is undertaken on a lump sum basis and the contractor absorbs the additional costs. Under this type of contract, the contractor is responsible for:

- Selecting the tamper and drop height to achieve the depth of improvement required.
- Selecting the proper energy to apply to reach the required degree of improvement.
- Determining whether a stabilizing layer is necessary for a working mat.
- Selecting the grid spacing and number of passes.

- Providing sufficient equipment to complete the work within the required time schedule.
- Maintaining a safe operation to prevent accidents.
- Keeping records of the rate of progress and submitting monthly reports as well as a final report.
- Performing their own independent tests as a check on the depth and degree of improvement and comparing them with the owner's test results.

Only specialty contractors can undertake performance-based work because of the specialized nature of this work and the expertise required in dynamic compaction. Four or five specialty contractors experienced in dynamic compaction are based in the United States.

Guidelines for preparing a performance specification are included below. A typical performance specification is included in appendix C.

If a performance specification is used, the required improvement of dynamic compaction should be clearly stated so the contractors can plan the field densification program to meet this objective. Some of the important considerations to be included in the specifications are listed below:

- Project Description - A general description of the project should be provided in the specifications. Soil boring logs, the geotechnical report, property line surveys, topographic maps, and enough drawings showing the new facility should accompany the specifications to fully acquaint the contractors with the site conditions and the proposed new construction.

- Work Area - The extent of the area to be improved by dynamic compaction should be outlined on a drawing or set of plans. This would include the entire area of the embankment or building plus the extension beyond the limits of the new facility that is also to be improved. Any utilities or subsurface features should be shown on these drawings because they could affect the dynamic compaction operations. If a different amount of improvement is to be achieved in different areas, these areas should be differentiated on the drawings. The total square footage of area to be dynamically compacted should be shown on the drawings.

- Required Improvement - The amount of improvement to be achieved at the project site should be presented in the specifications. This means that a certain amount of engineering must be undertaken prior to writing the specifications by the owner or his consultant. First, it must be ascertained whether dynamic compaction is appropriate for the prevailing subsurface conditions. If appropriate, then determine the minimum improvements that are needed so that the new structure or embankment will function satisfactorily. For example, if dynamic compaction is done to reduce the potential for liquefaction under a design earthquake, the owner or his consultant could undertake an analysis which will show the minimum required SPT value at various depths or the minimum relative density at various depths. The specifications could then reflect the minimum SPT or relative density values that are needed at the depths of concern. The contractor is then free to select the right amount of energy to attain these minimum test values. If after application of all the energy the minimum values are not met in certain areas, additional energy must be applied to improve the soils to the minimum standards. The owner (designer) should not choose a value of soil improvement that cannot be achieved.

In certain cases where the minimum improvement needed at a site is difficult to predetermine, such as at a recent landfill site, the specifications could state that the amount of deflection of a test embankment after dynamic compaction shall be less than a certain predetermined value. The test embankment must be designed to induce the pressures imposed by the final embankment. The test embankment may not be a true indicator of the final performance of the embankment because some long-term decomposition of the landfill will take place and settlements will increase over a period of time. However, no better way exists of specifying performance of landfill sites when conventional testing will not work.

On projects where conventional soils are being densified, such as natural or fill deposits of sand or silt or mine spoil, conventional soil sampling techniques consisting of SPT, CPT, or PMT could be used to evaluate the stability and settlement of these deposits with and without dynamic compaction. Minimum values of SPT, CPT, or PMT following dynamic compaction could then be specified.

It is important that a sufficient amount of preengineering is performed to identify the problem and determine the minimum parameters that are required following densification to ensure that the structure or embankment will perform satisfactorily. The minimum parameters should then be made clear to the contractor in the specifications.

- <u>Prequalification</u> - Because the desired end product is stated in the specifications without the methodology to achieve this end product, only qualified contractors should be allowed to bid on these projects. The contractors will have to rely upon their previous experience, engineering ability, and judgment to determine the right amount of energy to apply, the grid spacing, time delays between passes, drop heights, and size of tampers to achieve the final goal.

  One method of prequalification would be to allow only contractors who have completed some number of successful dynamic compaction projects to bid for the work. The documentation should be presented at the time of the bid. An alternative method of prequalification would be to require the contractor to submit a detailed work plan and an equipment list at the time of bidding for the owner (designer) to evaluate as a condition of accepting the bid. This presumes that the owner (designer) is sufficiently knowledgeable to screen out inexperienced contractors.

- Time Duration for Dynamic Compaction - Some means of assuring that the project will be completed on time should be specified in the specifications. This could be accomplished most easily by providing a certain length of time for the work to be accomplished, thereby requiring the contractor to bring in the proper pieces of equipment to meet the schedule. An alternate method would be to specify a minimum number of dynamic compaction rigs, which at an average amount of production per day would also complete the work within time. The difficulty with the latter approach is that if there are equipment breakdowns or if there is poor weather, the time to complete the work might take longer than desired. With the first approach, the contractor might choose to work longer hours or on weekends to complete the work within the time schedule.

- Site Preparation - The condition and elevation of the existing site should be discussed in the specifications. If site preparation is required prior to dynamic compaction, it should be stated whether it is part of the dynamic compaction bid or whether some other subcontractor will be handling it. Site preparation could include removal of trees or surface debris, flattening a hilly terrain to a more nearly level surface, or placing new fill to change the grade. When this work is undertaken with a different subcontractor the specifications should be clear as to what the grades and condition of the area will be at the time of the dynamic compaction.

- Required Testing - To confirm that the minimum value of improvement has been achieved, certain tests must be performed. This would include SPT, CPT, or PMT tests in boreholes or monitoring of test embankments with settlement plates to determine the amount of ground deformation under load. Whatever method is selected for evaluating the improvement should be clearly spelled out in the specifications. One test method should be selected as the acceptance criteria to avoid confusion in the event that two or three different test methods all show different degrees of improvement. It should also be clearly stated who will perform these tests. Verification testing is generally done by the contractor. A representative of the owner should be present during the testing to provide quality control and interpret the tests. The specification should also detail how many tests will be performed and at what time intervals during the course of the project.

  If dynamic compaction is to be done adjacent to built-up areas, it will be necessary to specify that the contractor is required to obtain seismic readings to determine the magnitude of ground vibrations being transmitted off site.

- Recordkeeping - The contractor should be required to keep records of their operations. This would include, but not be limited to, grid patterns, drop heights, drop weights, number of blows, depth of crater penetration at each location, number of passes over the entire area, vibration readings, and ground settlement. The types of records that are kept should be agreed upon in advance and should be provided to the field engineer throughout the project.

- Payment - Work done on a performance basis is usually done on a lump sum basis. Separating the bid into itemized unit quantities is not possible because only the contractor knows what types of equipment will be provided at the site, how much energy will be applied, and whether any special additional work such as dewatering or bringing in more fill will be required. The contractor will include in the bid all the items necessary to undertake the work plus some engineering time for planning the dynamic compaction and for borings to monitor the work. The contractor must also include in the bid some additional funds to cover uncertainties and risks tht will tend to raise the bid price. On the other hand, an experienced contractor could use ingenuity and past experience to develop an economical field program to accomplish the goal, thereby off-setting some of the costs associated with assuming more risk.

  Exceptions to undertaking the work totally on a lump sum basis include landfill sites, since the quantity of granular material required to stabilize the surface of the landfill is usually unknown. Such contracts should be written for a lump sum for the dynamic compaction work with a unit rate for granular material to be brought in and placed over the area as required to maintain a stable ground surface.

COORDINATION BETWEEN DESIGNER AND SPECIFICATION WRITER

Close coordination between the design engineer and the person writing the specifications is essential. The designer has become familiarized with the project site by studying the subsurface conditions from the borings or test pits and has used guidelines and judgment in determining the proper approach and equipment required to successfully complete the dynamic compaction. This information needs to be conveyed via the specifications to the contractors, who are usually unfamiliar with the site but must prepare a proper bid.

Information gaps between the designer and the specification writer will result in information either not properly conveyed or understood by the contractor. Many times, the specifications contain standard language information that is not meaningful for a particular project site. This only tends to confuse the bidders and increase the bid price.

Consequently, the designer should work closely with the specification writer as a team so that a meaningful and clear specification can be produced to avoid confusion by the bidders. A commentary prepared by the designer indicating the intent or objective of the densification program would provide the bidders a better understanding of the designers' concerns. This commentary would be a non-binding part of the specification but would solicit cooperation between the designer and the contractor to work as a team to accomplish the goals of the densification.

CHAPTER 5
CONSTRUCTION MONITORING

INTRODUCTION

Monitoring of dynamic compaction should be undertaken to confirm that the work is completed in accordance with the specifications. Furthermore, a trained observer can determine if adjustments in the energy application or the total applied energy need to be made while the work is underway. Normally, dynamic compaction is undertaken on fill deposits that are quite erratic in composition. For example, field adjustments may be required if unusually loose pockets or soils that won't densify by dynamic compaction are present.

While dynamic compaction is underway, observations coupled with measurements should be made of:

- Ground heave and pore water pressure.
- The average induced settlement following application of the energy.
- Vibration monitoring.
- Soil borings with in situ testing or, alternatively, load tests.

Table 10 lists the type of monitoring to be undertaken and the action item pertinent to each observation or measurement. Details are presented in the following sections.

GROUND HEAVE AND PORE WATER PRESSURE

Ground heave was discussed in chapter 3, but a few additional comments relative to construction monitoring of ground heave and pore water pressure measurements are appropriate. Field personnel should observe the change in the surface of the land mass adjacent to the craters following the application of energy in any given area. A rise in ground surface between drop point locations is an indication of plastic soil deformation associated with high pore water pressures. Multiple passes with enough delay time allowed between passes can reduce the detrimental effect of heave on the ground improvement. Pore water pressure measuring units can be used to ascertain when the pressures dissipate sufficiently to allow for resumption of tamping. Rapid response piezometers should be used because the time between drops is less than 1 minute and it is essential to know the change in pore water pressure with each drop.

Heave which cannot be controlled even by delayed time between passes is an indication of a very saturated soft material that is not suitable for improvement by dynamic compaction. This deposit may need to be excavated and replaced with a more suitable material. Alternatively, if the weak deposit is not too thick, stabilization may be possible by the addition of a granular material that is driven into this deposit to intermix, resulting in a more favorable densified deposit. Figure 23 illustrates a ground heave between the drop point locations.

Table 10. Construction monitoring.

Type of Monitoring	Action Item
A. Site Observations	
1. Crater depths	If greater than height of tamper plus 0.3 m, stop energy application, level ground, and resume drops.
2. Ground heave	This is a sign of excess pore water pressure in deposit. Take site measurements (item B) and adjust drops.
B. Site Measurements	
1. Ground heave	Measure ground heave with elevation readings on pins embedded in ground at various distances from crater. If incremental volume increase in crater is equal to volume of ground heave, stop dynamic compaction. Allow excess pore water pressure to dissipate before resuming work. Take additional heave readings.
2. Pore water pressures	Install piezometers in saturated fine-grained deposits to measure pore water rise and dissipation during impact. Use data to adjust number of passes or phases required.
3. Induced settlement	Measure surface settlement on grid basis before and after dynamic compaction. Settlement should be 5 to 10 percent of the improved layer thickness except in landfills.
4. Ground vibrations	Use seismograph on ground adjacent to buildings or over buried utilities. Compare measured particle velocity with permissible values.
C. Verification Tests	
1. Standard penetration test (SPT) Pressuremeter test (PMT) Cone penetrometer test (CPT) Other in situ tests	Compare SPT, PMT, and CPT values after dynamic compaction with values before dynamic compaction to check depth and degree of improvement. If data is obtained while the dynamic compaction equipment is on site, additional energy can be applied if needed.
2. Load tests	For landfills and nonhomogeneous deposits, load tests before and after dynamic compaction are sometimes used. Load is applied with a soil stacked to heights of 9 to 11 m over a settlement monitoring plate.
3. Energy at impact	If there is a doubt about the efficiency of the equipment to deliver the required energy, measurements of the tamper velocity can be made with a radar gun. The kinetic energy can then be calculated.

Figure 23. Ground heave induced by dynamic compaction.

INDUCED SETTLEMENT

Before dynamic compaction begins, surface elevation readings should be obtained on a grid basis to establish the approximate ground surface. Following application of the energy, the ground should be levelled using a dozer to blade the soil between the craters into the craters. Elevations should be obtained on the same grid basis to determine how much the ground has compressed. For most projects, the induced ground settlement generally ranges from 6 to 10 percent of the thickness of the deposit being densified. In recent landfill deposits, the ground compression can be on the order of 20 to 25 percent of the thickness of the landfill.

Field personnel will have an idea of how well dynamic compaction is proceeding if readings of induced settlement are taken as the work is underway. In addition, if elevation readings indicate the ground has depressed significantly more in one area versus the remainder of this site, this could be an indication of a looser than normal deposit. Further exploration with test pits or even borings will determine whether additional energy needs to be applied.

GROUND VIBRATIONS

In an urban area or if off-site facilities are located nearby, vibration readings should be taken using a seismograph. The vibration readings should be monitored at varying distances from the point of impact to determine the peak particle velocity occurring in the ground adjacent to the facility of concern. As long as the particle velocity measurements are below the permissible values, dynamic compaction can proceed as planned. However, if the values exceed the minimum, alterations in the dynamic compaction process would have to be made either by reducing the drop height or by constructing a trench to reduce the transmission of vibrations off site.

Communication with persons in adjacent areas is important. It is helpful to meet with the people to discuss the proposed monitoring to put them at ease. Even if the vibration readings are well below danger levels, people will feel the vibrations and become concerned. Sufficient vibration readings should be obtained and recorded in the event adjacent property owners file a complaint. The recorded information would be useful to allay suspicions and fears of the adjacent property owners.

Condition surveys should be made of nearby structures to observe and record existing cracks or distress prior to dynamic compaction. Additional observations should be made after completion of the work. Dated photos or videos should be made of the most crucial structures.

VERIFICATION TESTING

Complete some of the soil borings with in situ tests before the dynamic compaction equipment leaves the site to determine if the required depth and degree of improvement has been attained. A decision can be made at this time as to whether the improvement has essentially been achieved. It has been found by numerous investigators that the soil properties improve with

Figure 24. Load test.

time. [32,42,51] To measure the delayed improvement, additional soil borings and in situ testing should be taken approximately one month after dynamic compaction is finished.

On some sites such as loose underconsolidated landfill deposits, especially of recent origin, conventional soil sampling and in situ testing may be meaningless. In these deposits, load tests have been performed to evaluate the effectiveness of dynamic compaction. Generally, load tests are performed before and after dynamic compaction to determine the reduction in settlement as a result of densification. Figure 24 shows a load test set up at a field site. The vertical pipe extending above the top of the stockpile is connected to a steel plate buried within the loose deposit. Figure 25 shows the results of one load test performed before and after dynamic

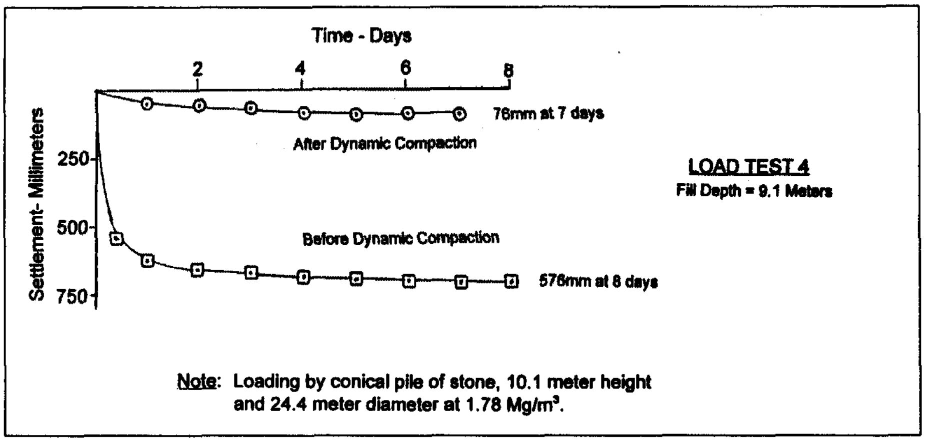


Figure 25. Results of a load test.

compaction at a project site. Ordinarily, the readings are taken for a period of at least 7 days or at least until the settlement readings stabilize.

At sites such as minespoils or landfills, the SPT values after dynamic compaction are frequently the same order of magnitude or only slightly better than the SPT values before dynamic compaction. However, the ground subsidence has reached reasonable values such as 5 to 10 percent of the original thickness of the formation, which indicates that densification has taken place. At these same sites, pressuremeter tests have frequently shown significant improvements. The reason for the discrepancy between the different methods of field testing is that the pressuremeter test measures the stiffness of the soil deposit, which is one of the primary reasons for dynamic compaction. The increase in stiffness results in the reduction in compressibility of the soil mass. In the standard penetration test, the sampling method is insensitive to the stiffness because of the remolding of the soil as the sampler is being driven.

Deposits that are more granular generally exhibit a marked increase in the SPT value following dynamic compaction because of the interlocking of the soil grains as a result of densification.

Another verification measurement that can be undertaken is to record the actual velocity of the tamper just prior to impact. From the velocity measurement, the energy delivered from a single drop can be calculated. Measurements of efficiency of a single drop have been made as part of the FHWA study. [32] Subsequent to this investigation, additional measurements of tamper velocity have been made. Table 11 summarizes these results. For a tamper with a single cable, the measured velocity at the point of impact is about 90 percent of the theoretical velocity for a tamper falling in a vacuum. The results are fairly consistent for different size tampers and different geographic locations. However, measurements can be made at any specific project site using a radar gun to measure the velocity of the falling tamper to see if the equipment is performing satisfactorily.

Table 11. Velocity of Tamper Prior to Impact.[28]

Site	Tamper Weight (Mg)	Drop Height Less 0.6 m (m)	Theoretical Velocity (m/sec)	Measured Velocity (m/sec)	Ratio V Measured / V Theoretical
Becancour, Canada	15	3	7.7	7.1	0.92
		6.1	10.9	9.6	0.88
		17.7	18.6	16.8	0.90
Tulsa, Oklahoma	16.3	5.5	10.4	9.3	0.9
		11.6	15.1	13.1	0.87
		22.3	20.9	18.3	0.88
St. Mary's, Georgia	29 (Free Fall)	29.9	24.2	23.8	0.98
		29.9	24.2	23.6 (Radar)	0.97
Great Lakes, Illinois	5.4	5.5	10.4	9.5	0.91
		10.1	14.1	13.0	0.92
Roseville, California	31.8	33.5	25.7	23.8	0.93
Vernal, Utah	27.2	32.9	25.4	23	0.9

Note: 1.) The laser device extends 0.6 m above grade so the drop heights were adjusted accordingly.
2.) The tampers at all the sites except the Georgia site were lifted by the cranes using a single cable and a free spool drum. The tamper at the Georgia site was lifted by cables but then allowed to drop free fall.
3.)The energy of impact can be calculated as $\frac{0.5(W)(V)^2}{g}$ where g = acceleration of gravity.

OWNER AND CONTRACTOR RESPONSIBILITIES

The responsibility for the monitoring will depend to some degree on whether the job is structured as a method or a performance specification.

If a method specification is selected, the owner should provide the monitoring services to ascertain that the intent of the owner's design objectives and the intent of the specifications are being fulfilled. Depending upon ground response, adjustments in the field operation may also be necessary so the owner's field representative can communicate this information through the proper channels and get field changes authorized.

If a performance specification is selected, the contractor generally provides field monitoring and the verification borings to confirm that the minimum design value of SPT, CPT or PMT is met. The contractor will adjust the field densification program as necessary to obtain the desired result. For these projects, it is still useful to have an owner's field engineer on the project to monitor, record, and interpret the dynamic compaction operations in case questions or disputes arise later.

CHAPTER 6
ADJUSTMENTS DURING DYNAMIC COMPACTION

MULTIPLE PHASES AND PASSES

During the design stage it is difficult to determine if it will be necessary to use multiple phases or passes. If the soils are highly permeable or have a low degree of saturation, one phase and one pass of energy application should be sufficient. If the soils have a moderate to low permeability, such as the zone 2 or 3 soils of figure 5, and the deposits are near full saturation, high pore water pressures will develop during impacting. Sometimes the high pore water pressures cause surface boils as seen in figure 26. This will result in water rising into the craters or ground heave adjacent to the craters. Whenever this occurs, dynamic compaction should cease until the high pore water pressures dissipate. In these deposits, multiple phases and multiple passes should be used.

Figure 26. Sand boil formed from dissipation of pore water pressure in silty sand.

In between these two extremes of high and low saturation and field permeability, judgement coupled with some field experimentation will be required to plan the proper phase sequence and number of passes. The initial portion of the dynamic compaction field work should be planned as a test section to refine the best sequence of energy application.

THICKNESS OF GRANULAR WORKING MAT

If the surface soils at a site are very soft, the tamper could plunge into the ground to a depth greater than the height of the tamper. When this occurs, the tamper will be difficult to extract from the ground because soils could cave on top of the tamper and suction forces may develop as the tamper is extracted. This can result in cable damage and a reduced production rate.

Whenever sites are very soft at the ground surface, a working mat of granular material should be used. The purpose of the granular material is to prevent the sticking of the weight and deep penetrations of the tamper into the deposit. The thickness of the stabilizing layer should be limited so that the tamper does not lose its effectiveness for deep densification. A thick granular layer also increases the costs. The thickness of the granular mat could be adjusted as the work is underway.

GROUND WATER CONTROL

At sites where the ground water table is closer than about 2 m from ground surface, the depth of the craters might approach the water table, and the effectiveness of dynamic compaction will be reduced. At some sites, drainage ditches have been dug along the perimeter to lower the ground water table. At other sites, the grade has been raised by the placement of fill to provide a greater distance between the water table and the working surface.

If raising the grade or dewatering in advance of dynamic compaction is not possible, then water must be pumped from the craters as the work is underway. Stone or other granular material must also be added as the craters are being formed so that the dynamic compaction is always being undertaken from a higher level.

GROUND VIBRATIONS

If dynamic compaction will be undertaken in close proximity to adjacent facilities, vibrations will be transmitted to adjacent structures. Methods for predicting ground vibrations were discussed in chapter 2, but field measurements of ground vibrations are necessary. Soils are a complex medium and vibrations may be transmitted to greater or lesser magnitudes than predicted. The dynamic compaction energy should be regulated to keep the ground vibrations below damage level. This can be accomplished by adjusting the drop energy, digging isolation trenches, or densification in layers as discussed in chapter 2.

BURIED ENERGY ABSORBING LAYERS

Frequently fill deposits contain a layer of a softer fine-grain deposit such as clays or organic materials that are nearly saturated. These deposits act as energy absorbing layers and do not transmit the full energy to the underlying deposits. A thorough subsurface exploration in advance will generally reveal the presence of these layers. However, isolated pockets may be present at the site and may have to be dealt with only after the work is underway. Additional energy could be applied in these locations. If the weak deposits are close to the ground surface, they can be undercut and replaced with a more suitable material. Alternatively, coarse granular material can be introduced into these deposits and stabilized by intermixing the coarse granular materials with the fine-grain soils.

CHAPTER 7
CASE HISTORIES AND DESIGN EXAMPLES

INTRODUCTION

Two case histories are presented in this chapter to illustrate the dynamic compaction design and planning and also to indicate the results obtained. Each case history follows a certain format.

First, the type of project is described along with the structural loading and design requirements. In addition, the typical soil profile is shown.

The second portion of the example uses the guidelines suggested in this manual to determine the anticipated depth of improvement for the tamper and drop height selected, the amount of energy to apply to achieve the improvement, and the anticipated degree of improvement.

The third portion of the example shows the actual energies used at the job site plus the measured improvements.

Finally, there is a commentary at the end illustrating the lessons to be learned from that particular case history.

DENSIFICATION OF A LANDFILL DEPOSIT

Introduction

A highway embankment was constructed over a landfill that had been closed approximately 13 years. The thickness of the landfill typically ranged from 7.3 m to 8.2 m but was found to be as deep as 9.1 m at one location. The landfill was operated from 1965 to 1975 and then covered with 0.6 m of clay. Methane gases were still exiting from vent pipes installed in the landfill at the time the initial soil boring investigation was made. However, the majority of the highly organic materials had already decomposed. The landfill was described as a mixture of soil that is primarily silts and clays with wood, cinders, glass, and brick fragments. Figure 27 is a generalized profile through a portion of the area.

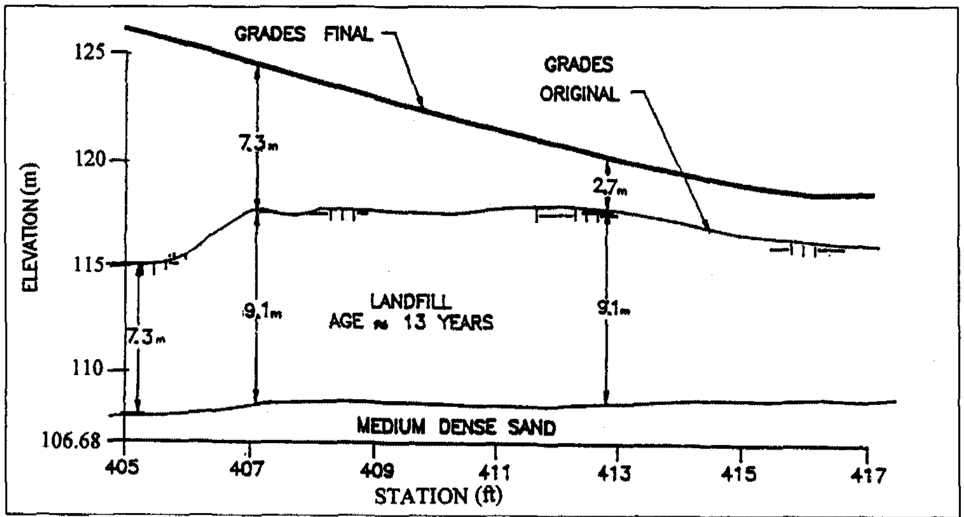


Figure 27. Cross section of highway embankment over landfill, Indiana.

Standard penetration tests performed prior to site improvement indicate SPT values ranging from about 5 to 25 with an average of 13. A typical SPT profile is shown in figure 28.

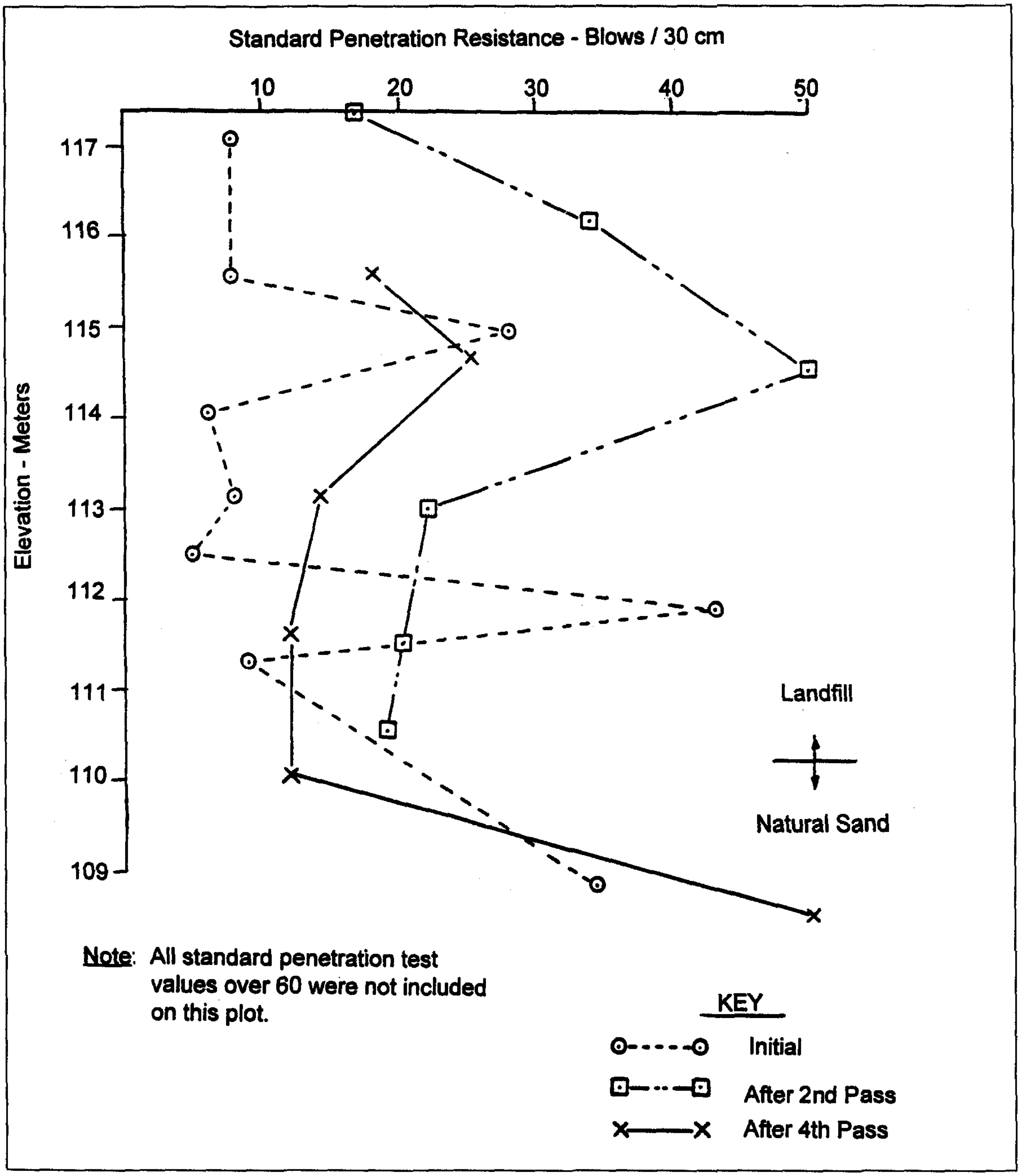


Figure 28. Increase in SPT values with energy application.

Pressuremeter tests were also performed in the fill deposits prior to dynamic compaction, and the variation in pressuremeter parameters in the fill is shown in figure 29.

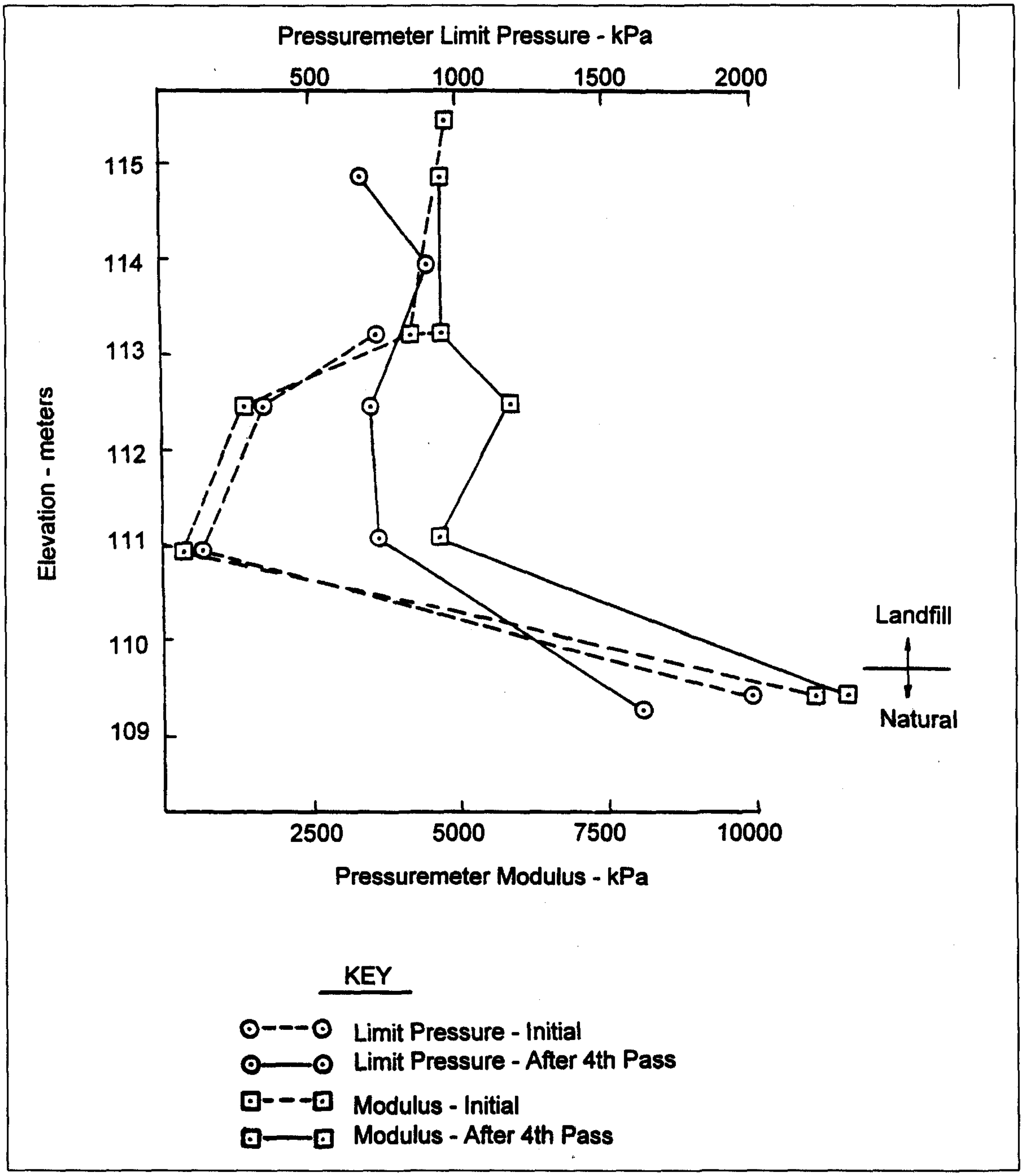


Figure 29. Increase in PMT values with energy application.

The new embankment to be built on top of the landfill was to range in height from a low of 2.7 m to as much as 7.3 m. In the area where the embankment height was the greatest, the prediction of settlement for the typical existing conditions ranged from 43 to 74 mm. Secondary settlement was estimated at 200 mm. Because of the possibility that there could be voids and loose pockets within the landfill, dynamic compaction was selected to reduce the anticipated differential settlement. Because the surface of the landfill was quite soft, a 0.6 m thick layer of crushed stone was specified as a working mat.

DYNAMIC COMPACTION CONSIDERATIONS

Typical grain size gradation tests of the landfill deposits are shown in figure 30. The significant number of fines within the formations resulted in the deposit being ranked as a Zone 2 type of soil for dynamic compaction (see figure 5). This means that the soils will densify, but phasing of the energy application and/or multiple passes are required because the generation of pore water pressures will take some time to dissipate. The dynamic compaction method specification prepared for this project is included in appendix B.

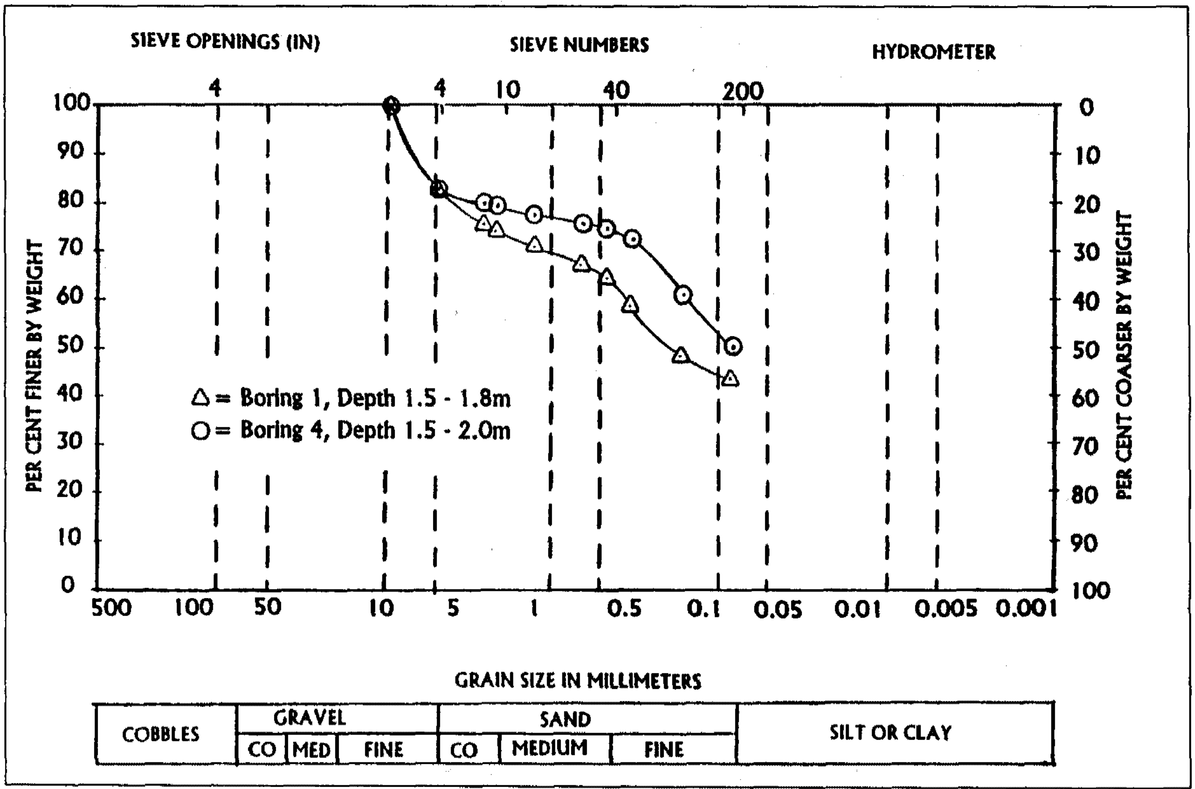


Figure 30. Gradation of landfill deposits, Indiana site.

For a desired depth of improvement of 8.2 m and an empirical *n* value of 0.35, the required energy per blow (*WH*) computes to 5.4 MJ. The contractor had an 18.2 Mg tamper so the drop height was selected at 29.9 m. This provides an energy per blow of 5.35 MJ.

Using table 8 for applied energy requirements as a guide, the suggested applied energy for a landfill would be in the range of 600 to 1100 kJ/m^3. Because this deposit is of middle age, and not in a loose condition except in local areas, the unit applied energy was selected at 735 kJ/m^3. For an 8.5 m depth of improvement, the suggested total applied energy comes to 6.25 MJ/m^2. This energy should be applied in increments to allow for pore water pressure dissipation during energy application. Two phases with two passes per phase was selected.

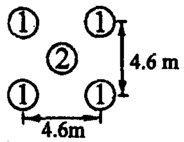
The maximum anticipated degree of improvement following dynamic compaction according to table 2 would be an SPT value in the range of 20 to 40 and a limit pressure between 0.5 and 1.0 MPa. These are upper bound values, and the degree of improvement could be less depending upon the amount of energy applied. Based on this anticipated final value of SPT or PMT value, the amount of immediate settlement under the 7.6 m embankment was calculated to be about 25 mm to 152 mm, respectively, which was considered acceptable.

Actual Project Records

The work pattern followed at this site is shown in table 12. Two phases of energy application labelled drop points 1 and 2 were made throughout the area. Two passes were also made at each point. The total applied energy was 6.7 MJ/m^2. The measured ground compression after dynamic compaction calculated to be 10 percent of the thickness of the landfill. The contractor placed a 0.9 m thick working mat of crushed stone prior to dynamic compaction. Figure 31 is an aerial view of the site illustrating the widely spaced drop point locations of phase 1 plus the working blanket of crushed stone.

Table 12. Work pattern at Indiana landfill site.

Work Pattern - Indiana Landfill



Tamper: 18.2 Mg
Drops: 6 from 29.9 m
Working Mat: 0.9 m

Phase 1, 2 passes	E = 3.12 MJ / m^2
Phase 2, 2 passes	E = 3.12 MJ / m^2
Ironing pass	E = 0.42 MJ / m^2
	E = 6.66 MJ / m^2

$$\text{Unit Energy} = \frac{6.66\ \text{MJ}/\text{m}^2}{9.15\ \text{m}} = 0.73\ \text{MJ}/\text{m}^3$$

$$= 1.20\ \text{Std. Proctor}$$

SPT and PMT tests were performed at approximately the same location as the tests prior to dynamic compaction, and the results are shown on figures 28 and 29. The pressuremeter modulus after dynamic compaction was approximately 3 to 5 times larger, and the limit pressure also experienced a similar increase. However, the SPT results after the fourth pass of dynamic compaction were only slightly higher than the initial values. The SPT after the second pass was higher than after the fourth pass, which is unusual. This is attributed to the variability of landfill deposits.

Three static load tests were performed before and after dynamic compaction using a 10.7 m high conical pile with a settlement plate embedded at the original ground surface. Readings were taken prior to placement of the fill and for 7 days after placement. One of the load test results has previously been presented in figure 25. Before dynamic compaction, the ground compression ranged from 0.37 m to 0.58 m. After dynamic compaction, load tests taken at an area immediately adjacent to the initial tests indicated ground compressions ranging from 0.07 m to0.14 m. This represents a reduction on the order of 4 to 5 times in settlement, which agrees with the approximate increase in pressuremeter modulus and limit pressure.

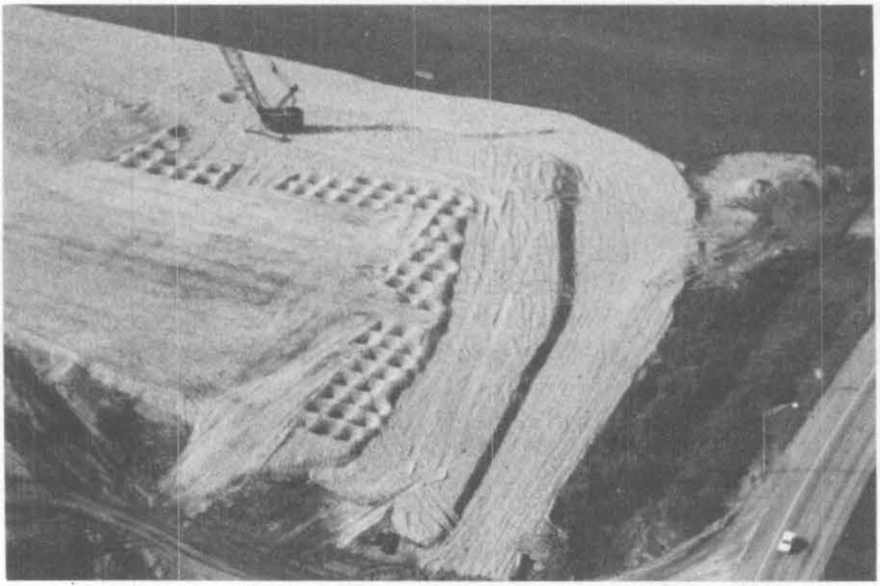


Figure 31. Aerial view of dynamic compaction operation.

Settlement readings taken while the landfill was constructed and immediately thereafter indicate a movement on the order of 180 mm where the embankment height was 6.4 m, 117 mm where the embankment height was 3.4 m, and 66 mm where the embankment height was less than 1.5 m. Unfortunately, long-term readings were not obtained at this site because some secondary compression of the landfill was anticipated for a period of years after construction.

Important Conclusions From This Project

- The depth of improvement of 7.6 m to 9.1 m was reached with the 18.2 Mg tamper and drop height of 29.9 m. This was confirmed by the increase in limit pressure and modulus of the pressuremeter test.
- The energy that the contractor used for densification was almost the exact value given in the guideline table 8. The upper bound PMT limit pressure value of 1 MPa was reached or even slightly exceeded following dynamic compaction. However, after the fourth pass, the SPT showed only slight improvement. The SPT after the second pass showed more improvement.
- Prediction of settlement based upon SPT and PMT tests before dynamic compaction was misleadingly low. In underconsolidated deposits such as landfills, the use of conventional settlement prediction procedures not appropriate because the deposits are still consolidating under their own weight.[24] The prediction of post densification settlement by the PMT agreed with the load test and measured settlements.

DENSIFICATION OF LOOSE POCKETS AND VOIDS

INTRODUCTION

A three-story structure was planned over an 8000 m^2 site in Florida. The structural loads were relatively light; but the initial subsurface exploration indicated the presence of sinkholes and voids due to dissolution of the limestone formations. In addition, there was a large amount of heterogeneity in the subsurface profile throughout the site, which led to large predicted differential settlements.

A typical boring log is shown in figure 32. The predominant soil type is a silty fine sand grading to a fine sand with seams of sandy clay. The low SPT values are indicative of either a void or a soil that has collapsed into a void. Other soil borings that are not shown indicate a relatively dense soil profile especially where the calcareous materials within the silty sand have caused some cementation. Thus, the foundation support would range from very good load support on the cemented materials to very poor load support in the cavernous areas.

The initial soil profile led to settlement predictions ranging from 23 mm to 74 mm assuming no large collapse of voids. The resulting 51 mm differential settlement was considered too large for the structure to tolerate. In addition, the presence of a cavity a short distance below foundation level would result in a very risky design.

The designer indicated that shallow foundations could be used for this project provided the soils were made more homogeneous as far as load support and no voids were present within the depth range of 7.6 m to 9.1 m below ground surface.

DYNAMIC COMPACTION CONSIDERATIONS

The soils at this site are predominantly a silty sand formation that would place them into the Zone 2 category according to figure 5. This means that the soils would be suitable for dynamic compaction, but that multiple phases and/or passes would need to be made throughout the area since the generation of pore water pressures takes time to dissipate.

For a depth of improvement of 7.6 m, the use of equation 1 and an empirical n value of 0.4, the energy per blow (WH) computes to 3.56 MJ. The local contractor doing dynamic compaction had a 15 Mg tamper, available and for this size tamper the required drop height computes to be 24 m.

Using table 8 for applied energy requirements as a guide, the average applied energy would calculate to be approximately 300 kJ/m^3 multiplied by the required depth of improvement of 7.6 m,resulting in an average applied energy at the surface of 2.28 MJ/m^2. This energy should be applied with two phases and two passes per phase to allow pore water pressures to dissipate between each pass. Because of the possibility of voids or caverns at any location, additional energy might need to be applied where large ground depressions would occur.

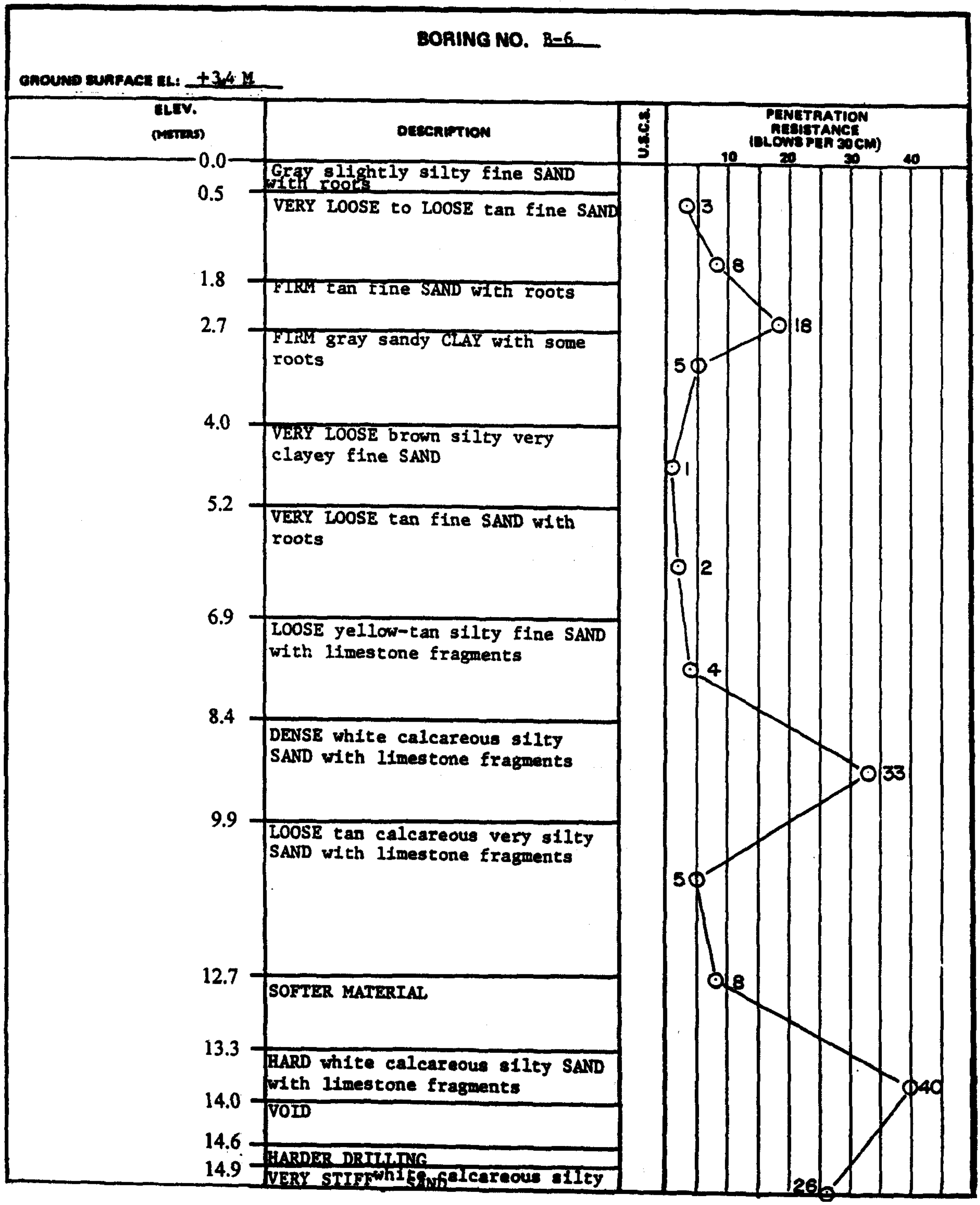


Figure 32. Soil boring log - Florida site.

The maximum degree of improvement following dynamic compaction according to table 2 would be an SPT value on the order of 35 and a maximum limit pressure of a pressuremeter test of 1.4 to 1.9 MPa. These are upper-bound values, and the degree of improvement would be less than this depending on the amount of energy applied.

ACTUAL PROJECT RECORDS

The site improvement was undertaken using a performance specification with a specialty contractor. The contractor selected a 15 Mg tamper and a drop height of 20 m. The energy was applied in 2 phases with 3 passes in the first phase and 2 passes in the second phase. Additional drops were made at sinkhole locations. The energy application is summarized in table 13. The average energy application was 1.6 MJ/m^2. The induced ground compression calculated to be 9.1 percent of the anticipated depth of improvement of 7.6 m.

Table 13. Florida project.

Phase	**Pass**	**Grid (m)**	**Location**	**Blows/print**	**Energy (kJ/m^2)**	**Induced Settlement (mm)**
1	1	9.1 x 9.1	Primary	8	281	121
1	2	9.1 x 9.1	Primary	9	317	98
1	3	9.1 x 9.1	Primary	9	317	70
2	1	9.1 x 9.1	Intermediate	9	317	97
2	2	9.1 x 9.1	Intermediate	10	352	93
Ironing		Over-lapping	Continuous	1	35	89
7		Void	At observed sink hole locations	10	---	
Total				Total of 8895 blows	1,619	694

A comparison of average SPT values taken before and after dynamic compaction is shown in figure 33. Although some improvement occurred in the standard penetration resistance values, the improvement is still less than one would predict. The specialty contractor felt the SPT values were somewhat misleading for this project. For this reason, pressuremeter tests were also performed before and after dynamic compaction. Figure 34 indicates the average limit pressure and pressuremeter modulus values before and at two time intervals after completion of the dynamic compaction. The limit pressure and the modulus show a relatively uniform degree of improvement with depth, which was one of the desired results, and the limit pressure is also in accordance with the predicted value shown in table 2.

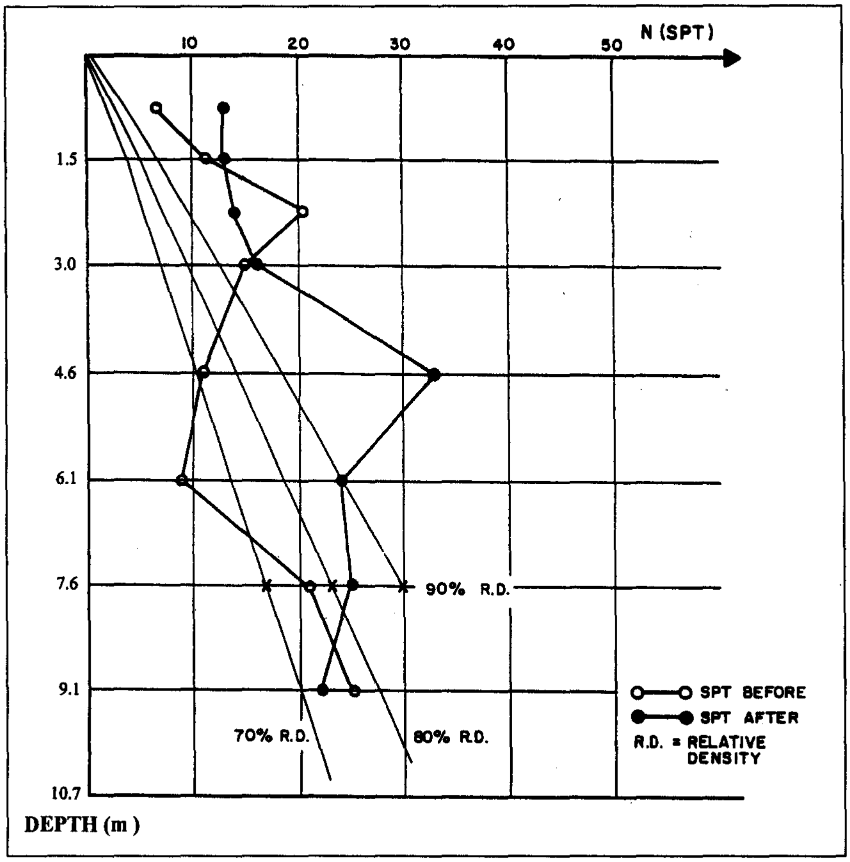


Figure 33. SPT values before and after dynamic compaction..

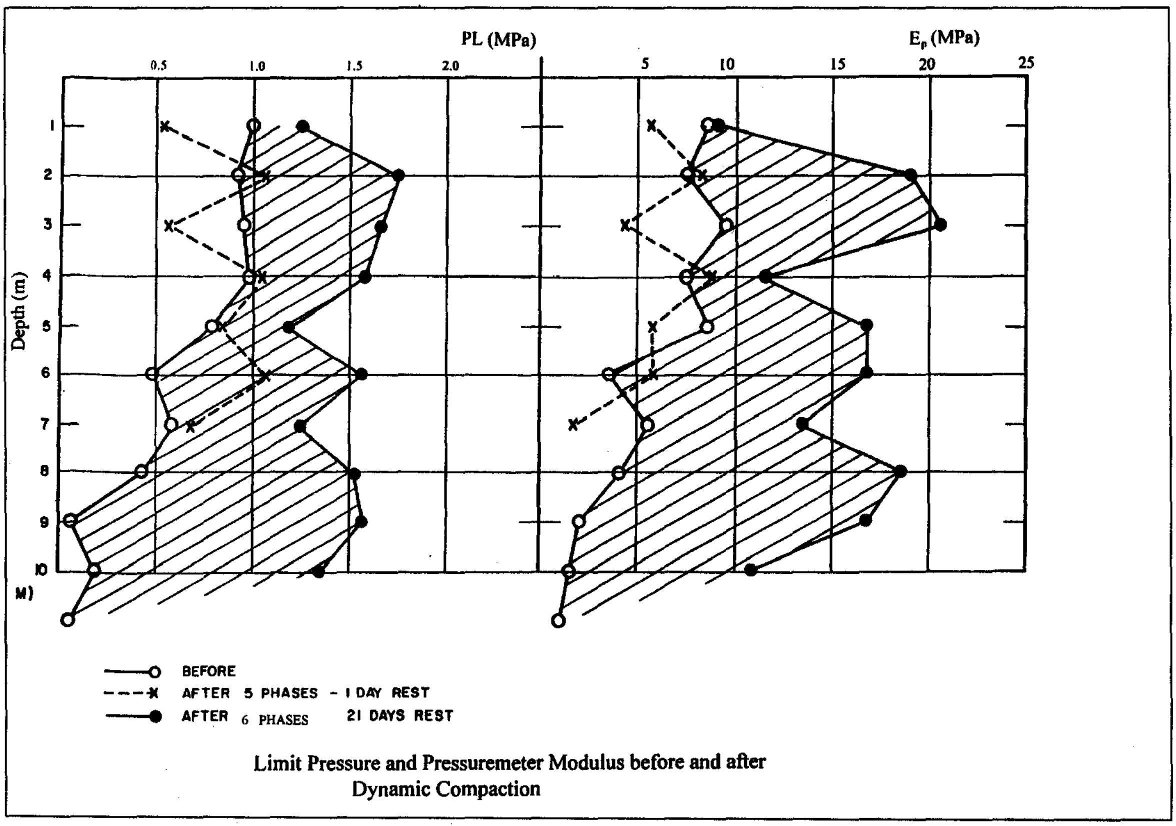


Figure 34. PMT values before and after dynamic compaction.

The pressuremeter test results performed at various intervals of time after dynamic compaction illustrate the improvement that takes place well after the energy has been applied.

During dynamic compaction, settlements were taken on a grid basis throughout the project site. Figure 35 shows the induced settlement contours following the first three phases of dynamic compaction. These contours indicate that there are two locations where the settlement is much greater than normal. This would correspond to approximate column locations K-6 and C-6. The greater settlement in these areas indicates the presence of cavities or very loose deposits. For this reason, additional energy was applied in these areas.

IMPORTANT CONCLUSIONS FROM THIS PROJECT

- The depth of improvement of 7.6 m was reached even though the energy per blow was slightly less than recommended by equation 1.

- The energy that the contractor used for densification was slightly less than suggested by table 8. The pressuremeter test shows good improvement was reached, but the SPT values show that there could have been more improvement if additional energy had been applied

- Plotting of the settlement pattern following different phases of energy application was very helpful in determining where cavities or sinkholes were present. In these areas, additional energy was applied.

- The increase in pressuremeter properties with time is clearly demonstrated by figure 34. This phenomena of strength increase following rest periods has been measured at many sites ranging from sandy soils to fine grain soils. Borings with tests made during dynamic compaction or immediately thereafter will therefore not measure the total improvement.

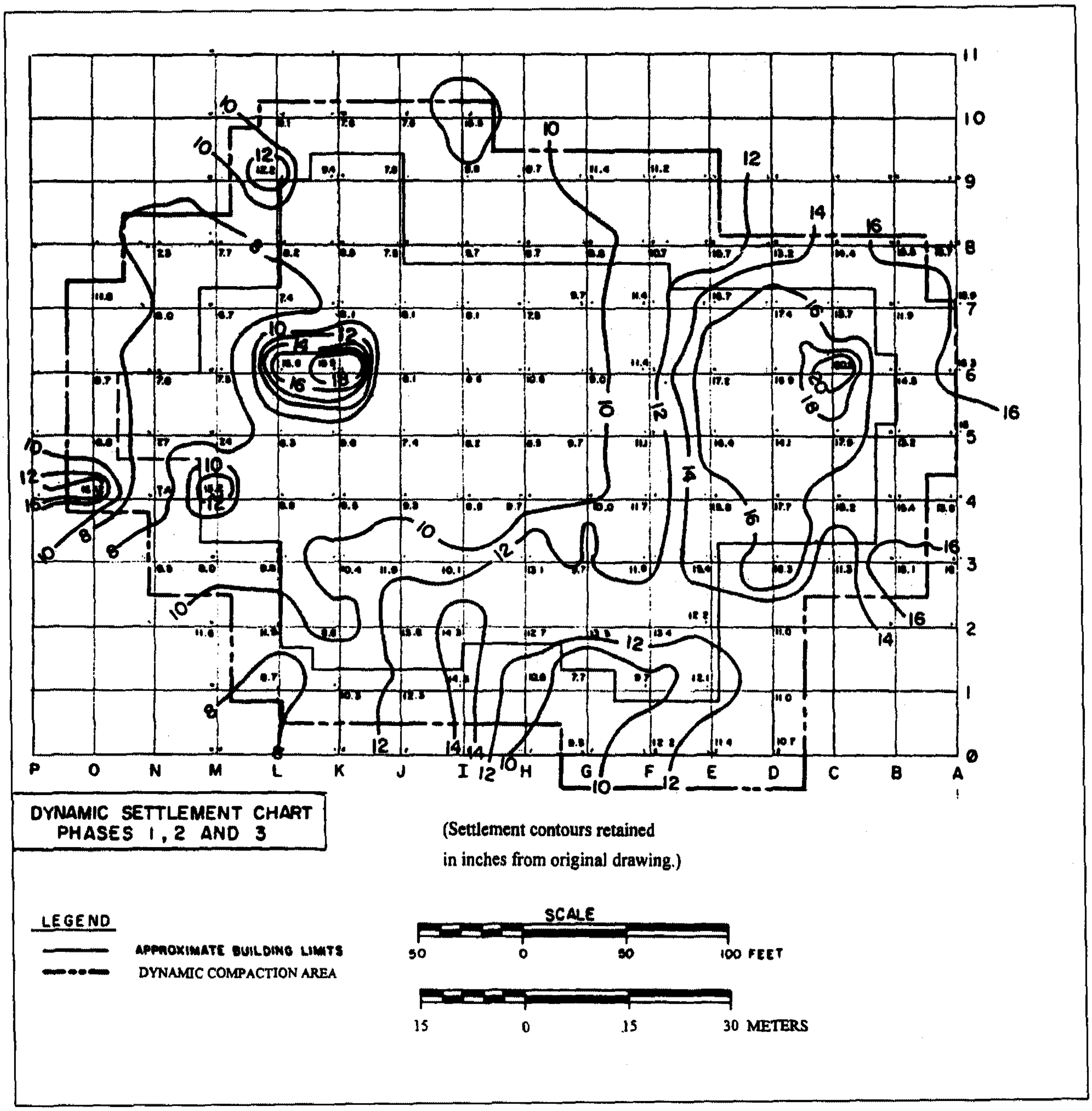


Figure 35. Induced settlement contours. Note the two locations of potential cavities at column lines K-6 and C-6.

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GLOSSARY

Certain words or terms unique to dynamic compaction are used in the text and are described as follows:

APPLIED ENERGY	Average energy applied at ground surface, which is calculated on the basis of the sum of all the energy applied by dynamic compaction divided by the surface area of the densified soil. The typical units are Joules per meter squared.
CRATER	Depression in the ground at the drop point location that results from energy application.
DEPTH OF IMPROVEMENT	Maximum depth to which measurable improvement is attained.
DROP ENERGY	Energy per blow, which is calculated on the basis of the tamper mass multiplied by the drop height.
HIGH-LEVEL ENERGY	Energy applied to cause densification to the depth of improvement.
INDUCED SETTLEMENT	Average ground settlement following densification, which is determined by elevation readings taken before and after dynamic compaction.
LOW-LEVEL ENERGY	Energy applied to compact the surface deposits to the depth of crater penetration following high-level energy application. Low-level energy application frequently is called the ironing pass.
PASS	The application of a portion of the planned energy at a single drop point location. Multiple drops are required to deliver the energy at each drop point. If all the drops cannot be applied at one time because of deep craters or excess pore water pressures, another pass or passes will be required after excess pore water pressures dissipate or the craters are filled with granular fill. There is generally a waiting period of at least a few days between passes.
PHASES	Describes the pattern in which the energy will be applied. For example, every other drop point of the grid pattern could be selected to be densified as Phase 1. After completion of Phase 1, the intermediate drop points could be densified as Phase 2. Some projects use only one phase but others have been undertaken with five phases.

APPENDIX A
TYPICAL METHOD SPECIFICATION PREPARED FOR MISCELLANEOUS FILL

DESCRIPTION OF SITE

The existing fill deposits that are present below the proposed alignment of the mainline between approximate Stations 435 and 445, as well as the existing fill along the southeast ramp between approximate Stations 435 and 447 will be densified in place by dynamic compaction. The dynamic compaction operations will be undertaken prior to any embankment filling for the roadways.

Along the mainline, the thickness of the fill is typically on the order of 1.5 to 4.5 m in thickness, and consists primarily of clayey fill that was presumably placed as part of the railroad embankment construction. The thickness of the fill along the southeast ramp is typically on the order of 4.5 to 9 m and is a former landfill which contains miscellaneous types of fill deposits. Soil borings have been made throughout this area and the logs are included on Drawings ___.

DESCRIPTION OF DYNAMIC COMPACTION OPERATIONS

Dynamic compaction is a process whereby a heavy tamper is repeatedly raised and dropped from a specified height to impact onto the ground surface, thereby transmitting high compaction energy into the soil mass. The depth of improvement depends upon the tonnage of the weight and the height of the fall. The degree of improvement depends upon the amount of energy applied per unit area. The tamper shall be raised and dropped by a single cable with a free spool hoisting drum.

The tamper weight shall be constructed to resist the high impact stresses. The high energy compaction shall be applied in two phases which is designated on the drawings as the primary (first phase) and secondary (second phase) locations. After energy application at any primary location, there shall be a minimum waiting period of three days before energy application at the immediately adjacent secondary location. Multiple passes may be required to deliver the full energy. One pass is described as either of the following, whichever occurs first:

A. The application of all the specified drops at a grid point location, or
B. Whenever the crater depth reaches 1.5 to 2.0 m regardless of the number of drops at a grid point location.

After the last pass has been completed, the ground surface shall be levelled and a low-level energy pass called an ironing pass shall be applied. The ironing pass consists of dropping the tamper from heights of 4.5 m to impact the surface at a tight spacing.

DYNAMIC COMPACTION EQUIPMENT

The high energy dynamic compaction shall be undertaken with an 18.2 Mg tamper with a minimum 18 m drop height. The contractor shall provide the equipment capable of raising and dropping this tamper on a repeated basis without a significant amount of down time. The contractor shall also provide equipment to level the ground surface between passes.

The contractor shall provide a minimum of two cranes and two tampers for the dynamic compaction operations. Each tamper shall be 18.2 Mg and the contact pressure which is the weight of the tamper divided by the base area shall be in the range of 38 to 72 kPa.

The contractor shall stake (with wood lathe or wire markers with flags) all of the grid point locations as shown on figures. The tamper will be dropped with the staking accurate to the nearest ± 0.3 m. Following each pass and after the ground is level, the stakes or wire markers with flags shall be replaced for the next pass.

SITE PREPARATION

The site has been cleared of trees and surface vegetation. However, there is some surface debris, including chunks of concrete that may not be able to be broken up by the dynamic compaction operations that will have to be removed. The existing grade shall also be smoothed such that dynamic compaction takes place from an essentially level surface. This does not mean that ravines such as adjacent to the railroad shall be filled prior to dynamic compaction, since the intent of the dynamic compaction is to apply the energy from the existing grade. However, sharp vertical drops shall be flattened to provide access for the cranes for lifting and dropping of the weights. Small hills or stockpiles of miscellaneous rubble should be smoothed out and bladed to a more nearly level surface.

ENERGY APPLICATION

Drawing ___ indicates the limits of the dynamic compaction operation. Dynamic compaction is proposed along the mainline from Station 435 to Station 445, and along the southeast ramp from Station 434+75 to Station 447. The proposed drop point locations are shown on a grid spacing of 4.6 m center to center. The open circles or squares represent the primary drop points and the solid circles or squares are the secondary drop point locations.

The total area for dynamic compaction can be divided into smaller work sections with one section completed before another section is started. However, the contractor will level the ground at the end of each work day for safety reasons and to prevent ponding of water within the craters if rain were to occur. Within any one portion of the overall dynamic compaction area, the construction sequence shall consist of one pass of dynamic compaction at all primary drop point locations, followed by ground levelling and then one pass at the secondary drop point locations followed by ground levelling.

The proposed dynamic compaction work is divided into two portions, i.e., Area A and Area B. Different amounts of compactive energy will be applied in each area as discussed below.

Area A - Within this area, the fill depths range from 1.5 to 4.5 m and the fill is primarily clayey and is presumed to have been placed as part of the original railroad embankment construction. Within this area, 1.6 MJ/m^2 of energy will be applied exclusive of the ironing pass. This energy application can be achieved with a total of five drops at each grid point location using the 18.2 Mg tamper and 18 m drop. It is anticipated that this amount of energy can be applied in one pass. However, energy application will stop if the depth of the crater exceeds 1.5 to 2 m as measured from the ground surface. Whenever this occurs the ground will be levelled and an additional pass or passes will be applied to administer the remaining drops.

After five total drops have been applied at each grid point location, an ironing pass will be used to densify the upper portion of the land mass. The ironing pass will consist of three drops from a height of 4.6 m, with an 18.2 Mg tamper at a grid spacing of 3 m center to center. This will result in an additional 270 kJ/m^2 of energy application, raising the total amount of energy for Area A to 1.9 MJ/m^2.

Area B - Within Area B, the depth of the fill is on the order of 6 to 9 m and this is the site of a former landfill. The amount of energy that will be applied to this area is 5.4 MJ/m^2 exclusive of the ironing pass. This amount of energy can be achieved by a total number of 17 drops at each grid point location using the 18.2 Mg tamper and a drop height of 18 m. It will be necessary to apply this energy using multiple passes because of the crater depth limitation of 1.5 to 2.0 m per pass. At least two passes are anticipated. Between each pass, the ground shall be levelled and trackrolled to allow for passage of the construction equipment to apply the dynamic compactive energy.

After all 17 drops have been applied at all the grid point locations, an ironing pass will be used to densify the upper portion of the fill. The ironing pass shall consist of three drops from a height of 4.6 m with the 18.2 Mg tamper at a grid point spacing of 3 m center to center. This will result in an additional energy application of 270 kJ/m^2 for a total energy application of all energy within Area B of 5.7 MJ/m^2.

ADDITIONAL WORK

Because of the varying subsurface conditions of the existing fill deposits, some additional energy application may be required at select locations. This decision will be made in the field as the work is underway by the field engineer who is monitoring the operation. This additional work will be paid at a pro-rated rate based upon the bid item for energy application.

It may also be necessary to import granular fill such as coarse gravel, rubble, or broken rock to stabilize the upper portion of the soil mass in poor ground support areas. The need for additional fill will not be known until the project is underway. A pay item should be provided for granular backfill in the event granular fill is needed.

MONITORING

A. By State Highway Department Representative

As the work is underway, the dynamic compaction operations will be monitored and the monitoring will be paid for by the State Highway Department. The monitoring will include, but not be limited to observations of crater depths, monitoring ground vibrations adjacent to building, determining if heave is occurring adjacent to certain craters, deciding on the need for additional tamping at select locations or the need for importation of granular fill to stabilize weak ground. The monitoring will also include soil borings at select locations to determine the depth and degree of improvement.

B. By the Contractor

The contractor shall be responsible for obtaining ground elevations on a 30 m grid pattern. These ground elevations shall be made immediately prior to dynamic compaction and additional elevation readings will be taken following ground levelling after each pass of the dynamic compaction. The elevations shall be obtained at the same locations to determine how much ground loss was induced by the dynamic compaction. The contractor shall also be responsible for counting the number of drops at each grid point location to be sure that the proper energy is applied. If any additional tamps are requested by the field engineer, these shall also be recorded by the contractor. If granular fill is brought in at select locations, the contractor shall record the amount of fill that was hauled onto the site.

PROTECTION OF PERSONS AND ADJACENT PROPERTIES

A detailed safety program will be required to provide protection for job site personnel, off-site personnel, and adjacent properties. This safety program should be submitted prior to commencement of the work for review by the State Highway Department. The safety program should include required setback distances from the point of impact from the weight for personnel so that they are not within range of flying particles that may occur from impact of the weight into the ground. It should also include the manner in which the cable is attached to the tamper and the frequency of safety checks on the cable and associated equipment to prevent failure during dynamic compaction operations. Photographs should also be made of nearby structures that might be affected by the dynamic compaction operations and included with the safety plan submittal. All items associated with the safety program shall not be paid for separately, but shall be included in the cost of the dynamic compaction operations.

RECORDS

The contractor shall keep accurate records of the construction operation, i.e., the locations where the drops have been made, the number of drops per location, depth of crater penetration, the pass number, ground surface elevations following each pass, and these results shall be available in the contractor's trailer on a daily basis. On a weekly basis, this information shall be submitted to the field engineer representing the State Highway Department.

Any circumstances affecting the work or intended improvement as a result of dynamic compaction should be brought to the attention of the field engineer.

BASIS OF PAYMENT

The work to be paid for shall be the measured quantity in square yards of dynamic compaction as shown on the drawings. If additional work is necessary based upon field observations or borings made as the work is underway, this additional work will be paid for at the prorated energy rate per square yard basis as per the bid item.

APPENDIX B
TYPICAL METHOD SPECIFICATION
PREPARED FOR A LANDFILL

DESCRIPTION OF WORK

The work shall consist of increasing the density of the soil by Dynamic Compaction to the area and extent shown on the drawings. No compaction work shall be done on this project unless the water table is at least 2 m below the grade of the working areas. A 0.6 m thick layer of rock backfill shall be placed over the portion of the site to be densified.

BLANKET FILL

Prior to beginning dynamic compaction operations, the contractor shall level the terrain. Rock backfill shall then be placed over the landfill area to a thickness of 0.6 m. This material shall be graded and compacted to support the construction equipment during dynamic compaction. This work platform shall be graded to drain and shall be suitable for movement of large crawler cranes and other equipment. Rock backfill shall consist of quarry limestone or dolomite conforming to Class E or better requirements as set out in 903.02(b). The maximum size shall be 300 mm. The material shall not have more than 15 percent passing a 41 mm sieve and not more than five percent passing a 20 mm sieve.

After each pass, additional rock backfill shall be placed in the craters to raise the grade to prevailing level.

DEFINITION

Dynamic compaction is a process whereby a heavy tamper is repeatedly raised and dropped from specified heights to impact into the ground surface thereby transmitting high compaction energy into the soil mass. The depth of improvement depends upon the mass of the tamper and the height of the fall. The degree of improvement depends upon the amount of energy applied per unit area. The tamper is raised and dropped by either of two methods:

1. A single cable with a free spool hoisting drum.
2. A number of cables or single cable extending through a series of pulleys to lift the tamper, provided the tamper is dropped free fall.

The tamper is generally constructed of solid steel to resist the high impact stresses, however it could be constructed of another approved material.

SPECIFIC JOB REQUIREMENTS

The work area is shown on the drawings. It is identified as the BFI Landfill. In this area, municipal landfill extends to depths ranging from 6 to 9 m below present grade, except at the very edges of the landfill.

The contractor shall employ an 18.2 Mg tamper with a minimum drop of 23 m or as directed by the Engineer. The energy shall be applied on a grid system in two phases. The primary phase shall be completed with a grid spacing of 4.5 m. The secondary phase will also be undertaken at a grid spacing of 4.5 m but at locations intermediate to the primary locations. At least one week of time must elapse between energy application of the primary and secondary phases. The average energy to be applied to this area exclusive of the ironing pass is 6.3 MJ/m^2. This will require 16 drops at each grid point location. Energy application will cease if the depth of the crater exceeds 1.5 m. It is anticipated that eight blows can be applied at each grid point location. If a crater depth greater than 1.5 m occurs before the application of this energy, additional passes will be required. Following each pass, the craters will be filled with additional rock backfill and the ground levelled. Care should be taken to minimize the amount of material falling into craters from areas adjacent to the craters. After the 6.3 MJ/m^2 energy is applied, the ground shall be levelled and the upper soil mass densified with an ironing pass which is a low-level energy application applied over the entire surface. The average energy applied during the ironing pass shall be 450 kJ/m^2. Thus, the total energy applied from the primary through the ironing passes will be 6.75 MJ/m^2.

For the area designated as the Lambert fill site which is located south of the levee, the dynamic compaction shall be undertaken with a minimum 13.6 Mg tamper and a minimum 23 m drop or as directed by the Engineer. The energy shall be applied on a grid basis with a grid spacing of 4.5 m. The energy will be applied in three phases to result in an average applied energy of 3.6 MJ/m^2. This is exclusive of the ironing pass. No further energy will be applied at a grid point when the crater depth exceeds 1.5 m. Care should be taken to minimize the amount of material falling into craters from areas adjacent to the craters. This may require multiple passes to apply the full required energy.

The first phase of energy will be applied at 4.5 m centers, and the second phase at the same grid spacing at points intermediate to the first phase. The third phase will be applied at the same location as the first phase. Following application of this energy, the surface materials will be leveled and the upper soils compacted with an ironing pass. A minimum energy of 400 kJ/m^2 shall be applied during the ironing pass. Thus, the total energy applied to this area will be 4 MJ/m^2.

The unit contact pressure of the base of the tamper applying this high energy shall be in the range of 42 to 60 kPa. The unit contact pressure at the base of the tamper used for the ironing pass shall be in the range of 19 to 38 kPa.

SOIL BORINGS AND PRESSUREMETER TESTS

As the work progresses, soil borings will be made as a check on the degree and depth of improvement achieved. The depth of the borings will be equal to the thickness of the existing fill plus 1.5 m. Samples will be obtained at 0.8 m intervals using split barrel sampling procedures in accordance with ASTM D-1557. Approximately twenty-five (25) borings will be made on five separate occasions to check on the work as the work progresses. The contractor shall be responsible for completing the borings and submitting the final results to the owner.

While the borings are being made, pressuremeter tests will be performed within the boreholes at selected intervals by a representative of the Highway Department. A standby time of three hours per boring will be required to allow the pressuremeter tests to be performed while the crew is standing by.

Payment for the borings will be made at the contract unit price per each for "Boring," as set out in the Itemized Proposal.

ADDITIONAL WORK

Based upon the results of the boring tests, or load tests as described in a subsequent section, or information obtained from ground subsidence readings, it may be necessary to apply additional energy to certain areas. This additional work will be paid for as an extra to the basic contract but will be paid at the pro-rated rate on a per square meter basis as per the bid item. It is anticipated that not more than ten percent of additional energy over that originally specified will be applied as an extra.

MONITORING

Monitoring of ground elevations and the amount of stone brought into the dynamically compacted areas shall be maintained by the contractor. Ground elevations shall be obtained on a 30 m grid pattern immediately prior to start of the dynamic compaction in that area. Additional elevation readings will be taken after each pass of the dynamic compaction at the same locations to determine how much settlement was induced by the dynamic compaction. The amount of stone placed in the area shall also be estimated on the basis of the number of trucks used to haul the stone into the area.

LOADING TESTS

Four static load tests shall be conducted before and four static load tests after the dynamic compaction at locations directed by the Engineer. The purpose of these loads is to assist in demonstrating how much settlement has been removed from the landfill by dynamic compaction. The contractor shall construct a pile of material approximately 21 m in diameter at the base and 11 m high with one to one side slopes, exerting a pressure of 98 kPa on a steel plate 1.2 m by 1.2 m by 130 mm placed on the surface of the existing grade with a 75 to 100 mm diameter PVC pipe extending up through the center. An individual reading shall be taken when fill commences, and readings every 1.5 m interval as material is placed up to the maximum height. The contractor shall supply and utilize this pipe and plate for testing over a period of seven days.

Settlement readings shall be made every four hours for the first day and every eight hours for the remaining six days of each load test. After completion of the individual load test, the loading material must be removed by the contractor. The contractor will be allowed to utilize the rock backfill used in dynamic compaction for the initial test loading and "B" borrow in the final test loading. However, no direct payment will be allowed for the construction and removal of the test load and payment of these materials will be allowed only if these materials are used in the final completed roadway structure.

PROTECTION OF PERSONS AND ADJACENT PROPERTIES

A detailed safety program will be required to verify that job site personnel, off-site personnel and adjacent properties are protected. The safety program will require the contractor to perform, by a specialist approved by the Department who is qualified in seismic testing, measurements before, during and after the Dynamic Compaction. Seismic readings shall be obtained at locations determined by the Engineer.

The safety program will address the proposed barriers, fences, etc., to be utilized in protecting off-site personnel. The safety program shall include a complete discussion of the special programs utilized to assure the crane safety. This will include, but not be limited to, the before modification to all parts of the crane affected by Dynamic Compaction, i.e. the crane boom, cables, drums, brakes, clutch, outriggers, etc., and the daily, weekly, and monthly maintenance program. A detailed safety program shall be submitted prior to the commencement of work outlining how the Contractor intends to protect his personnel, other personnel on the site, the safety of the adjacent structures, and the maintenance program required to assure the safe operation of the crane. The Contractor will be required to photograph all immediately adjacent structures before starting this work. All items needed for the safety program shall not be paid for separately, but shall be included in the cost of "Dynamic Compaction." If the seismic specialist determines that unacceptable conditions occur, the Engineer shall be notified immediately and all compaction work shall cease until such time as the Contractor takes all necessary precautions needed to meet safety requirements. Such precautions shall be approved by the Engineer.

RECORDS

The contractor shall keep adequate records of the construction operations, i.e. the locations where drops have been made, number of drops per location, depth of penetration of the tamper, the pass number, etc., and submit these daily. Any circumstances affecting the work or intended improvement as a result of dynamic compaction should be brought to the attention of the engineer.

BASIS OF PAYMENT

The work to be paid for shall be the measured quantity in square yards of "dynamic deep compaction." If additional work is necessary based upon the borings or load tests, the work will be paid for at the pro-rated energy rate per square meter basis as per bid item.

APPENDIX C
TYPICAL PERFORMANCE SPECIFICATION

DESCRIPTION OF WORK

Extent of Dynamic Compaction is indicated on drawings.

The work shall consist of densifying the landfill by Dynamic Compaction (DC) to the area and extent shown on the drawings. The work shall be performed by a Specialty Contractor who can meet the requirements as outlined below. The Specialty Contractor shall furnish all supervision, equipment (including cranes), labor and materials necessary or incidental to the completion of the DC for this project.

DEFINITION

DC is a process whereby a large tamper is raised above the ground and allowed to fall from heights up to 36 m impacting with high compactive energy. The depth of compaction improvement depends upon the mass of the tamper and the height of the fall.

SPECIALTY CONTRACTOR'S QUALIFICATIONS

The Specialty Contractor shall be regularly engaged in DC work and shall document that they have performed a minimum of the following work in the United States:

> Provided all supervision, labor, material and equipment to successfully densify by Dynamic Compaction, 25 separate projects utilizing energy inputs of between 13.6 and 27 Mg dropped from heights of over 24 m to improve soil for both liquefaction, landfill densification and bearing capacity using free fall, and single and double lines. Five of the documented, successfully completed projects shall be similar to this project in type of landfill to be densified, depth to be densified, energy input required and the type of modified cranes to be used.

Contractor shall submit specialty contractor's qualifications to the Engineer for approval prior to the preconstruction conference.

TESTING

Construction fills, sanitary landfills, and mine spoils do not lend themselves to in-place testing such as standard penetration, cone penetrometer and dilatometer tests, due to their non-penetrability, non-homogeneity, etc. These strata can be best tested by before and after load tests. The contractor shall install a settlement plate 460 by 460 mm approximately 0.3 m beneath the existing ground with a 50 mm diameter steel pipe extending from the settlement plate to 4.5 m above the existing ground. The ground shall then be filled to a height of 3 m with soil in a conical shape approximately 9 m in diameter at a location over the landfill selected by the engineer. Settlement shall be monitored for seven days. After Dynamic Compaction a similar settlement test shall be conducted adjacent to the first test. If settlement has not been reduced 75 percent, additional compactive effort shall be applied until a 75 percent reduction can be obtained. This testing shall be the responsibility of the contractor and performed under the observation of an independent registered Professional Engineer who shall submit six (6) copies of certified test reports to the Owner.

INSPECTION SERVICES

The City will furnish full time inspection; however, this shall not relieve the Specialty Contractor from keeping adequate records of the operations, including but not limited to, location number, number of drops, rate of penetration of weight, pass number, and submit these daily.

PROTECTION OF PERSONS AND ADJACENT PROPERTIES

A detailed safety program will be required to verify that job site personnel, off-site personnel and adjacent properties are protected. The safety program will require the contractor to perform by a qualified specialist a detailed monitoring and documentation before, during and after the DC of all structures within 90 m of the densification and structures noted on the plans outside this zone. The safety program will address the proposed barriers, fences, etc., to be utilized in protecting off-site personnel. The safety program shall include a complete discussion of the special programs utilized to assure the crane safety. This will include, but not be limited to, the before modification to all parts of the crane affected by Dynamic Compaction, i.e., the crane boom, cables, drums, brakes, clutch, outriggers, etc., and the daily, weekly and monthly maintenance program.

PRODUCTS

Provide equipment, materials and personnel required to achieve the results shown on the drawings.

Crane shall be rigged so that at least 75 percent of potential energy is realized at the point of impact.

EXECUTION

The Specialty Contractor shall submit a detailed work plan showing impact layout, schedule, etc.

Prior to beginning the DC, a mat of stone, crushed concrete, earth, sand or other suitable material shall be placed over the site where required to assure 1.2 m of cover over the top of the landfill. The DC shall then be performed in a minimum of four passes across the site. It may be necessary at the completion of each pass to fill the resulting craters with material from the mat. This shall be the responsibility of the Specialty Contractor.

On this project the depth of the densification required varies in general from 3 to 6 m, and a minimum weight of 13.6 Mg shall be dropped from a minimum height of 20 m. The minimum applied energy required for this project is 750 kJ/m^2.

In order to ensure compaction of loose material between grid points, an ironing pass shall be applied over the entire treatment area on a 2 m x 2 m grid or less.

METHOD OF PAYMENT

The quantity to be paid shall be based on the plan quantity in square meters of DC regardless of the number of passes needed to meet the energy requirements specified herein.

GROUND MODIFICATION USING IMPACT DENSIFICATION
PART I GENERAL

1.1 REFERENCES

The publications listed below form a part of this specification to the extent referenced. The publications are referred to within the text by the basic designation only. American Society for Testing and Materials (ASTM):

D1586-84	Penetration Test and Split-Barrel Sampling of Soils.
D2487-83	Classification of Soils for Engineering Purposes
D2488-84	Description and Identification of Soils (Visual-Manual Procedure)

1.2 REQUIREMENTS

1.2.1 General Requirements

The work includes the provision of impact densification procedures to improve the strength and compressibility characteristics of surface and subsurface soils. The soils existing to a depth of 6 m below the existing ground surface shall be modified by impact densification to accept the indicated shallow foundation. The shallow foundation design is based on allowable soil bearing capacity of 145 kPa and associated settlements not to exceed 25 mm (total), or 12.5 mm (differential settlement between adjacent foundations). The Contractor shall perform quality control testing (test borings using Standard Penetration Test (SPT) procedures) to verify the success of the compaction/densification effort. All impact densification work shall be based upon the shallow foundation and soil boring logs presented in the contract drawings and supplemental geotechnical data presented herein.

1.2.2. Special Requirements

The Contractor shall utilize the services of a Specialty Geotechnical Contractor (SGC) to accomplish all ground modification using impact densification.

1.2.2.1 Qualifications of Specialty Geotechnical Contractor

Improvement of the foundation soils by impact densification shall be done only by a Contractor who is normally engaged in specialty foundation work and who can furnish proof of having done satisfactory work of this specific nature for a minimum of five years. Certification shall be submitted, listing the proposed Specialty Geotechnical Contractor's training, experience, a minimum of ten satisfactorily completed jobs using impact densification and facilities and equipment available to do the work. The Contractor shall provide experienced, competent, and quality personnel to continuously observe the densification procedures and furnish daily logs which include the data specified herein to the Contracting Officer.

1.3 QUALITY CONTROL

Except for inspections and approvals specified to be performed by the Contracting Officer, provisions of the section entitled "Quality Control" shall apply. Unless otherwise specified herein, requirements for supervision, inspection, sampling, testing approval, directing, authorizing, and other requirements of similar import shall be the responsibility of the Contractor's Quality Control manager. The SGC shall commission the services of a Geotechnical Consulting Engineer (a registered Professional Engineer) to prepare and implement the requirements and recommendations (as set forth by the compaction/densification plan) for ground modification using impact densification, provide required records, supervise and provide recommendations for compaction/densification procedures and acceptance of completed work, evaluate monitoring and impact densification test data, and meet and consult with the Contracting Officer and/or the Contractor when requested to do so, either during the course of the work or subsequent thereto for purposes of discussing recommendations and/or results. The Contractor's Quality Control manager and the Geotechnical Consulting Engineer shall not be the same individual. Provide services of the SGC and Geotechnical Consulting Engineer, and any associated personnel, and provide equipment and materials to satisfy the requirements specified herein for impact densification. Approvals, except those required for field installations, field applications, and field tests, shall be obtained before delivery of materials or equipment to the project site.

1.4 SUBMITTALS

Submit the following in accordance with Section 01300 "Submittals."

1.4.1 SD-13, Certificates

Certificate attesting qualification of SGC and his Geotechnical Consulting Engineer.

1.4.2 SD-05, Design Data Preconstruction Compaction/Densification Plan

At least two weeks prior to beginning the impact densification work, the Geotechnical Consulting Engineer shall submit for approval two copies of a Compaction/Densification Plan describing the equipment (details and dimensions, including description of tampers) and techniques to be employed in the impact densification program. The plan shall include an outline detailing the compaction effort to be used, drop height, number of drops, sequence of drops, the spatial distribution of the compaction energy to be applied and the chronological sequence of its application, methods to be used in order to maintain a working platform throughout the work, and the manner and method in which the surface soil shall be prepared to receive foundations prior to construction of the structure. The format for recording and maintaining both field and final records as specified herein shall be set forth. The plan shall address any potential effects of the compaction/densification effort on adjacent structures or utilities and shall describe the instrumentation to be employed in monitoring ground vibration levels and any enforced ground settlement.

1.4.2.1 Change in PreConstruction Compaction/Densification Plan

Any change in the preconstruction Compaction/Densification Plan necessitated by a change in subsurface conditions shall be submitted to the Contracting Officer.

1.4.3 SD-18, Records

Keep a complete and accurate record of the location of compaction imprints, depth of imprints, energy applied, measurement of enforced settlement of the ground surface, and all required pressuremeter, standard penetrometer, and/or cone penetrometer test results. Submit records of ground modification progress and final results to the Contracting Officer within 15 calendar days after successful completion of the ground modification. Daily field records of the ground modification process shall be made available to the Contracting Officer within 24 hours after completion of any compaction/densification effort.

1.4.3.1 Quality Control Test Records

Submit a complete and accurate record of quality control tests, including:

a. The type of test performed, and test equipment used.
b. The date, and time of each test hole.
c. The test hole number, location, ground surface elevation and bottom of the test hole elevation.
d. Complete log of materials encountered including description of soil in accordance with ASTM D-1586 when standard penetration testing procedures are used, number of blows required to sink a standard split spoon sampler for each 152 mm of penetration, weight and fall of drop hammer used to drive the split spoon sampler, length of sample obtained, type of material in split spoon sample, and elevation of standard penetration tests.

e. A complete record for driving borehole casing, if used, including size and weight of casing, weight of hammer, height of hammer drop, and number of blows per 300 mm required to drive the casing.
f. Any unusual occurrence during performance of quality control tests.
g. Report of data obtained and work performed including typed final logs of standard penetration test borings.

PART 2 PRODUCTS - NOT USED

PART 3 EXECUTION

3.1 SITE WORK PREPARATION

Strip site of topsoil 3 m outside of building limits. Excavate the site to 100 mm above the top of subgrade or bottom of capillary water barrier.

3.1.2 Foundation Preparation

The Contracting Officer shall stop the compaction process if compaction is detrimental to site. Granular fill with a thickness of 150 to 200 mm may be required during compaction for working platform, drainage and to prevent sticking. Confirm the soil improvement by drilling at least 14 soil borings 6 m deep in accordance with ASTM D-1586 except the initial 3 m shall be continuously sampled and standard penetration test performed, the use of the cone penetration test in accordance with ASTM D-3441 may be used with a minimum of five ASTM D-1586 6 m borings and 6 m cone penetrometer tests. The contractor shall submit the results of these tests for Contracting Officer approval prior to commencing any other work on the site improvement area. The Contracting Officer will take ten days to evaluate the results.

3.1.3 Dewatering

Dewatering measures such as trenching, ditching and sump/pumping will be required during the grading and foundation construction phase of the project.

3.1.4 Select Fill

Contractor shall provide compacted select fill as required to reestablish new top of subgrade during and after dynamic compaction.

3.2 EQUIPMENT

The Contractor shall use machines or combinations of machines and equipment that are in good, safe working condition and that will produce the results specified herein.

3.3 PROCEDURES

Procedural specifications are left to the Geotechnical Consulting Engineer to achieve the results specified herein.

3.4 GENERAL EXECUTION GUIDELINES

Use the following general guidelines. After required demolition is complete on the site to be compacted/densified, the site shall be levelled and rough graded. A layer of granular material may be required prior to, or during, the impact densification to relieve a sticking problem with the weights used in compaction, and/or maintain an adequate working platform for men and equipment. The Dynamic Compaction technique involves the dropping of a heavy weight (7 to 18 Mg), free fall, from a height of 15 to 30 m. The high energy levels which are developed produce a deep compaction of the underlying materials. Two or more passes shall be made over the designated area according to a predetermined impact grid pattern. The impact grid pattern, free fall distance, tonnage, and size of tamper shall be determined by the SGC and Geotechnical Consulting Engineer. During the final compaction pass, as much of the surrounding loose granular material as possible shall be utilized to level out the impact craters. After the final compaction pass is completed, and prior to beginning construction of any foundations, the compacted area shall be levelled and rough graded such that truck mounted testing equipment (drill rigs) may access and accomplish the required testing.

3.5 PROTECTION

Exercise care and take necessary precautions to avoid damage to existing structures, utilities, or any new work. Protect surrounding work and individuals from excessive vibration, noise, and debris originating from the area of work. Vibrations resulting from compaction operations shall be monitored and controlled. A total peak particle velocity of 50 mm/sec shall not be exceeded in order to avoid any disturbance to structure or utilities on or adjacent to the site. The monitoring, recording, and interpreting of vibrations shall be performed by qualified personnel. Any damage to structures or utilities (both existing or new resulting from the Contractor's operations shall be repaired to the Contracting Officer's satisfaction at the Contractor's expense.

3.6 QUALITY CONTROL TESTING

The Contractor shall provide all necessary equipment and labor for performing quality control testing. Contractor shall provide drilling equipment to perform test borings using SPT procedures prior to and following the compaction/densification process.

3.6.1 Standard Penetration Testing

Standard penetration tests shall be performed in accordance with ASTM D-1586 except as specified herein.

3.6.1.1 Casing and Records

If casing is used to advance the borehole, a continuous record shall be kept of the blows per 0.3 m required to drive the casing. The same weight of hammer and the same drop shall be used for driving all casing. The mass of hammer shall be 136 kg and the height of the free fall 457 mm, using a rope and cathead.

3.6.1.2 Penetration Test

Standard penetration tests shall be performed continuously for the initial 3 m of boring, then at intervals of 1.5 m using a standard split spoon sampler.

3.6.1.3 Positive Hydrostatic Pressure

A positive hydrostatic pressure shall be maintained in the borehole to prevent instability due to upward flow of water before or during testing. Additional water or drilling mud shall be added to the hole as necessary.

3.6.1.4 Visual Description

A detailed visual description shall be made of each standard penetration test sample in accordance with ASTM D2487 and D2488, and the description shall be entered on the boring log. Storage of samples will not be required unless requested by the Contracting Officer.

3.6.2 Quality Control Procedures

If quality control tests indicate the densification in any area doesn't meet the requirements specified herein, the area affected, as determined by the Geotechnical Consulting Engineer, shall have the densification procedure repeated (with the procedure revised when required) and the quality control tests then repeated. All quality control tests shall be accomplished, the results assessed by the Geotechnical Consulting Engineer, and the Geotechnical Consulting Engineer's evaluation and recommendations approved by the Contracting Officer prior to the Specialty Geotechnical Contractor's equipment leaving the project site. The Contracting Officer reserves the right to take up to three working days to approve the Geotechnical consulting Engineer's evaluation and recommendations from the time quality control test field records and the Geotechnical Consulting Engineer's evaluation and recommendations are in the possession of the Contracting Officer. Further work on the structure or utilities within an area not achieving the compaction/densification requirements specified shall not commence until the requirements are complied with as verified by quality control tests.

3.7 ACCEPTANCE

If the results of on-site testing are determined by the Contracting Officer to not satisfy the requirements for acceptance as specified herein:

Design and provide a revised shallow foundation for those new buildings or structures situated within (totally or partially) the area not achieving the degree of compaction/densification required. The design shall be based on 1) a reduced allowable bearing value which reflects that actually developed by the impact densification as recommended by the Geotechnical Consulting Engineer, and 2) associated potential settlements (both total and differential) being within the parameters acceptable to the designer or record. The reduced allowable bearing value shall be determined by mutual agreement between the Geotechnical Consulting Engineer and the revised foundation designer of record and must be approved by the Contracting Officer. Any revised design shall be subject to the requirements of the contract specifications and submitted to the original foundation designer of record for approval.

3.7.1 Incidental Costs

All design, construction and incidental costs associated with the options specified herein shall be borne by the Contractor.

3.8 INSPECTION

The Contractor shall notify the Contracting Officer of the intent to employ an impact densification program at least 14 days prior to commencement of the program so that the Contracting Officer may observe the program. The Contracting Officer reserves the right at any time to observe and inspect the compaction/densification operations.

3.9 PAYMENT

All costs associated with and incidental to providing ground modification using impact densification and preparation of the resulting ground surface to receive the foundations indicated shall be included in the lump sum contract bid price.