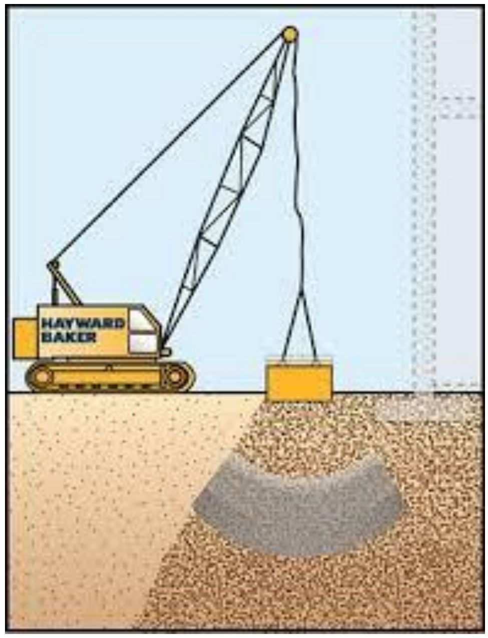
Dynamic compaction or Heavy Tamping



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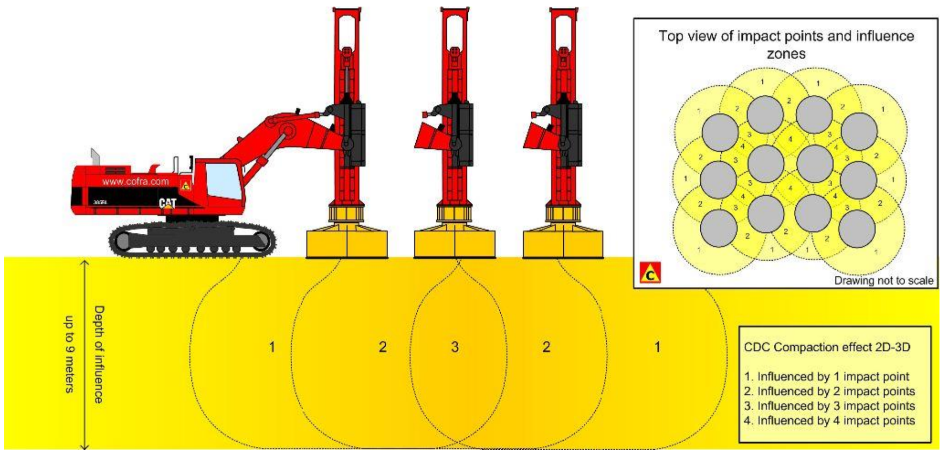
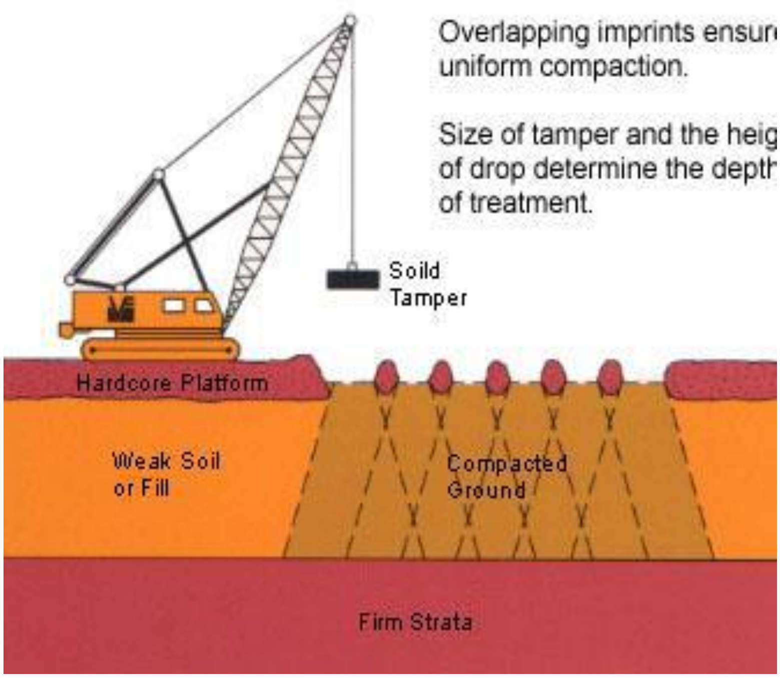


Top view of impact points and influence zones
Drawing not to scale
www.cofra.com
Depth of influence
up to 9 meters
1
2
3
2
1
CDC Compaction effect 2D-3D
1. Influenced by 1 impact point
2. Influenced by 2 impact points
3. Influenced by 3 impact points
4. Influenced by 4 impact points



Overlapping imprints ensur
uniform compaction.
Size of tamper and the heig
of drop determine the deptl
of treatment.
Soild
Tamper
Hardcore Platform
Weak Soil
or Fill
Compacted
Ground
Firm Strata

Dynamic compaction, also called heavy tamping

- consists of repeated dropping of heavy weights onto the ground surface to densify the soil at depth.

- For unsaturated soil, the process of dynamic compaction is similar to a large-scale Proctor compaction test.

- For loose, fully saturated, cohesionless soils, the impact from the weight liquefies the soil and the particles are rearranged in a denser, more stable configuration. At developed sites, a buffer zone around structures of about 30 to 40 meters is required (vibrations can damage nearby structures).

- Dynamic compaction involves weights of 2 to 40 tons dropped from heights of 10 to 40 meters at grid spacings of 2 to 6 meters, in square or circular pattern in plan. Typically 7-15 Drops of the weight are applied at each point.

- Dynamic compaction works best on loose sands and silty sands, with a maximum effective densification depth of about 10 meters.

- The maximum improvement occurs in the upper two-thirds of the effective depth.

Weights used may be concrete blocks, toughened steel plates bolted together or thick steel shells filled with concrete or sand.

Durability of the weight is important because of large number of drops.

An example treatment : 2-3 drops /m^2

2 or 3 coverages of an area.

The time interval between coverages depends on the rate of dissipation of excess porewater pressures and strength regain.

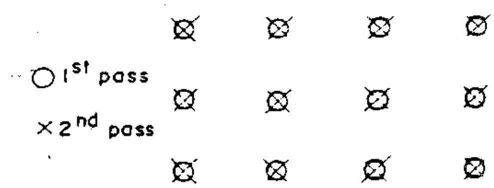
Example for coarse sand, days, and for fine grained soil, weeks, may be necessary.

Ground surface is usually levelled between coverages by imported granular material.

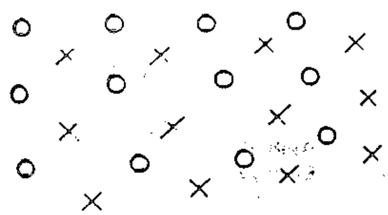
Before further passes of tamping, measurements are done after levelling to assess average forced settlement.

To assess the true volume compression measurements and calculations are done at selected points.

Application patterns



Preferred in relatively deep deposits



Preferred in not very deep deposits

Before starting tamping a surface blanket of unsaturated granular material 1 m thick or more is spread over the area to be tamped if this does not occur naturally to lessen local shear & to allow effective compaction.

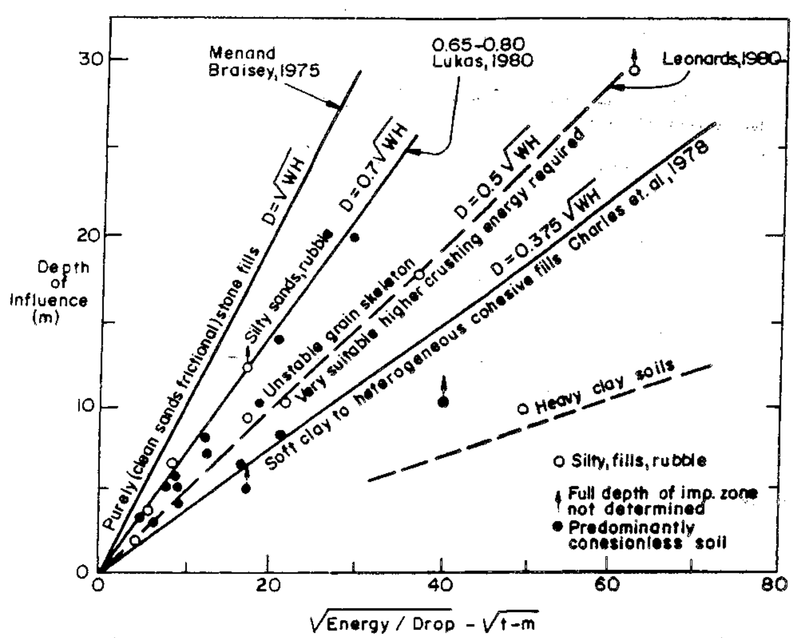
"Ironing" is full coverage of the area by small impacts. It compacts the surface layers (h = 2-3 m). It can be done by surface rolling.

The relationship between the **effective depth**, the weight and the height of the drop can be expressed as:

$$D = (0.3 \text{ to } 0.7)\,(W \times H)^{0.5}$$

where
D = maximum depth of improvement, m
W = falling weight, metric tons
H = height of drop, m.

The lower values for the coefficient generally apply to silty sands, whereas, clean coarse, cohesionless soils are densified to a greater effective depth for a given value of W*H (see future slides for FHWA (1995) table about this coefficient).



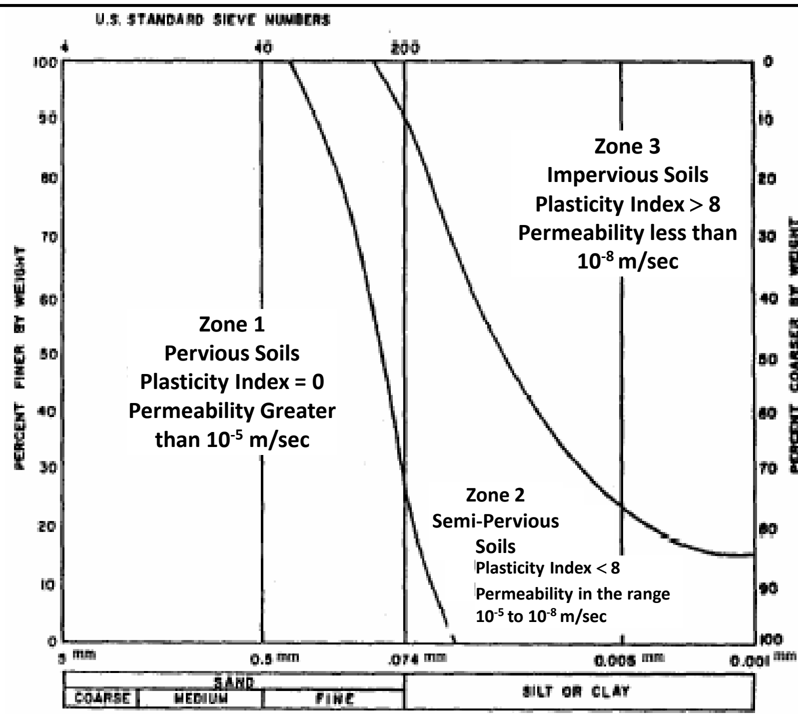
W: Metric tons, H: Height of Drop (m), D: (m) Max. deepth of Influence
Figure 2.10 Depth of Influence in Dynamic Compaction

Successfully used to improve many types of weak ground deposits including:

- Loose naturally occurring soils such as alluvial, flood plain, or hydraulic fill deposits.
- Landfill deposits both recent and old. Building rubble and construction debris deposits.
- Strip mine spoil. Partially saturated clay fill deposits that are elevated above the water table.
- Collapsible soils including loess.
- 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.
- Special wastes.

Assess the suitability of a site for DDC (FHWA 1995)

1. **Categorize soil type**. The properties, thicknesses, and extent of the weak ground must be known. Types of soils 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. Especially important in urban areas where roadways or buildings might be situated nearby 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.
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



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 pore pressure	—
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 51 mm per sec allowable if adjacent to buildings	Adjacent to: modern construction, > 19 mm per second
Lateral Ground Displacements	Dynamic compaction > 7.6 m from buried utilities	Most buried utilities can tolerate 76 to 127 mm per second	Immediately adjacent to easily damaged
Water Table	> 2 m below grade	< 2 m below grade, with drainage provided to lower water table	< 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 1 m or more in thickness at a depth that is impractical to remove
3. Determine Design Requirements			
Settlement	< 0.3 to 0.6 m for embankments	> 0.3 to 0.6 m if site conditions preclude large differential settlements	Settlement > design engineer can tolerate
Minimum Soil Property	Can usually achieve relatively high SPT, CPT, and PMT	May need wick drains in saturated Zone 2 soils to facilitate drainage	—
Depth of Improvement Limitation	Deposit < 9 m thick	Special equipment required for deposits in range of 9 to 12 m	Soils cannot be significantly Improved below 11 m
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	—	1 m layer could cost more than dynamic compaction

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. 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.

Intermediate Soil Deposits -Zone 2

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.

UnfavorableSoil 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 than10^{-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.

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 US Bureau of Mines (1980) has studied the effect of ground vibrations on structures and has established threshold particle velocities beyond which cracking in walls of homes may occur

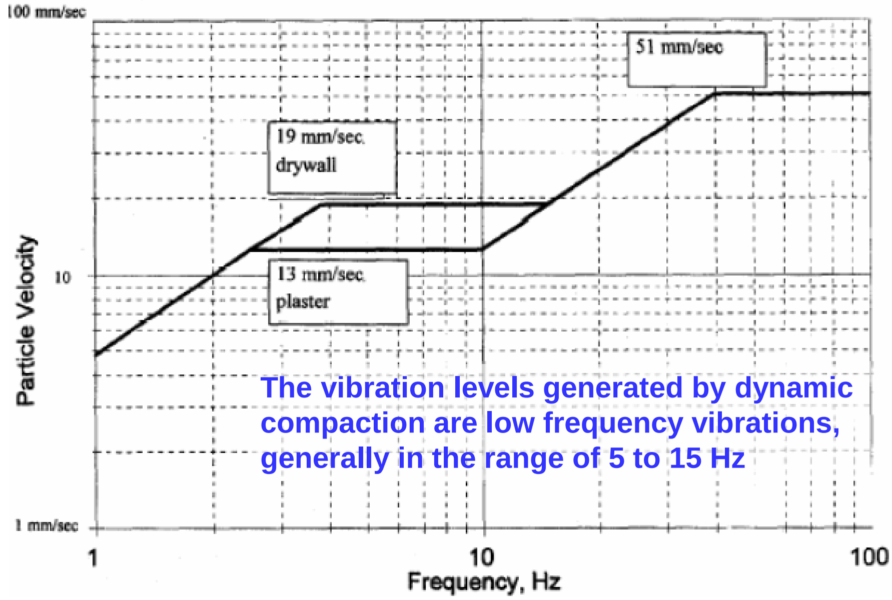
Ground Vibrations

Measurements in projects have indicated that the frequency of ground vibrations from dynamic compaction is in the range of 5 to 15 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.

Ground Vibrations

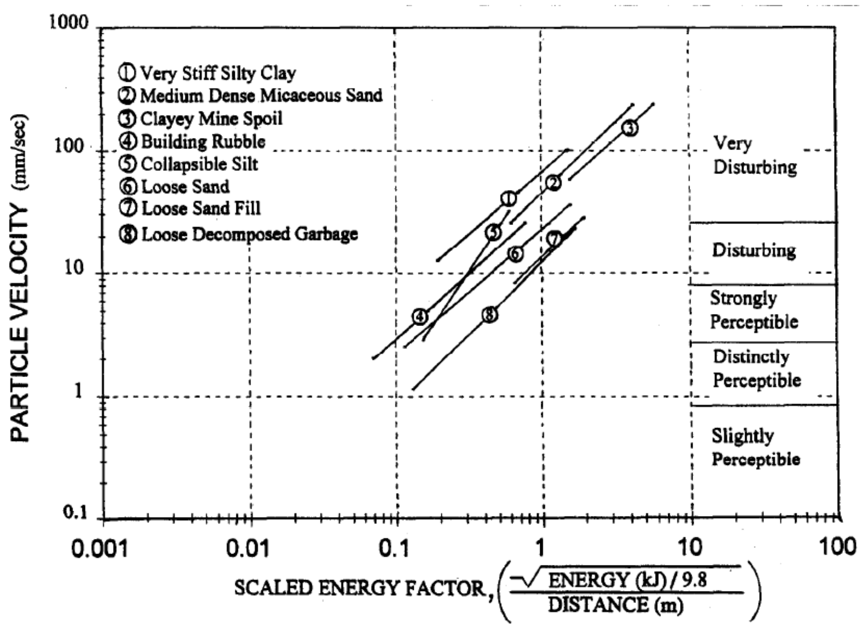
Particle velocities can be measured with a portable field seismograph and compared with the criteria shown. Readings should be taken on the ground adjacent to the concerned facility. The particle velocities that will develop as a result of dynamic compaction should be predicted in advance of construction to determine if threshold vibration levels will be exceeded

Safe levels of blasting vibrations for houses



US Bureau of Mines (1980)

Energy vs. Particle Velocity

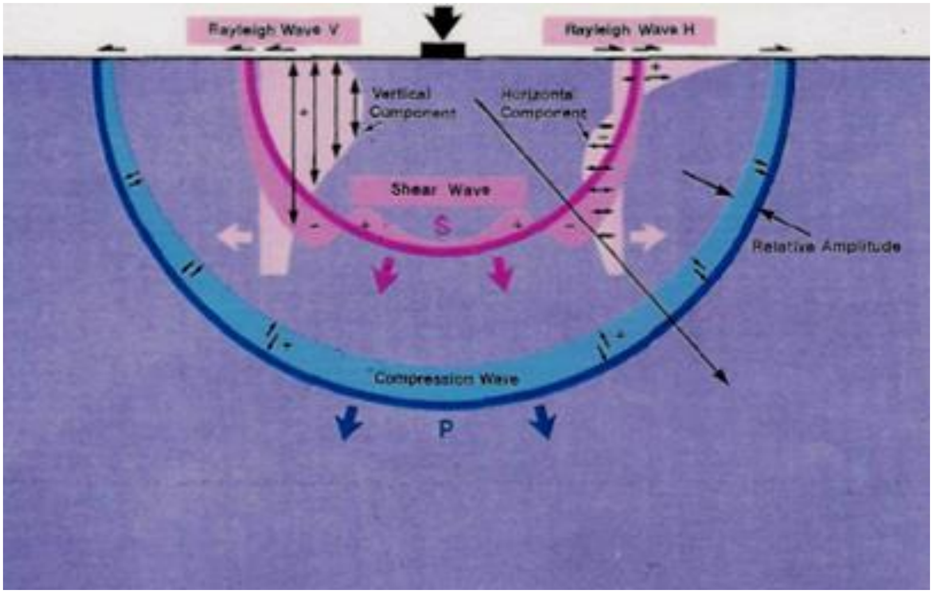


The scaled energy factor incorporates the energy imparted into the ground from a single drop plus the distance from the point of impact to the point of concern. **The chart is entered with the calculated scaled energy factor.** A horizontal line is then extended laterally and the predicted particle velocity 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.

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 cutoff 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 density 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 (1995) study on dynamic compaction 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. 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.

Lateral ground displacements

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. (Wiss, 1981) Particle velocities of 76 mm/set have not damaged pipes and mains.

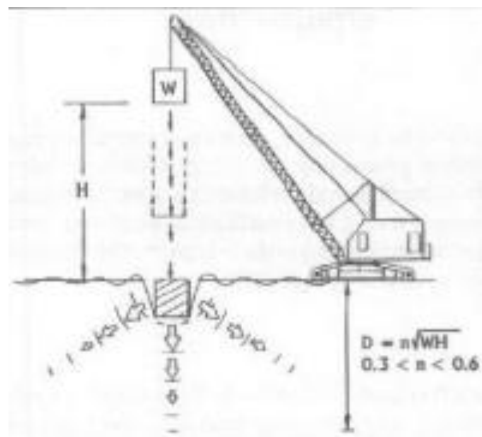
High Water Table

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

Example

A dynamic compaction is planned with 890 kN weight falling from a height of 15 m to compact a 9 m thick loose sand layer. Is a building 30 m away from this site, OK?



Example

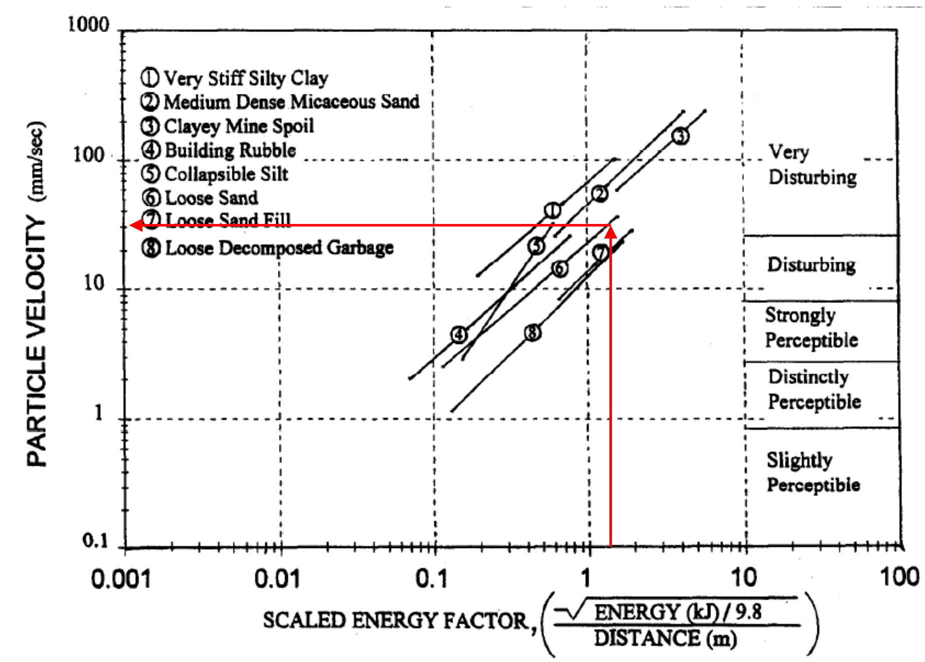
A dynamic compaction is planned with 890 kN weight falling from a height of 15 m to compact a 9 m thick loose sand layer. Is a building 30 m away from this site OK?

$$\text{Scaled Energy} = \frac{\sqrt{\text{Energy (kJ)}/9.8}}{\text{Distance (m)}}$$

$$\text{Scaled Energy} = \frac{\sqrt{(890\,\text{kN} \times 15\,\text{m})/9.8}}{(30\,\text{m})}$$

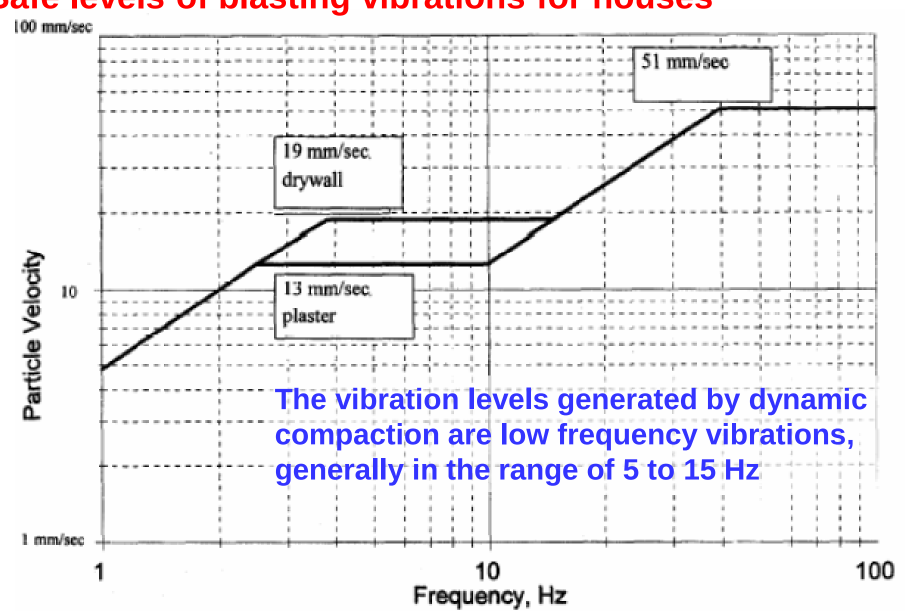
$$\text{Scaled Energy} = 1.23$$

1 kJ = 1 kN.m



≈ 30 mm/sec particle velocity expected

Safe levels of blasting vibrations for houses



Particle velocity up to ≈ 19 mm/sec is allowable.
Building that is 30 m away from this site is NOT OK.

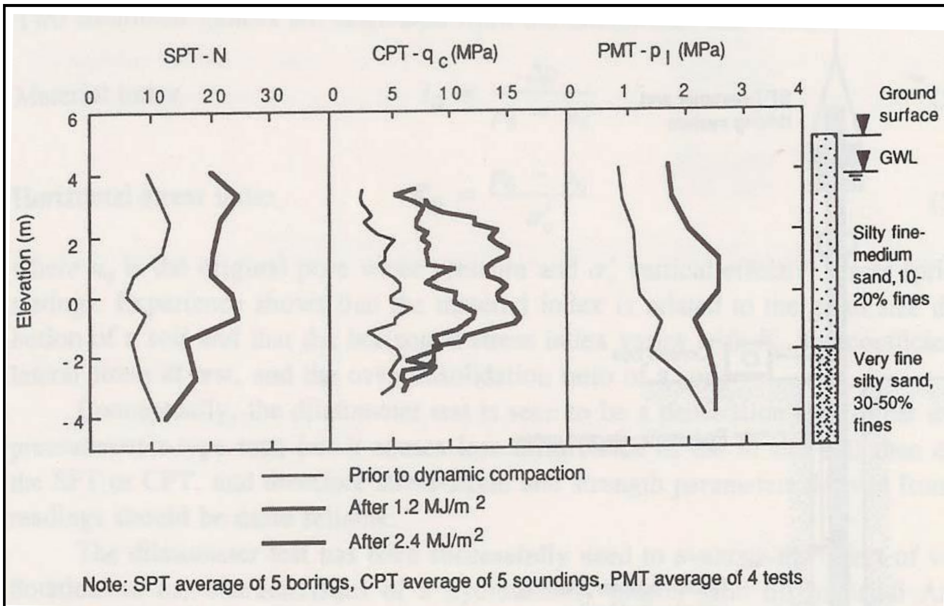
Improvement

The estimated post-densification settlement can be made using table 2 and figures following.

Some judgement is required

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



SPT-N values before and after dynamic compaction (also CPT and pressuremeter before and after)

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 non-liquefiable for a design magnitude earthquake.

Dynamic compaction would then be planned to impart enough energy to reach this minimum desired SPT value

Table 2. Upper bound test values after dynamic compaction.[32]

Soil Type	Maximum Test Value 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.

FHWA (1995)

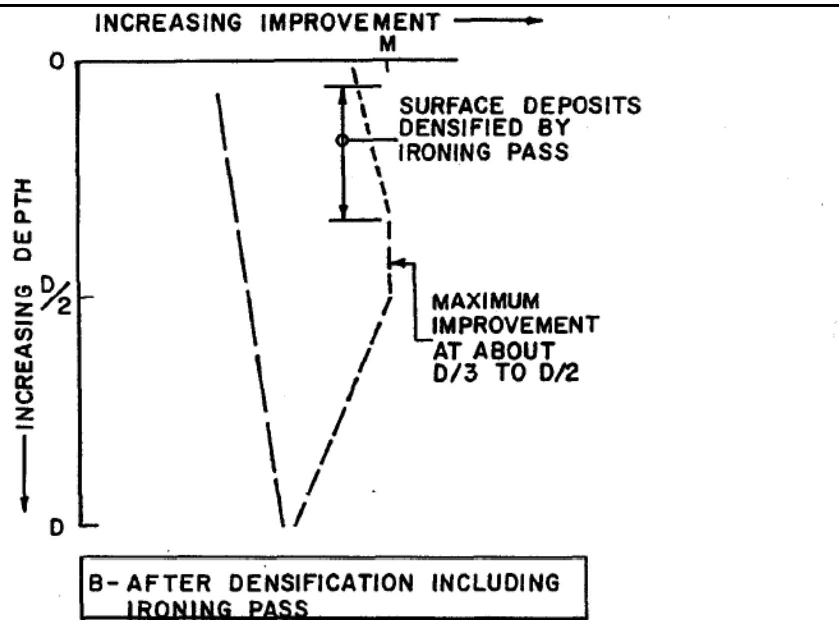


Figure 10. Variations in improvements with depth during dynamic compaction.[32]

FHWA (1995)

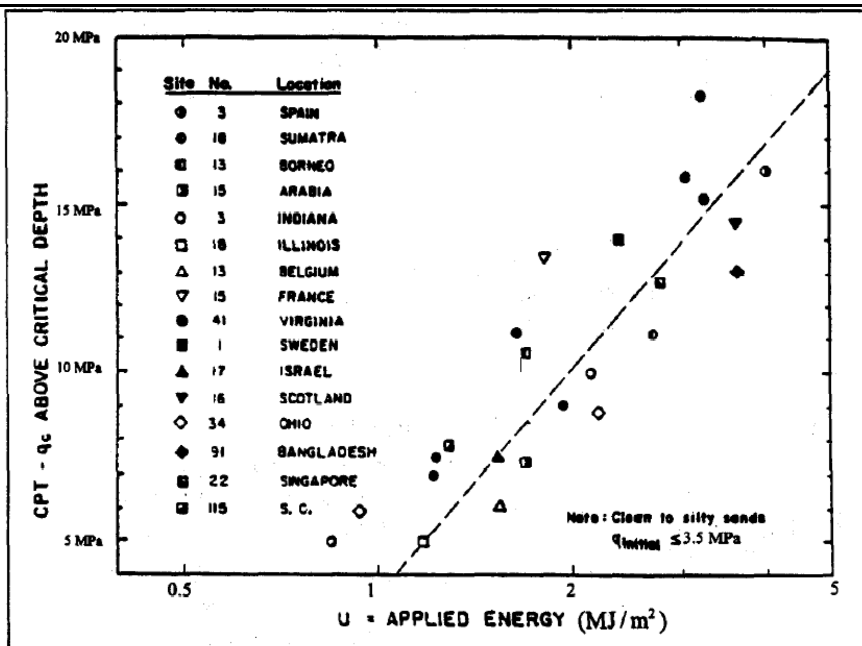


Figure 11. Increase in cone resistance in granular soils with applied energy.[38]

FHWA (1995)

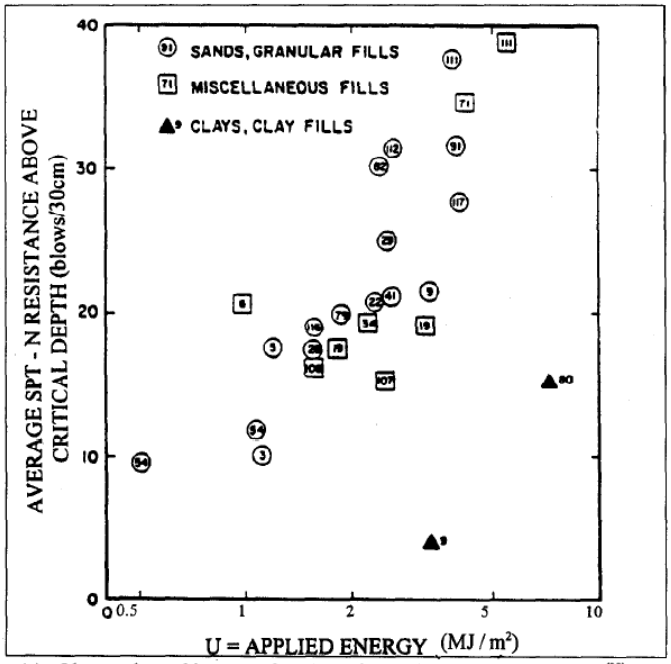


Figure 14. Observed trend between SPT-N Value and applied energy level.(38) (See reference 38 for details of the numbers included in this figure.)

FHWA (1995)

Design

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.

Usually the thickness of the loose deposit and hence the required depth of improvement is known from the subsurface exploration

FHWA (1995)

Design Guidelines

Parameters to be Determined
Step 1: Selection of tamper and drop height for required depth of improvement Equation 1: $D = n(WH)^{0.5}$

Evaluation Process
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.

FHWA (1995)

The relationship between the **effective depth**, the weight and the height of the drop can be expressed as:

$$\mathbf{D = (0.3\ to\ 0.7)\ (W \times H)^{0.5}}$$

n

where
D = maximum depth of improvement, m
W = falling weight, metric tons
H = height of drop, m.

The lower values for the coefficient generally apply to silty sands, whereas, clean coarse, cohesionless soils are densified to a greater effective depth for a given value of W*H.

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.

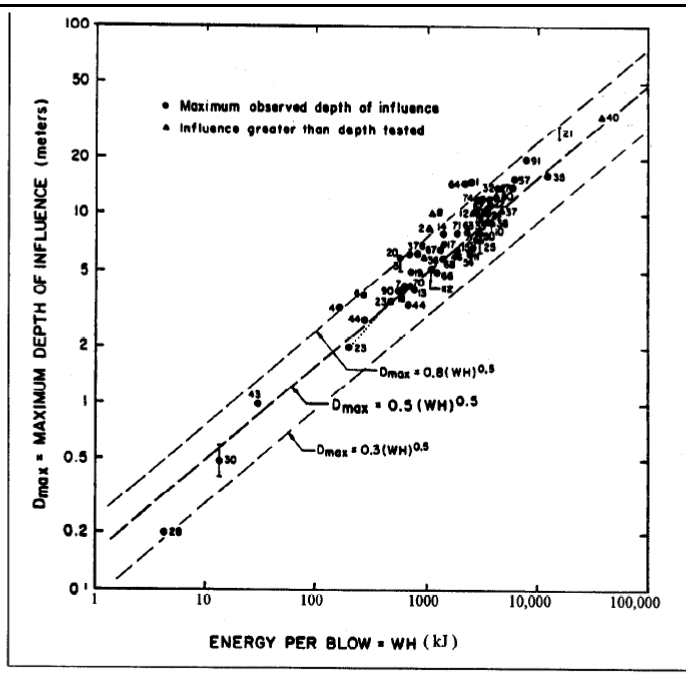


Figure 18. Trend between apparent maximum depth of influence and energy per blow.[38]
(See reference 38 for details of the numbers included in this figure.)

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.

FHWA (1995)

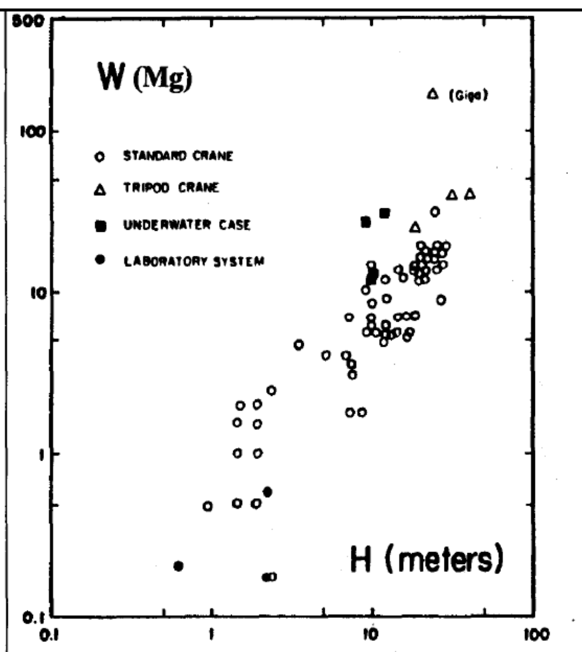


Figure 21. Relationship between size of tamper and drop height. [38]

1 Mg = 1 ton = 10 kN

FHWA (1995)

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.

FHWA (1995)

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.

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.

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

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

On typical projects, the average applied energy ranges from about 1 to 5 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.

More energy should be applied to the looser deposits and less to the denser deposits.

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.

FHWA (1995)

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.

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

Assumption : all the energy will be applied in one pass

A. Select a grid spacing ranging from 1.5 to 2.5 times the diameter of the tamper.

Most of the tampers reported in the literature have a diameter, or width, ranging from 1 to 3 m

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.

FHWA (1995)

In the fine grained 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.

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

FHWA (1995)

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

When writing the specification, it is preferable to specify multiple passes or phases for deposits classified as Zone 2 or Zone 3 soils

Step 6: Surface stabilizing layer

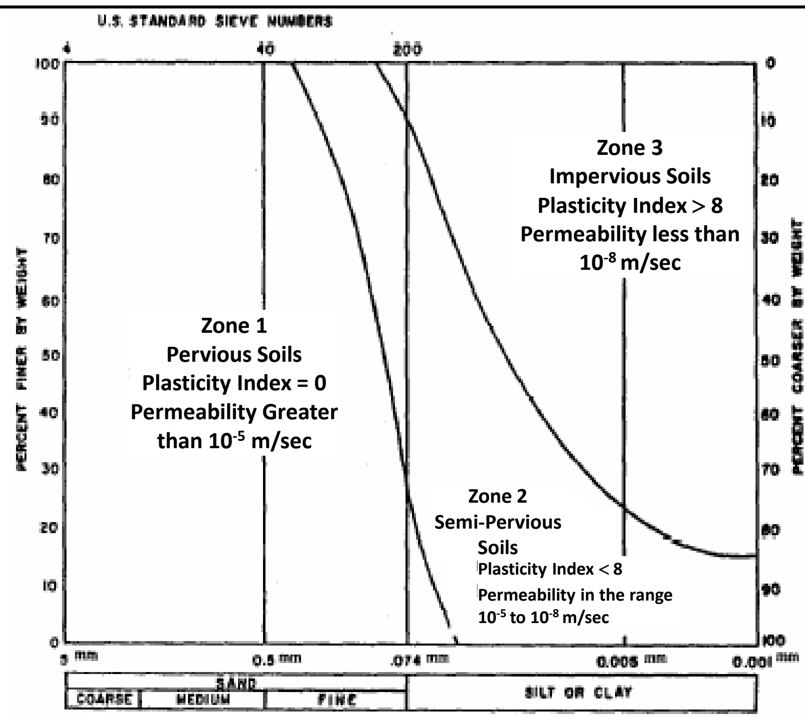
A. Not needed for Zone 1 soils. May be required for Zone 2 soils if nearly saturated. Usually required for landfills.

B. When surface stabilizing layer is used, the thickness generally ranges from 0.3 to 0.9 m.

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

FHWA (1995)



DENSIFICATION OF A LANDFILL DEPOSIT

CASE STUDY 1

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.

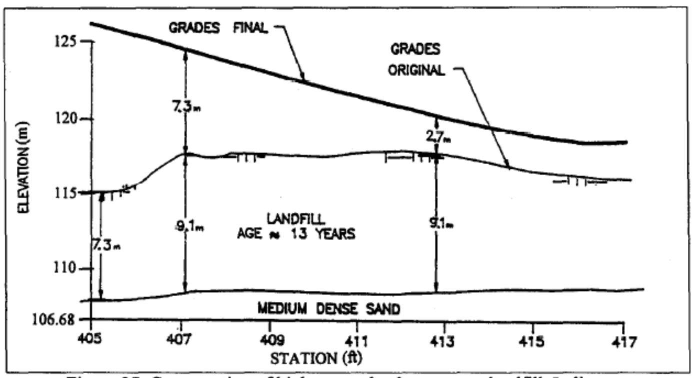


Figure 27. Cross section of highway embankment over landfill, Indiana.

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.

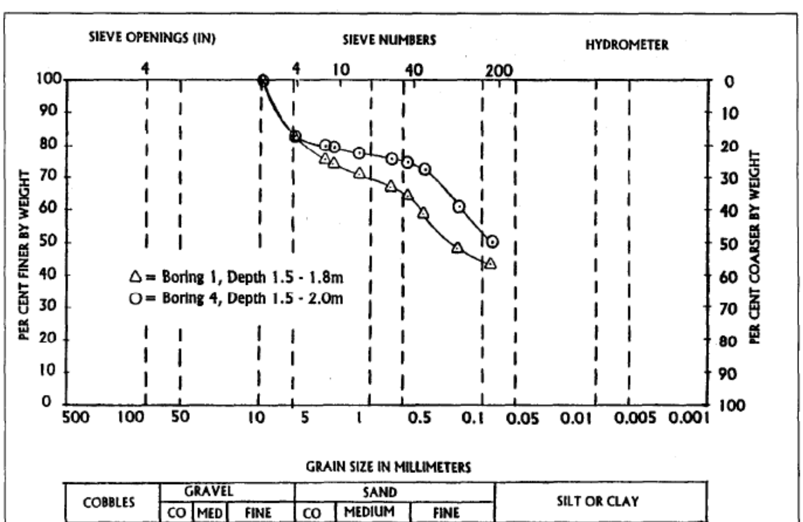


Figure 30. Gradation of landfill deposits, Indiana site.

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,

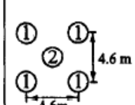
the amount of immediate settlement under the 7.6 m embankment was calculated to be about 25 mm to 152 mm, respectively, which was considered acceptable.

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.

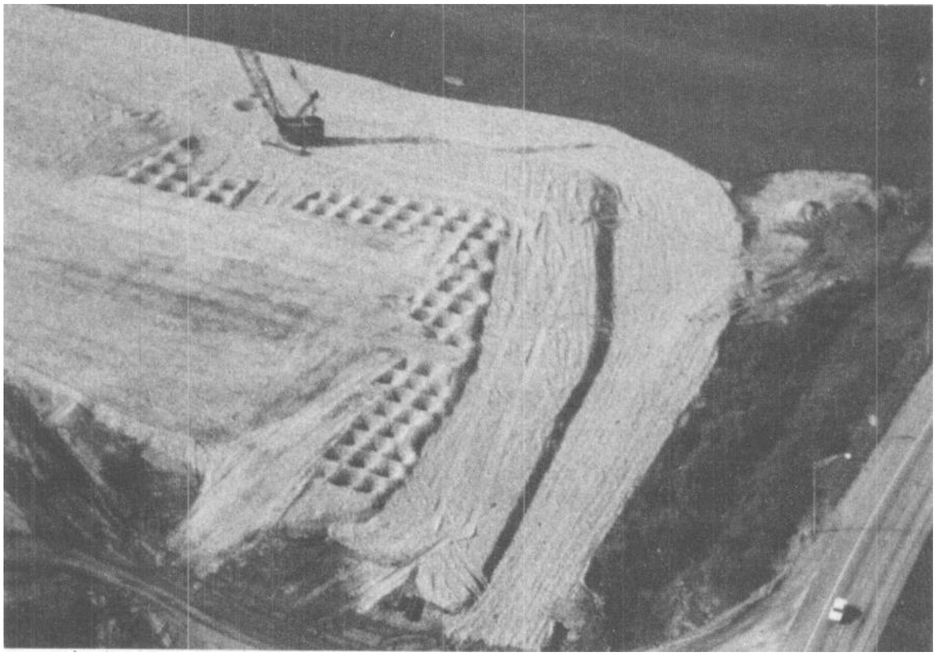
Work Pattern - Indiana Landfill



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

$$\text{Unit Energy} = \frac{6.66\ \text{MJ/m}^2}{9.15\ \text{m}} = 0.73\ \text{MJ/m}^3 = 1.20\ \text{Std. Proctor}$$



DENSIFICATION OF LOOSE POCKETS AND VOIDS CASE STUDY 2

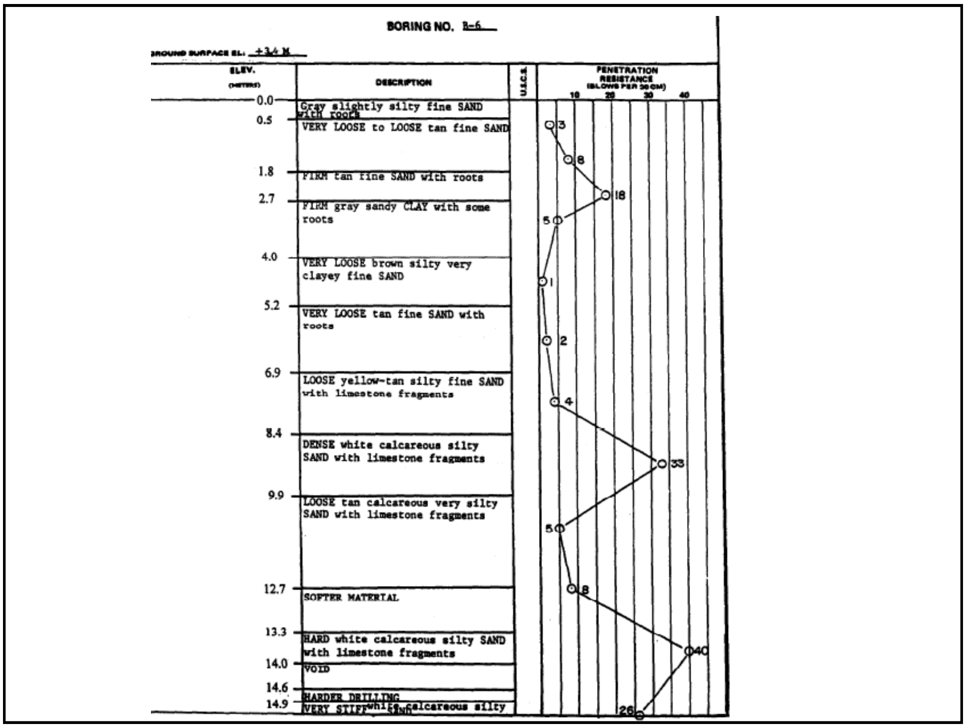
INTRODUCTION

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.



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.

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

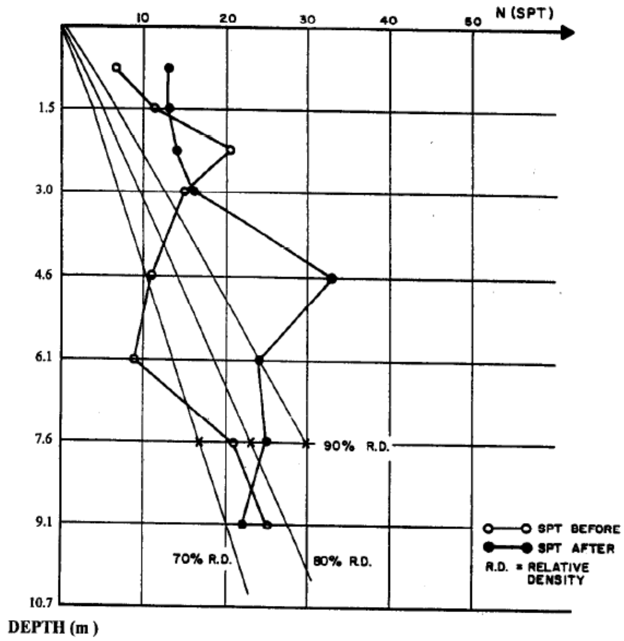


Figure 33. SPT values before and after dynamic compaction..

Example

Design a dynamic compaction method to improve 10-m thick, loose granular soil above water table

Design Guidelines

Parameters to be Determined
Step 1: Selection of tamper and drop height for required depth of improvement Equation 1: $D = n(WH)^{0.5}$

Evaluation Process
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.

FHWA (1995)

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 plasticity 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/m² and for a tamper drop using a single cable with a free spool drum.

FHWA (1995)

$$Depth = n \cdot \sqrt{Weight \times Height}$$

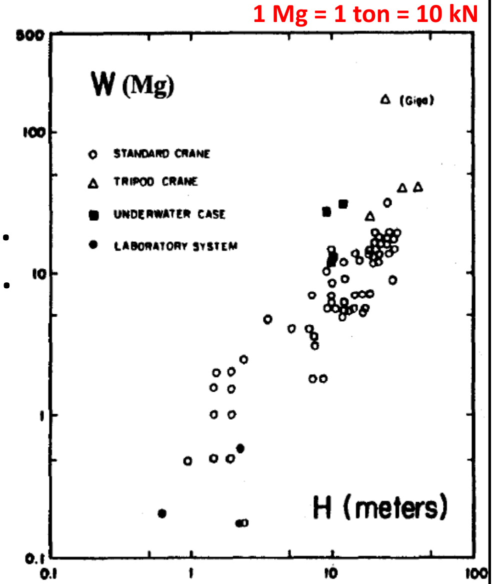
$$10\ m = 0.55 \cdot \sqrt{Weight \times Height}$$

$Weight \times Height = 331$ kN.m (or kJ)

Consider 10 Mg tamper....
Consider 5 Mg tamper......
Find drop height

Consider 10 Mg tamper:
3.3 m drop height
Consider 5 Mg tamper:
6.6 m drop height

1 Mg = 1 ton = 10 kN



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.

FHWA (1995)

Table 8. Applied energy guidelines.[32]

Type of Deposit	Unit Applied Energy (kJ/m³)	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 .

$225\ kJ/m^3 \times 10\ m = 2250\ kJ/m^2$

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

Assumption : all the energy will be applied in one pass

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.

$Weight \times Height = 331$ kN.m (or kJ)

$$Applied\ Energy = \frac{N \cdot W \cdot H \cdot P}{(grid\ spacing)^2}$$

$$2250\ kJ/m2 = \frac{N \cdot (331\ kJ) \cdot P}{(grid\ spacing)^2}$$

Consider 1 pass (Zone 1 Soil, granular),
7 drops at each location, then find grid spacing

$$2250\ kJ/m2 = \frac{7 \cdot (331\ kJ) \cdot 1}{(grid\ spacing)^2}$$

Find $grid\ spacing = 1\ m$

Too small, NOT GOOD!
(see next page)

A. Select a grid spacing ranging from 1.5 to 2.5 times the diameter of the tamper.

Most of the tampers reported in the literature have a diameter, or width, ranging from 1 to 3 m

If we use tamper having a diameter 1 m:

Grid spacing: 1.5 x 1 = 1.5 m

$$2250\ kJ/m2 = \frac{N \cdot (331\ kJ) \cdot P}{(grid\ spacing)^2}$$

$$2250\ kJ/m2 = \frac{N \cdot (331\ kJ) \cdot 1}{(1.5)^2} \qquad N = 15$$

Use Number of drops=15 drops, and 1.5 m spacing

Note about tamper diameter:

Pressure = Weight / Area

Assume tamper contact pressure of 40 kPa (typically 36-72 kPa)

Example:
40 kPa = (15 Mg) / ($\pi d^2/4$)
40 kPa = (150 kN) / ($\pi d^2/4$)
d = 2.19 m (diameter of tamper)

A. Select a grid spacing ranging from 1.5 to 2.5 times the diameter of the tamper.

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

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

FHWA (1995)