SOIL MECHANICS II CVSM308

PROBLEMATIC SOILS & GROUND IMPROVEMENT

About the Course

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List of References

- Han J., (2015), *Principles and Practices of Ground Improvement,* John Wiley & Sons, Inc., Hoboken, New Jersey.
- Coduto D.P., Kitch W. A. and Yeung A. R., (2016), *Foundation design: Principles and practices*, 3rd edition, USA, Pearson, ISBN 0-13-341198-3.
- Koerner R. M., (2012), *Designing with Geosynthetics*, 6th edition, Xlibris Corporation.
- Kirsch K. and Bell A., (2013), *Ground Improvement*, 3rd edition, CRC Press, Taylor & Francis Group.
- Kirsch K. and Kirsch F., (2010), *Ground Improvement by Deep Vibratory Methods*, Taylor & Francis e-Library, 2010.

Textbooks

Course Objectives

The goals of this course are to:
1. introduce various aspects of problematic geomaterials behaviour and their impact on civil constructions.
2. introduce principles of treatment and stabilization of cohesive and cohesionless soils.
3. describe various ground improvement techniques.

Course Outcomes

By the successful completion of this course, the student will be able to:
1. identify problematic soils and their potential risk on civil infrastructures.
2. develop proper solutions to geotechnical problems.
3. stimulate creativity and novelty in geotechnical engineering.

Prerequests

- Principles of Soil Mechanics.
- Strength of Materials

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Topic #1 Introduction

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WHAT TRIGGERS GROUND IMPROVEMENT ?

- Increasing demands for the use of land for better living and transportation.
- Suitable construction sites with favorable geotechnical conditions are becoming less available.

Popular geotechnical problems and challenges include:

bearing failure, large total and differential settlements, instability, liquefaction, erosion, and water seepage.

Popular problematic soils:

- soft clay and silt, loose sand, expansive soil, organic soil, collapsible soil, and frozen soil can be problematic to geotechnical applications.

The options to deal with problematic geomaterials and geotechnical conditions include:

(1) avoiding the site,

(2) designing superstructures accordingly,

(3) removing and replacing problematic geomaterials with better and non-problematic geomaterials, and

(4) improving geomaterial properties and geotechnical conditions.

Source: https://theconstructor.org/geotechnical/avoid-expansive-soil-effects-buildings/409740/

Expansive soil
Source: https://link.springer.com/chapter/10.1007/978-3-319-75527-4_6

Source: https://link.springer.com/referenceworkentry/10.1007%2F978-3-319-73568-9_61

Collapsible soil
Source: https://coloradogeologicalsurvey.org/2018/28848-collapsible-soils/

PROBLEMATIC GEOMATERIALS

Table 1.1 Problematic Geomaterials and Potential Problems

Type of Geomaterial	Name	Potential Problems
Natural	Soft clay	Low strength, high compressibility, large creep deformation, low permeability
	Silt	Low strength, high compressibility, high liquefaction potential, low permeability, high erodibility
	Organic soil	High compressibility, large creep deformation
	Loose sand	Low strength, high compressibility, high liquefaction potential, high permeability, high erodibility
	Expansive soil	Large volume change
	Loess	Large volume change, high collapsible potential
Fill	Uncontrolled fill	Low strength, high compressibility, nonuniformity, high collapsible potential
	Dredged material	High water content, low strength, high compressibility
	Reclaimed fill	High water content, low strength, high compressibility
	Recycled material	Nonuniformity, high variability of properties
	Solid waste	Low strength, high compressibility, nonuniformity, and high degradation potential
	Bio-based by-product	Low strength, high compressibility, and high degradation potential

Organic soil, http://www.roadex.org/e-learning/lessons/roads-on-peat/maintenance-of-existing-roads/

Reclaimed land, http://www.jandenul.com/en/activities/dredging-and-marine-works/land-reclamation-and-beach-replenishment

Loess, Source: https://en.wikipedia.org/wiki/Loess

PROBLEMATIC CONDITIONS

Natural conditions:

Geologic, geotechnical, hydraulic, and climatic conditions, such as earthquakes, cavities and sinkholes, floods, wind, and freeze−thaw cycles.

Examples of problematic geotechnical conditions are existence of problematic geomaterials, a high groundwater table, inclined bedrock, and steep natural slopes.

Human activities:

Mainly the construction of superstructures, substructures, and earth structures, can change geotechnical conditions, which may cause problems for projects, for example, excavation, tunneling, pile driving, rapid drawdown of surface water, elevation of surface water by levees and dams, and groundwater withdrawal.

https://www.nationalgeographic.com/environment/sinkhole/

Source: tunneltalk.com

PROBLEMATIC CONDITIONS

Notes:

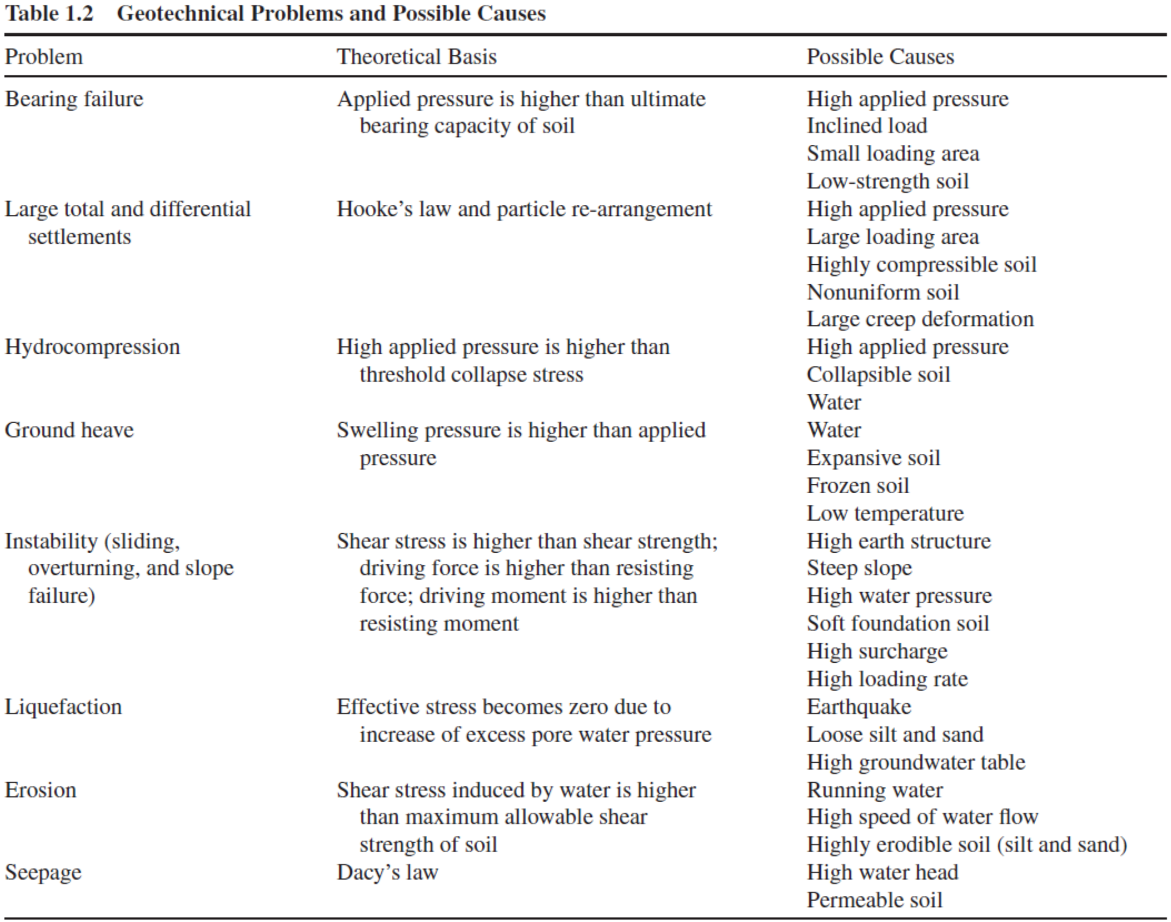

Table 1.2 Geotechnical Problems and Possible Causes

Problem	Theoretical Basis	Possible Causes
Bearing failure	Applied pressure is higher than ultimate bearing capacity of soil	High applied pressure Inclined load Small loading area Low-strength soil
Large total and differential settlements	Hooke's law and particle re-arrangement	High applied pressure Large loading area Highly compressible soil Nonuniform soil Large creep deformation
Hydrocompression	High applied pressure is higher than threshold collapse stress	High applied pressure Collapsible soil Water
Ground heave	Swelling pressure is higher than applied pressure	Water Expansive soil Frozen soil Low temperature
Instability (sliding, overturning, and slope failure)	Shear stress is higher than shear strength; driving force is higher than resisting force; driving moment is higher than resisting moment	High earth structure Steep slope High water pressure Soft foundation soil High surcharge High loading rate
Liquefaction	Effective stress becomes zero due to increase of excess pore water pressure	Earthquake Loose silt and sand High groundwater table
Erosion	Shear stress induced by water is higher than maximum allowable shear strength of soil	Running water High speed of water flow Highly erodible soil (silt and sand)
Seepage	Dacy's law	High water head Permeable soil

Source: https://www.ocf.berkeley.edu/~zellw/2015/12/14/san-francisco-bay-soil-liquefaction-hazard-and-population-analysis/

SOIL MECHANICS II

CVSM308

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Topic #2 Expansive Soils

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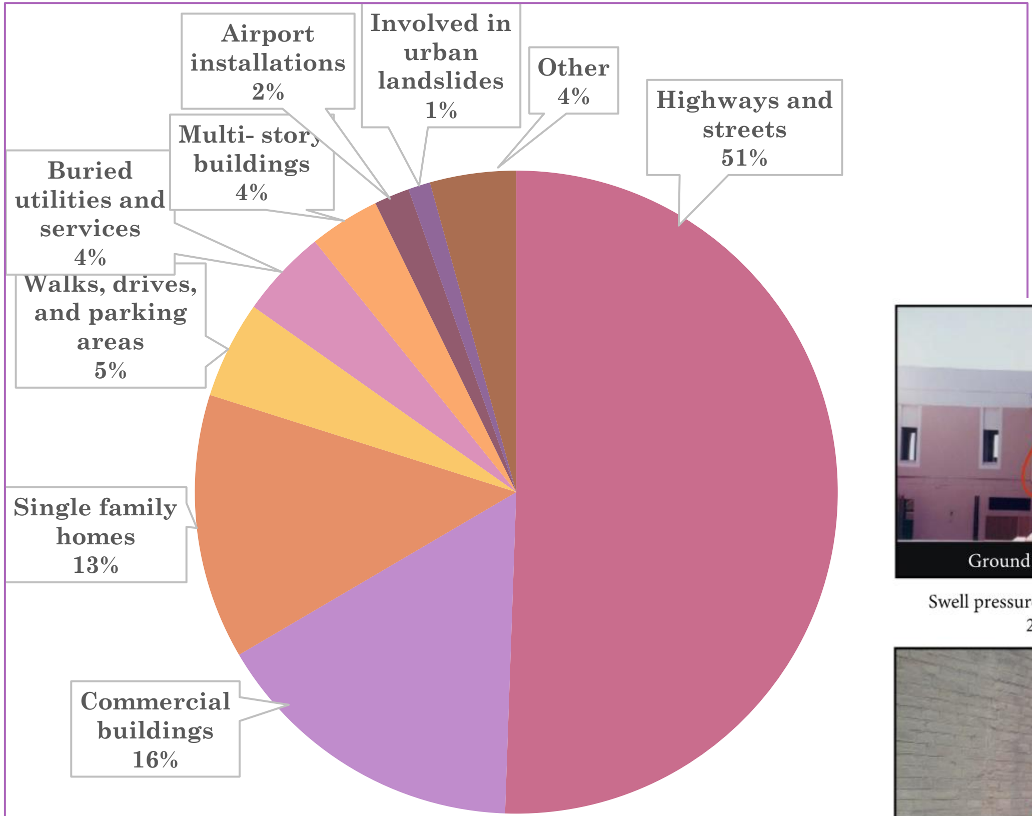
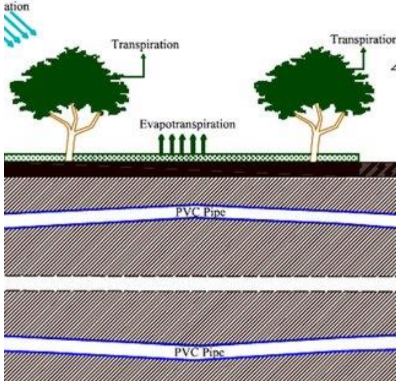
INFRASTRUCTURES AFFECTED BY EXPANSIVE SOILS-*USA EXAMPLE*



ANNUAL DAMAGE IN THE USA FROM EXPANSIVE SOILS, See Table 27.1 Coduto et al (2016)



Source: DOI:10.1186/s40703-015-0005-4

Swell pressure causes diagonal cracking in 2-storey building

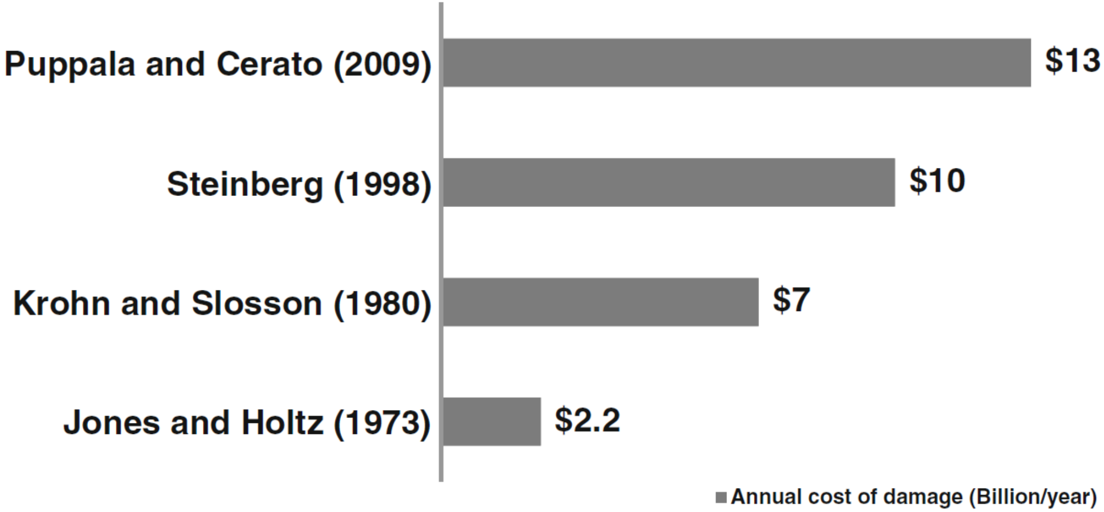
Uplifting of flexible pavement due to expansive soil

The wall is recorded to repeatedly crack after reconstruction

Expansive soils cause slope failure of embankment

Source: https://doi.org/10.1155/2020/1510969

INFRASTRUCTURES AFFECTED BY EXPANSIVE SOILS-*USA EXAMPLE*



The annual costs of damages to structures constructed on/with expansive soils in the United States since 1973

Source: Adem, H. H., & Vanapalli, S. K. (2016). Heave Prediction in a Natural Unsaturated Expansive Soil Deposit Under a Lightly Loaded Structure. Geotechnical and Geological Engineering, 34(4), 1181–1192. doi:10.1007/s10706-016-0037-3

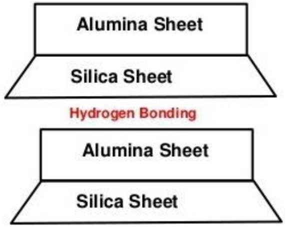
WHAT CAUSES A CLAY TO EXPAND?

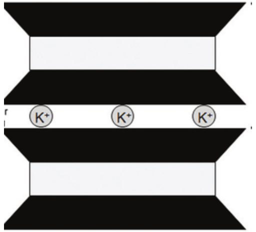
- The most common clay minerals are kaolinite, illite, and montmorillonite

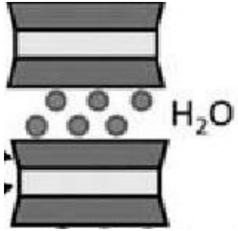
TABLE 27.2 SWELL POTENTIAL OF PURE CLAY MINERALS (adapted from Budge et al., 1964)

Surcharge Load		Swell Potential (%)		
(lb/ft^2)	(kPa)	Kaolinite	Illite	Montmorillonite
200	9.6	Negligible	350	1,500
400	19.1	Negligible	150	350

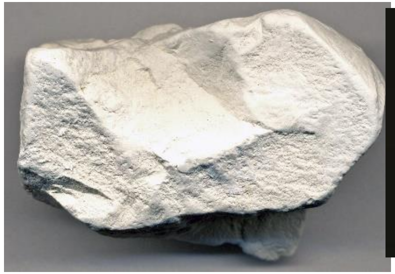
Structure of







Swelling occurs when water is absorbed between combined silica and alumina sheets that make up the molecular structure of clays, causing the combined sheets to separate.

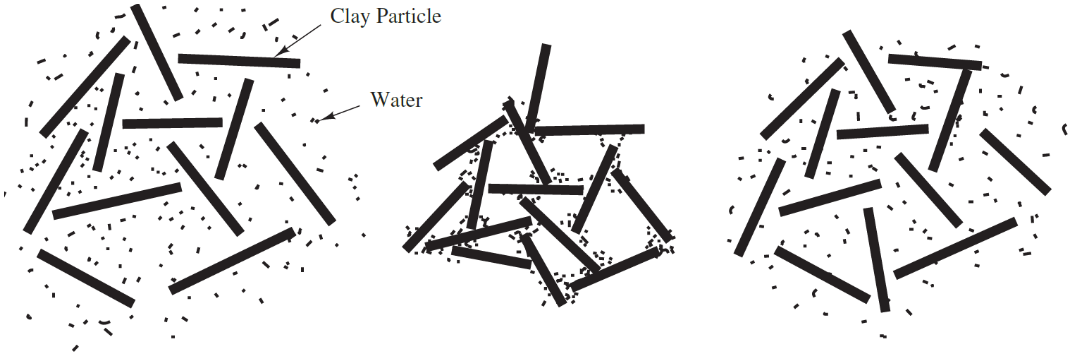


https://en.wikipedia.org/wiki/Kaolinite

https://www.assignmentpoint.com/science/geographic-minerals/illite-properties-occurrence.html

https://guernsey.desertcart.com/

WHAT FACTORS CONTROL THE AMOUNT OF EXPANSION?



(a) A saturated expansive clay

(b) The expansive clay shrinks upon drying

(c) The expansive clay swells upon wetting

Figure 27.4 Shrinkage and swelling of an expansive clay.

- The percentage of expansive clays in the soil: higher percentages correspond to more expansion. Soils typically expand by ≤ 50%.
- The initial moisture content and the surcharge pressure.
- Remolding a soil into a compacted fill may make it more expansive.
- For fills, the methods of compaction (kneading vs. static) and the compaction moisture content and dry unit weight.

Swell pressure is a surcharge pressure which suppresses all the swell resulting in no volume change for a given soil, **see** Figure 27.5.

➢ ***Why pavements are so susceptible to damage from expansive soils?***

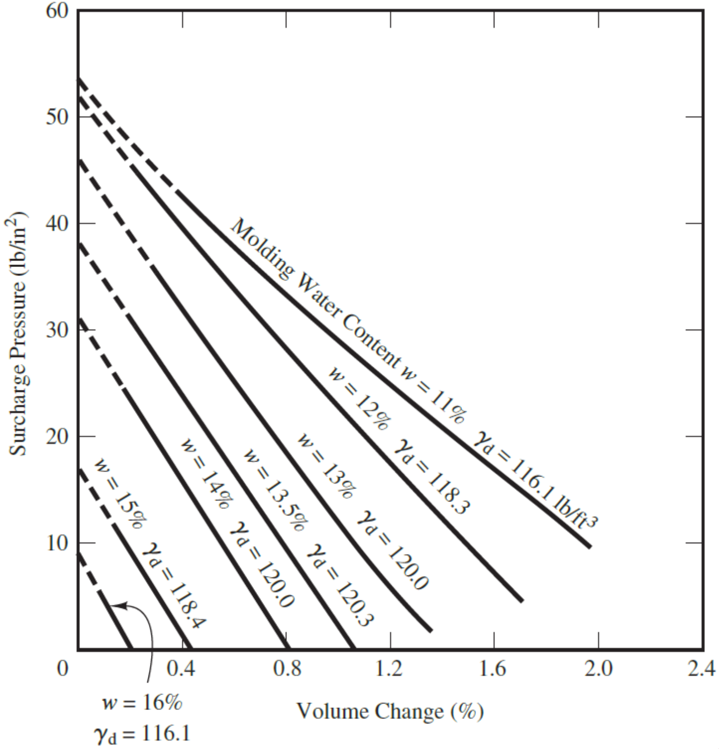


Figure 27.5 Swell potential as a function of initial moisture content and surcharge load (typical) (adapted from Seed et al., 1962).

DEPTH OF THE ACTIVE ZONE

- The moisture content of soils fluctuates more near the ground surface than at depth. This is because these upper soils respond more rapidly to variations in precipitation and evaporation/transpiration.
- The moisture content is reasonably constant below the depth where it fluctuates, so no expansion occurs below this point.
- In this case, the active zone for design can be taken as the zone of moisture content fluctuations.
- Depth of the active zone is probably between 1-9 m.
- The active zone depth may decrease with local human activities that provide water source to the soil.

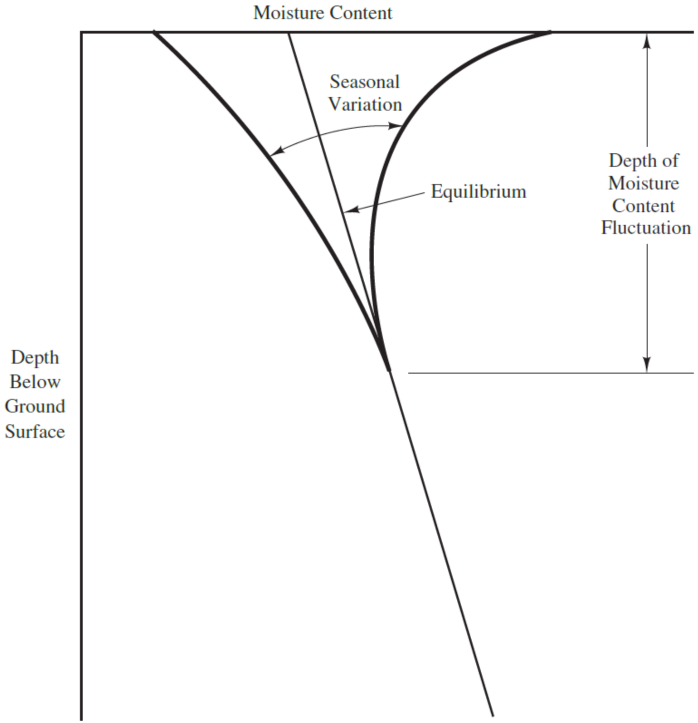


Figure 27.11 The layer of soil that has a fluctuating moisture content.

IDENTIFYING, TESTING, AND EVALUATING EXPANSIVE SOILS

- **Visual identification**
  - a soil must have a significant clay content,
  - Probable USCS symbol CL or CH (although some ML, MH, and SC soils also can be expansive).
  - A dry expansive soil will often have cracks and signs of previous swelling and shrinking.

- **Evaluation**
  - **Qualitative Evaluations** based on correlations with common soil tests

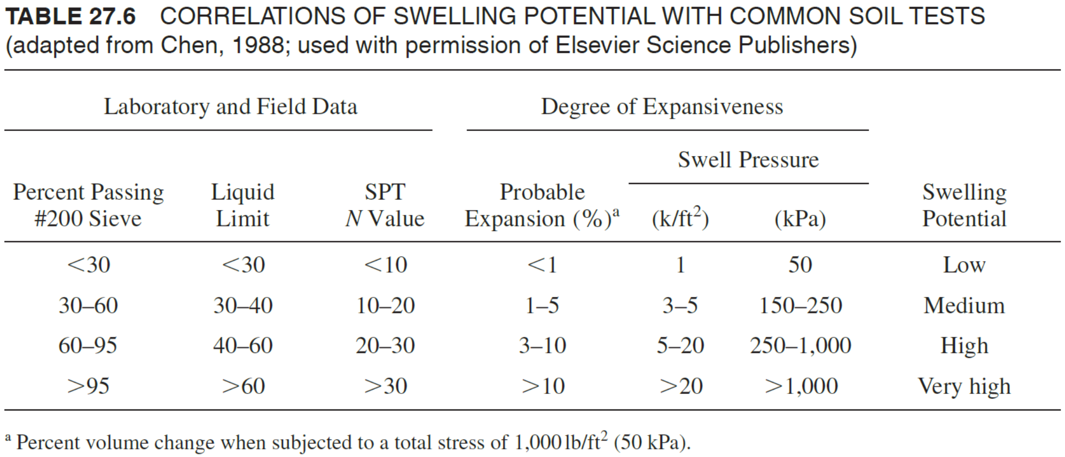


TABLE 27.6 CORRELATIONS OF SWELLING POTENTIAL WITH COMMON SOIL TESTS (adapted from Chen, 1988; used with permission of Elsevier Science Publishers)

Laboratory and Field Data			Degree of Expansiveness			
				Swell Pressure		
Percent Passing #200 Sieve	Liquid Limit	SPT *N* Value	Probable Expansion (%)[a]	(k/ft^2)	(kPa)	Swelling Potential
<30	<30	<10	<1	1	50	Low
30–60	30–40	10–20	1–5	3–5	150–250	Medium
60–95	40–60	20–30	3–10	5–20	250–1,000	High
>95	>60	>30	>10	>20	>1,000	Very high

[a] Percent volume change when subjected to a total stress of 1,000 lb/ft^2 (50 kPa).

- **Semiqualitative Evaluations** based on swell potential measured in the lab.

<u>ASTM D4546-14</u> for one-dimensional swell or collapse of soils, Methods A, B, and C.

Methods A

<u>Potential swell strain (ε_w)</u>

$$\varepsilon_w = \frac{\Delta h_2}{h_0 - \Delta h_1} \qquad (27.1)$$

where

h_0 = the initial height of the specimen,
Δh_1 is the change of the specimen's height at the geostatic stress at the depth of fill (Point A).
Δh_2 is the change of the specimen's height due to soaking (from Point A to Point B).
The swell pressure, $\boldsymbol{\sigma_s}$, represents the vertical stress at which no swelling occurs.

TABLE 27.8 TYPICAL CLASSIFICATION OF SOIL EXPANSIVENESS BASED ON LOADED SWELL TEST RESULTS AT IN SITU OVERBURDEN STRESS

Swell Potential (%)	Swell Classification
<0.5	Low
0.5–1.5	Marginal
>1.5	High

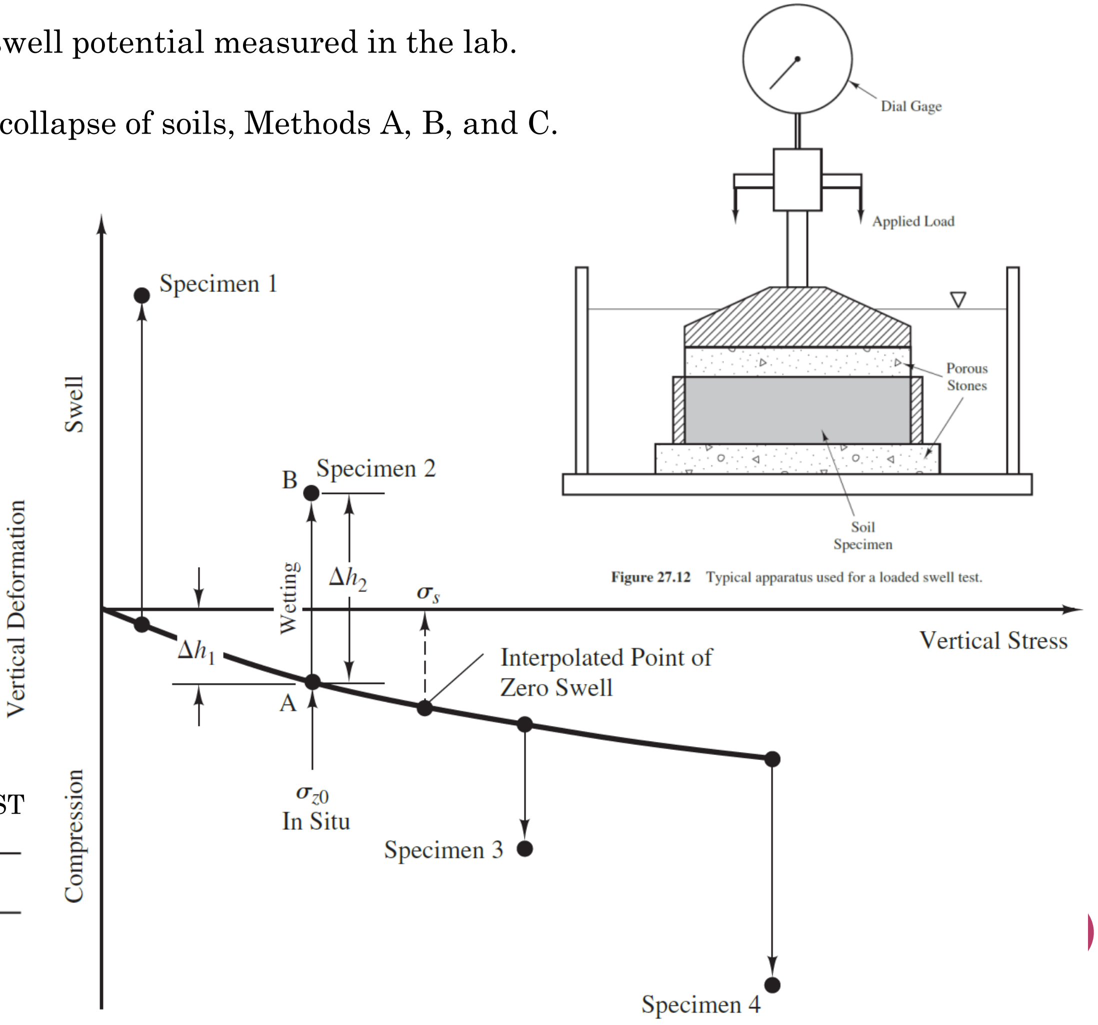


Figure 27.12 Typical apparatus used for a loaded swell test.

Figure 27.13 Loading steps followed in a loaded swell test following Method A of ASTM D4546.

ESTIMATING POTENTIAL HEAVE

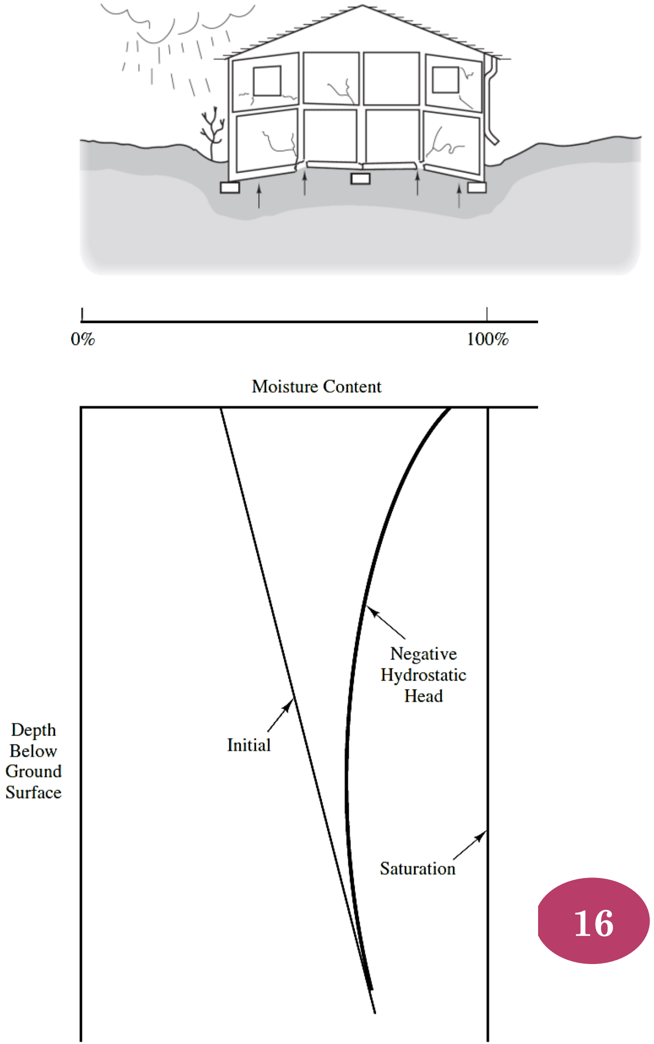
The heave caused by soil expansion is:

$$\delta_w = \sum \alpha H \varepsilon_w \qquad (27.4) \qquad\qquad \alpha = \frac{S - S_0}{1 - S_0} \qquad (27.3)$$

where

δ_w = heave caused by soil expansion
α = wetting coefficient
H = thickness of layer
ε_w = potential swell strain
S_0 = degree of saturation before wetting (in decimal form)
S = degree of saturation after wetting (in decimal form)

- Step 1. Divide the active zone of soil beneath the foundation into layers (perhaps 25 cm).
- Step 2. Compute the vertical total stress, σ_z, at the midpoint of each layer. This stress should be the sum of the overburden and induced stresses.
- Step 3. Using the results of the laboratory swell tests, compute the potential swell strain, ε_w, at the midpoint of each layer.
- Step 4. Determine the **initial** profile of degree of saturation versus depth. This would normally be based on the results of moisture content tests from soil samples recovered from an exploratory boring.
- Step 5. Estimate the **final** profile of degree of saturation versus depth.
- Step 6. Compute the heave for each layer and sum them using Equation 27.4.



Example 27.1

A compressive column load of 140 kN is to be supported on a 0.50 m deep square footing (B=1 m). The allowable bearing pressure is 150 kPa. The soils beneath this proposed footing are expansive clays that currently have a degree of saturation of 25 percent. This soil has a unit weight of 17.0 kN/m^3, and the depth of the active zone is 3.5 m. The results of laboratory swell tests are shown in Figure 27.17. Compute the potential heave of this footing due to wetting of the expansive soils.

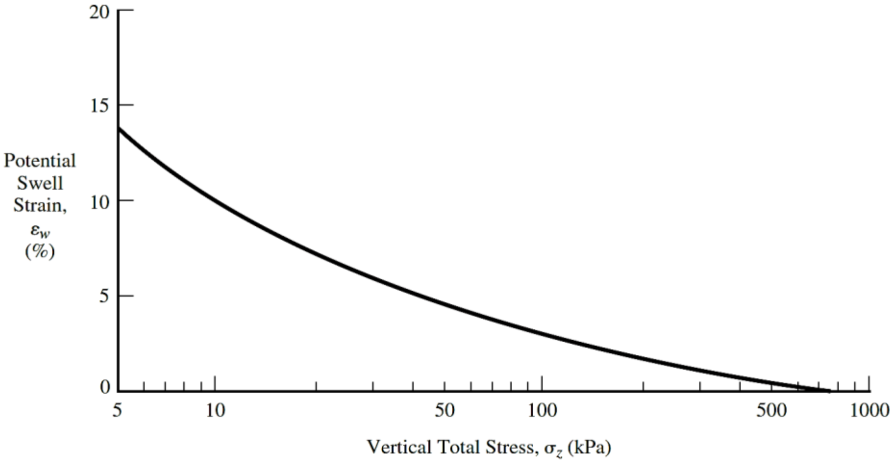


Figure 27.17 Potential swell strain versus swell pressure determined using a series of loaded swell tests on an expansive soil.

Solution

$$\sigma_{zD} = \gamma D - u = (17.0\ \mathrm{kN/m^3})(0.5\ \mathrm{m}) - 0 = 8\ \mathrm{kPa}$$

- Assume S after wetting varies from 100 percent at the ground surface to 25 percent at the bottom of the active zone.
- Compute σ_z, product of $(q - \sigma_{zD})$ and I_σ from Equation 3.14, and add it to σ_{z0} (the geostatic stress) to compute σ_z.
- Find ε_w using the lab data, α using Equation 27.3, and δ_w using Equation 27.4.

		At Midpoint of Soil Layer								
Depth (m)	H (mm)	z_f (m)	σ_{z0} (kPa)	$\Delta\sigma_z$ (kPa)	σ_z (kPa)	ε_w (%)	S_0 (%)	S (%)	α	δ_w (mm)
0.50–0.75	250	0.12	11	141	152	2.0	25	90	0.87	4.3
0.75–1.00	250	0.32	15	126	141	2.1	25	80	0.73	3.8
1.00–1.50	500	0.75	21	68	89	3.5	25	70	0.60	10.5
1.50–2.00	500	1.25	30	33	63	3.9	25	50	0.33	6.4
2.00–3.00	1000	2.00	42	14	56	4.5	25	30	0.07	3.1
									Total	28

The estimated heave is 28 mm.

Example 27.1

For square loaded areas,

$$I_\sigma = 1 - \left(\frac{1}{1 + \left(\frac{B}{2z_f} \right)^2} \right)^{1.76} \qquad (3.14)$$

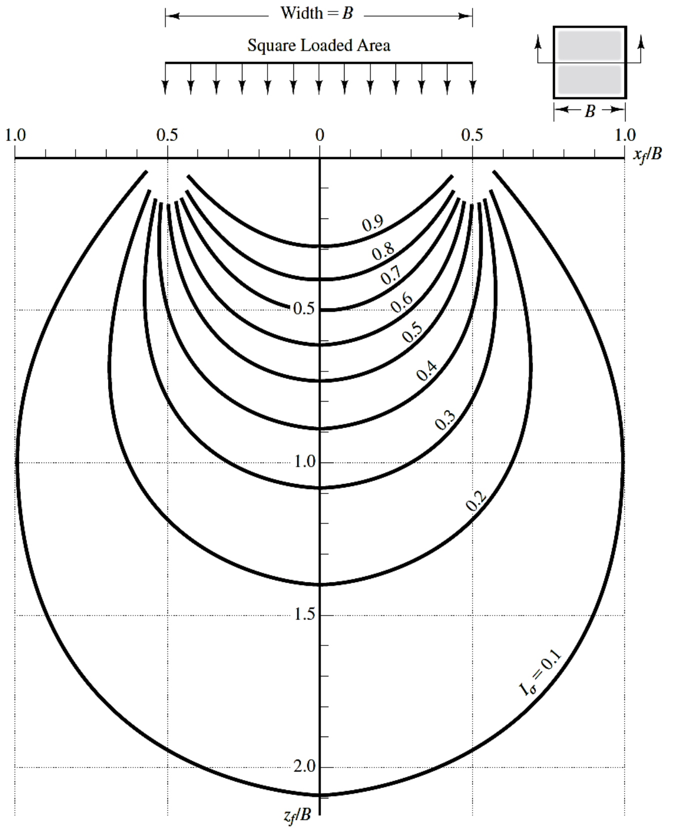


Figure 3.6 Influence factors for induced vertical stress under a square loaded area, per Boussinesq.

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Topic #3 Collapsible Soils

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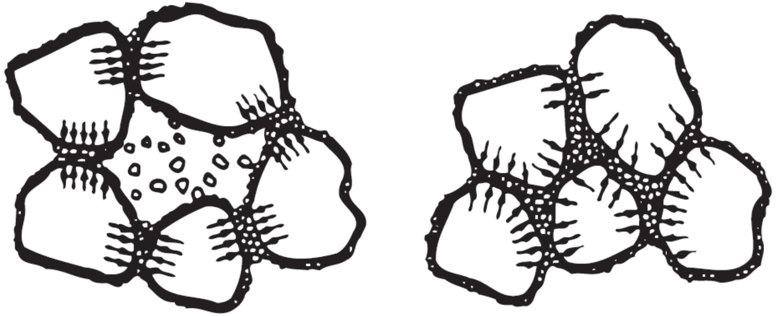
OCCURRENCE OF COLLAPSIBLE SOILS

- Often occur as deposits in arid and semiarid areas of the world
- Consist mostly of sand and silt size particles arranged in a loose "honeycomb" structure.
- These particles are cemented by water-softening agents, such as clay, gypsum or calcium carbonate.
- These soils are dry and strong in their natural state and appear to provide good support for foundations.
- However, if they become wet or subject to water flow, these soils consolidate, thus generating unexpected settlements.
- Sometimes called **metastable soils**, and the process of collapse is sometimes called **hydrocompression**.


Loaded Soil Structure
Before Inundation

Loaded Soil Structure
After Inundation

Figure 28.1 Microscopic view of a collapsible soil.

COLLAPSIBLE ALLUVIAL AND COLLUVIAL SOILS

- Alluvial soils are transported by water, colluvial soils are transported by gravity.
- When flow deposits dry by evaporation, the retreating water draws the suspended clay particles and dissolved salts toward the particle contact points.
- Colluvium is typically composed of a heterogeneous range of rock types and sediments ranging from silt to rock fragments of various sizes.
- The uppermost stratum may be collapsible, perhaps 1 to 3 m thick, whereas elsewhere the collapse-prone soils may extend 60 m or more below the ground surface.

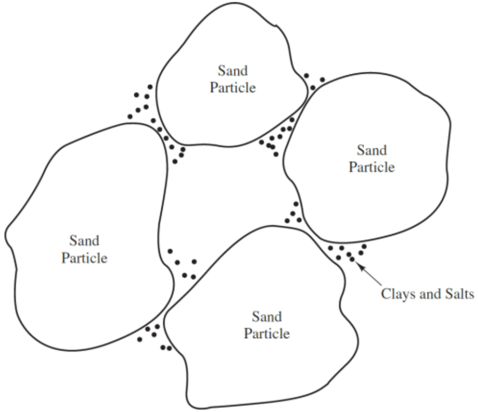


Figure 28.2 Microscopic view of a collapsible alluvial/ colluvial soil.

Source: Wikipedia : Alluvium deposits in the Gamtoos Vally in South Africa

Collapsible Aeolian Soils

- Aeolian soils are deposited by wind.
- These include windblown sand dunes, loess, volcanic dust deposits, as well as other forms.
- Loess (an aeolian silt or sandy silt) is the most common aeolian.
- Collapsible loess has a very high porosity (typically on the order of 50 percent) and a correspondingly low unit weight (typically 11-14 kN/m^3).
- The individual particles are usually coated with clay, which acts as a cementing agent to maintain the loose structure. This cementation is often not as strong as that in many alluvial soils.
- Collapse can occur either by wetting under a moderate normal stress or by subjecting the soil to higher normal stresses without wetting it.

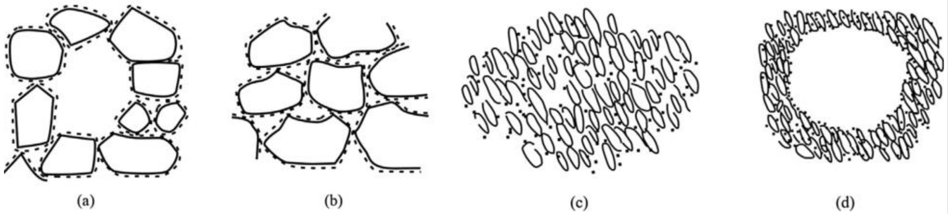


Fig. The classification for loess soil pores: (a) spaced pores; (b) intergranular pores; (c) intragranular pores and (d) macropore (modified after Gao, 1980a, 1981).

Sand dunes- Samawa/Iraq

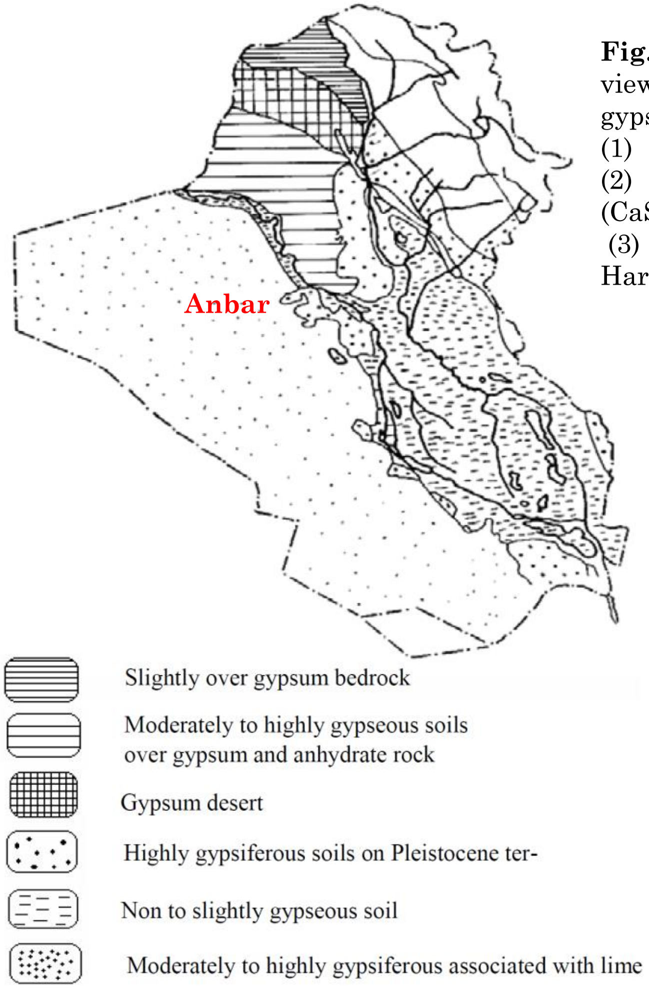
Destructive effect of sand dunes on asphaltic road

Source: https://www.researchgate.net/figure/Field-photographs-of-sand-dunes-showing-A-destructive-effect-of-sand-dunes-along-old_fig1_260365496

Source: Wikipedia : https://upload.wikimedia.org/wikipedia/commons/c/c7/Tn_1200_paulette_loess_soil_cliff_jpg.jpg

GYPSEOUS SOILS

- Soil particles are bonded mainly by gypsum ($CaSO_4.2H_2O$) or anhydrite ($CaSO_4$).
- Gypseous soils cover about 20 - 30 % of Iraqi land primarily on the west and south west parts.
- Gypseous soils experience considerable collapse upon exposure to water.



Distribution of gypsum in Iraq (Al Barazanji 1973)

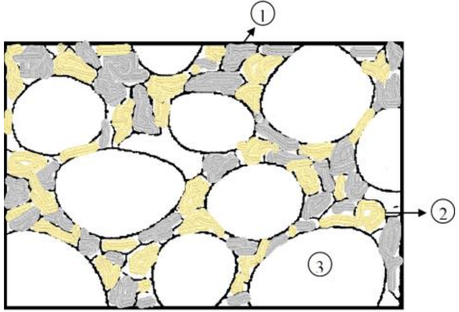


Fig. Microscopic view of a sandy gypseous soil : (1) Soil grains (2) Cementation ($CaSO_4.2H_2O$) (3) Voids, (After Harwood 1988).

Fig. Gypseous soil samples from the main campus area of Anbar University- Iraq
Depth: 0.5 m from NGS

IDENTIFICATION, SAMPLING, AND TESTING

- **Indirect identification**
  - Assessing collapse potential by correlating it with other engineering properties such as unit weight, Atterberg limits, or percent clay particles.
  - Soils having a low dry unit weight, low moisture content, and the grain size distributions described earlier are most likely to be problematic.
- **Direct identification**
  - Measuring the collapse potential to guide the design and remediation processes.

- **Laboratory Soil Collapse Tests**

ASTM D5333 describes a standard test procedure where:

- the sample is progressively loaded at its in situ moisture content until reaching a specified normal stress.
- After consolidating at this stress, the sample is then wetted and the additional strain, if any, due to wetting is measured.
- This strain is the collapse potential, I_c. If the sample is wetted at a standard normal stress of 200 kPa, then the strain is the collapse index, I_e.

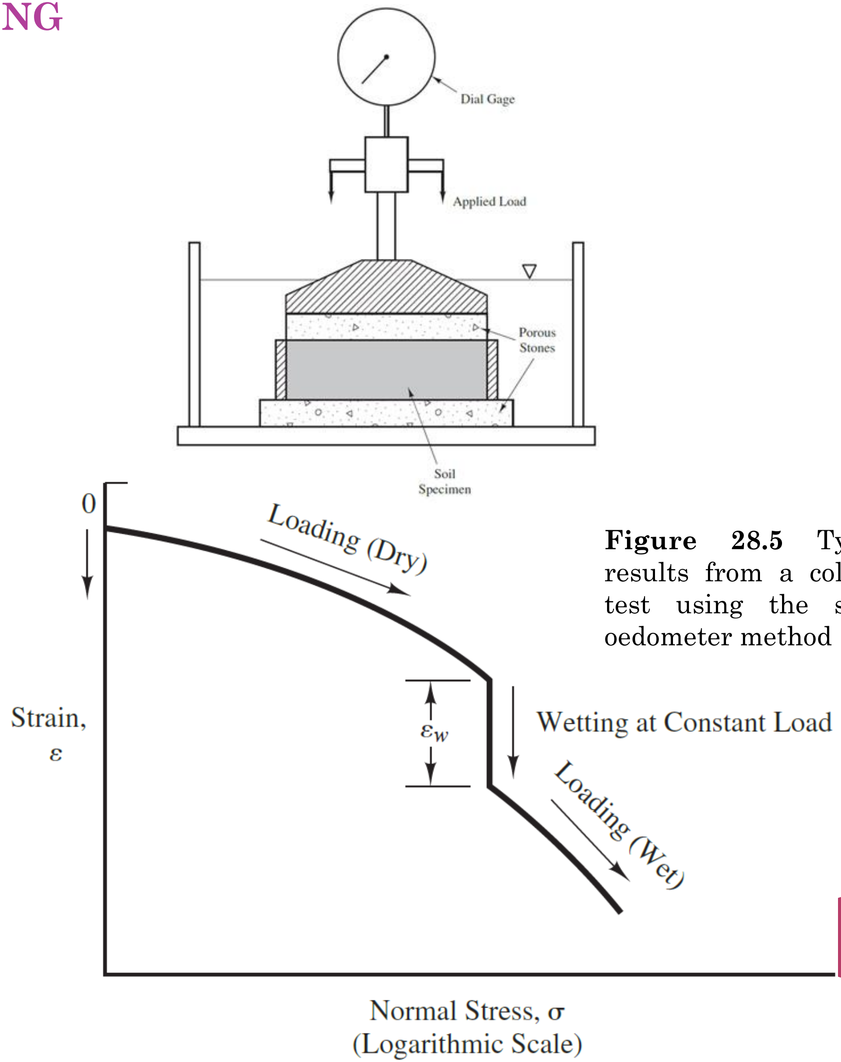


Figure 28.5 Typical results from a collapse test using the single oedometer method

WETTING PROCESSES

Usually, the water that generates the collapse comes from artificial sources, such as the following:

- Infiltration from irrigation of landscaping or crops
- Leakage from lined or unlined canals
- Leakage from pipelines and storage tanks
- Leakage from swimming pools
- Leakage from reservoirs
- Seepage from septic tank leach fields
- Infiltration of rainwater as a result of unfavorable changes in surface drainage

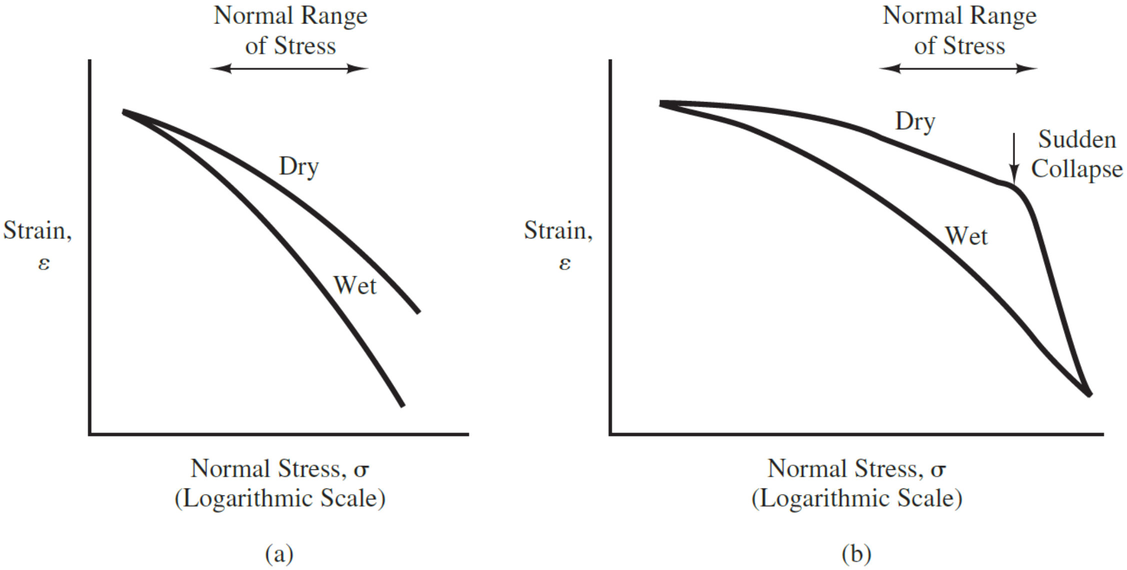


Figure 28.6 Relationship between hydrocollapse strain and normal stress: (a) for most collapsible soils; and (b) for loess.

Settlement Computations

The potential hydrocollapse settlement:

$$\delta_w = \sum \alpha H \varepsilon_c \qquad (28.1)$$

δ_w = settlement due to hydroconsolidation
α = wetting coefficient
ε_c = collapse strain potential (at saturation)
H = depth of layer

- The total depth should be from the base of the footing to the maximum anticipated depth of wetting.

- The wetting coefficient at a given vertical stress:

$$\alpha = \frac{\text{Collapse due to wetting}}{\text{Collapse due to saturation}}$$

- $\alpha \approx 0.5$ to 0.8.

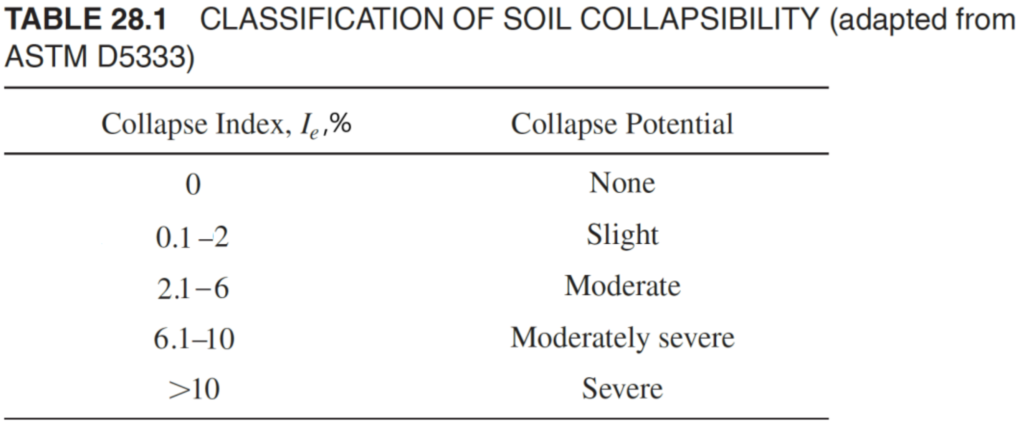


TABLE 28.1 CLASSIFICATION OF SOIL COLLAPSIBILITY (adapted from ASTM D5333)

Collapse Index, I_e,%	Collapse Potential
0	None
0.1 –2	Slight
2.1 – 6	Moderate
6.1–10	Moderately severe
>10	Severe

SOIL MECHANICS II CVSM308

PROBLEMATIC SOILS & GROUND IMPROVEMENT

Topic #4 Ground Improvement Techniques-an Overview

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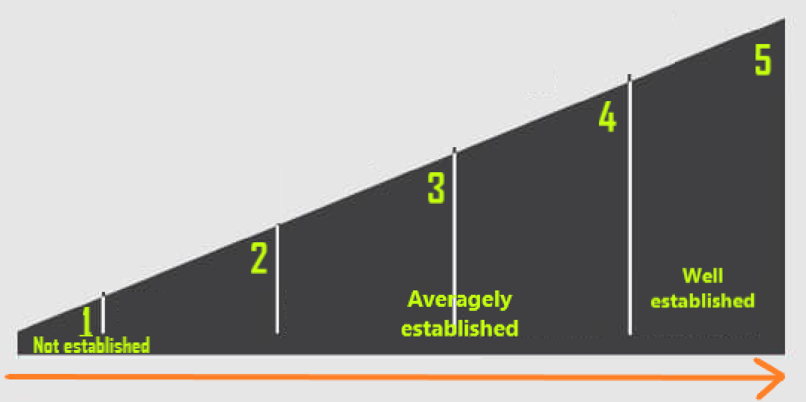
Image source: https://www.fugro.com/about-fugro/our-expertise/innovations/field-compaction-technology

GROUND IMPROVEMENT METHODS

Ground Improvement Categories

- 1. Densification
  - Shallow < 3m
  - Deep > 3m
- 2. Replacement
  - Shallow < 3m
  - Deep > 3m
- 3. Drainage, dewatering and consolidation
- 4. Chemical stabilization
  - Shallow
  - Deep
- 5. Reinforcement
  - Fill
  - In *situ* ground
- 6. Thermal and biological treatment

Level of Technology Establishment



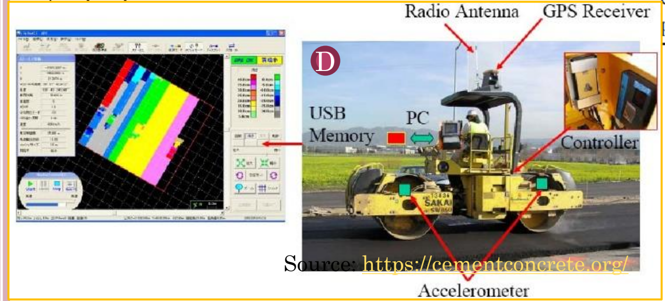
DENSIFICATION:- SHALLOW COMPACTION

Table 1.5 General Descriptions, Functions, and Applications of Ground Improvement Methods

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Densification	Shallow compaction	Traditional compaction Ⓐ Level = 5	Apply static or vibratory load on ground surface in a certain number of passes to densify problematic geomaterial	Increase density, strength, and stiffness; reduce deformation, permeability, collapsible potential, and ground heave	Suitable for a wide range of fills to a lift thickness of 0.3 m; used to compact fill
		High-energy impact roller compaction Ⓑ Level = 2	Apply a lifting and falling motion by a roller with high-energy impact on ground surface to densify or crush problematic geomaterial	Increase density, strength, and stiffness; reduce deformation, permeability, collapsible potential, and ground heave; crush rock and concrete into rubble	Suitable for a wide range of geomaterials to a depth of 2 m; used to improve subgrade and foundation soil and compact fill
		Rapid impact compaction Ⓒ Level = 2	Use an excavator to drop a weight repeatedly on ground surface to densify problematic geomaterial	Increase density, strength, and stiffness; reduce deformation, permeability, collapsible potential, and ground heave	Suitable for granular geomaterials up to 6 m deep; used to improve subgrade and foundation soil and compact fill
		Intelligent compaction Ⓓ Level = 2	Apply and adjust compaction energy based on on-board display from measurements in real time to densify problematic geomaterial	Increase density, strength and stiffness; reduce deformation, permeability, collapsible potential, and ground heave, identify areas of poor compaction, and maximize productivity	Suitable for granular geomaterials; used to improve subgrade and foundation soil and compact fill

Source: https://acedemo.com/grading-excavations-compaction-services/

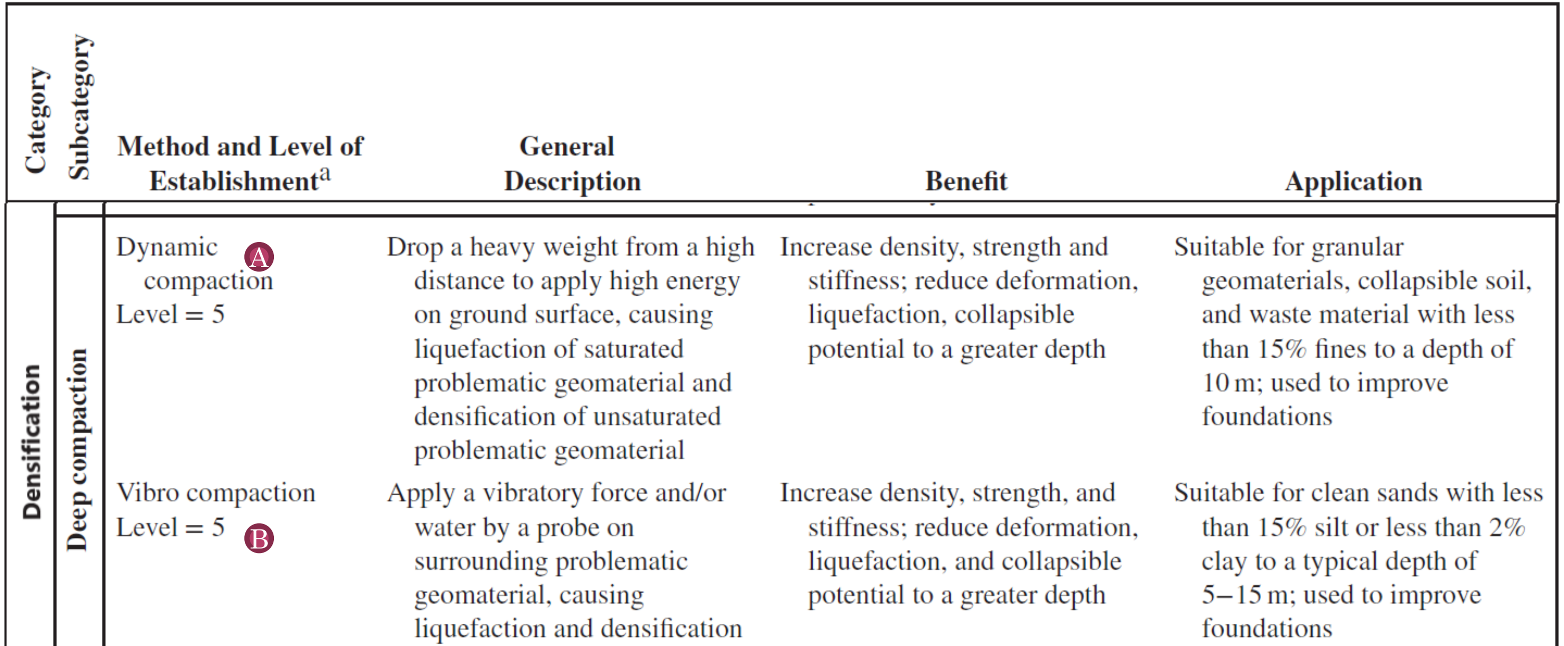
Source: https://landpac.com/typical-applications/



Source: https://cementconcrete.org/

Source: https://dir.indiamart.com/

DENSIFICATION:- DEEP COMPACTION



Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Densification	Deep compaction	Dynamic compaction Ⓐ Level = 5	Drop a heavy weight from a high distance to apply high energy on ground surface, causing liquefaction of saturated problematic geomaterial and densification of unsaturated problematic geomaterial	Increase density, strength and stiffness; reduce deformation, liquefaction, collapsible potential to a greater depth	Suitable for granular geomaterials, collapsible soil, and waste material with less than 15% fines to a depth of 10 m; used to improve foundations
		Vibro compaction Level = 5 Ⓑ	Apply a vibratory force and/or water by a probe on surrounding problematic geomaterial, causing liquefaction and densification	Increase density, strength, and stiffness; reduce deformation, liquefaction, and collapsible potential to a greater depth	Suitable for clean sands with less than 15% silt or less than 2% clay to a typical depth of 5–15 m; used to improve foundations

Source:
http://www.ffgb.be/Business-Units/Retaining-Walls---Utilities/Dynamische-verdichting.aspx?lang=en-US

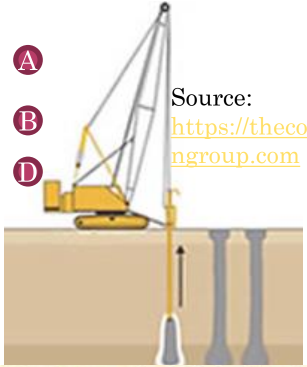
Source:
https://www.vibromenard.co.uk/techniques/vibro-compaction/

REPLACEMENT:- SHALLOW REPLACEMENT

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Replacement	**Shallow replacement**	Overexcavation and replacement Level = 5	Remove problematic geomaterial and replace with good-quality geomaterial	Increase strength and stiffness; reduce deformation, liquefaction, collapsible, and ground heave potential	Suitable and economic for a wide range of geomaterials with limited area and limited depth (typically to 3 m deep and above groundwater table)

Source: https://acedemo.com/grading-excavations-compaction-services/

REPLACEMENT:- DEEP REPLACEMENT



Source: https://thecollingroup.com

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Replacement	Deep replacement	Sand compaction columns Level = 5* Ⓐ	Displace problematic geomaterial by driving a casing into the ground and backfill the hole with sand (densified by vibration during casing withdrawal)	Increase bearing capacity and stability; reduce settlement and liquefaction potential; accelerate consolidation	Suitable for a wide range of geomaterials to a typical depth of 5–15 m; used to improve foundations
		Stone columns Level = 5* Ⓑ	Jet water or air to remove or displace problematic geomaterial by a probe and backfill the hole with stone to form a densified column by vibration	Increase bearing capacity and stability; reduce settlement and liquefaction potential; accelerate consolidation	Suitable for a wide range of geomaterials (undrained shear strength >15 kPa) to a typical depth of 5–10 m (up to 30 m); used to improve foundations
		Rammed aggregate columns Level = 4 Ⓒ	Predrill a backfilled with aggregate, densified by ramming	Increase bearing capacity and stability; reduce settlement and liquefaction potential; accelerate consolidation	Suitable for a wide range of geomaterials to a typical depth of 5–10 m with a deep groundwater level; used to improve foundations
		Vibro-concrete columns Level = 3 Ⓓ	Drive a vibrating probe to the ground to displace problematic geomaterial, replaced with concrete	Increase bearing capacity and stability; reduce settlement	Suitable and economic for very soft soil to a typical depth of 5–10 m; used to improve foundations
		Geosynthetic-encased columns Level = 2* Ⓔ	Drive a steel casing to the ground to displace problematic geomaterial, replaced with a geosynthetic casing and fill	Increase bearing capacity and stability; reduce settlement; accelerate consolidation	Suitable and economic for very soft soil (undrained shear strength <15 kPa) to a typical depth of 5–10 m; used to improve foundations

Source: https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29GT.1943-5606.0000316

DRAINAGE, DEWATERING AND CONSOLIDATION

Source: https://hh-today.com/roadside-ditches-wetlands-rules/

Source: https://builderup.com

https://vancouver.ca/

Source: https://www.vakpumps.gr/en/product/welpoits/

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Drainage, dewatering, and consolidation	Drainage	Fill drains Ⓐ Level = 5*	Place a layer of permeable fill inside a roadway or earth structure	Reduce water pressure and collapsible and ground heave potential; accelerate consolidation; increase strength, stiffness, stability	Suitable for low permeability geomaterial; used for roads, retaining walls, slopes, and landfills
		Drainage geosynthetics Ⓑ Level = 4	Place a layer of nonwoven geotextile or geocomposite in ground or inside a roadway or earth structure	Reduce water pressure and collapsible and ground heave potential; accelerate consolidation; increase strength, stiffness, stability	Suitable for low permeability geomaterial; used for roads, retaining walls, slopes, and landfills
	Dewatering	Open pumping Level = 5 Ⓒ	Use sumps, trenches, and pumps to remove a small amount of water inflow in open excavation	Remove water to ease construction	Suitable for a small area, relatively impermeable soil, and lowering of the groundwater table by a limited depth in open excavation
		Well system Level = 4 Ⓓ	Use well points and/or deep wells to remove a large amount of water inflow in open excavation	Remove water to ease construction and increase stability of excavation	Suitable for a large area, relatively permeable soil, and lowering of the groundwater table by a large depth for excavation
		Electro osmosis method Level = 2	Create electric gradients in soil by installing anode and cathode to induce water flow and collect and discharge the water by a cathode well point	Remove water to ease construction	Suitable for relatively impermeable silt or clayey soil

DRAINAGE, DEWATERING AND CONSOLIDATION

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Drainage, dewatering, and consolidation	Consolidation	Fill preloading Level = 5 Ⓐ	Apply temporary surcharge on ground surface for a duration and then remove the surcharge for construction	Increase soil strength; reduce settlement	Suitable for saturated inorganic clay and silt; used to reduce settlement for foundation soil
		Vacuum Ⓑ preloading Level = 3	Apply vacuum pressure on ground surface and/or through drains into the ground for a desired duration and then remove the pressure for construction	Increase soil strength; reduce settlement	Suitable for saturated inorganic clay and silt; used to reduce settlement for foundation soil

(a)

(b)

Case Study: Ground Improvement of Yangtze River Floodplain Soils with Combined Vacuum and Surcharge Preloading Method

DOI: 10.1061/(ASCE)GM.1943-5622.0001516.

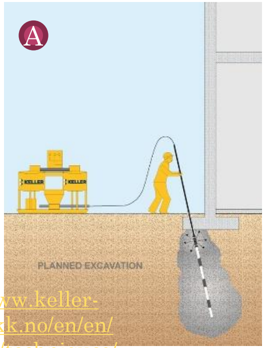
CHEMICAL STABILIZATION:- SHALLOW STABILIZATION

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Chemical stabilization	Shallow stabilization	Chemical stabilization of subgrade and base Level = 5	Mix lime, cement, and/or fly ash with subgrade and base course in field and then compact the mixture; have chemical reaction with soil particles to form a cementitious matrix	Increase strength and stiffness; reduce ground heave potential	Suitable for unsaturated clay and silt; mainly used for roadway construction with a typical lift thickness of 0.3 m or less

Source: https://theconstructor.org/geotechnical/lime-soil-stabilization-method/27105/

Source: https://globalroadtechnology.com/lime-in-soil-stabilization/

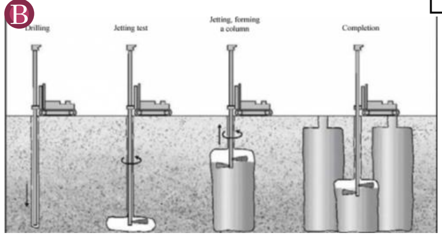
CHEMICAL STABILIZATION:- DEEP STABILIZATION



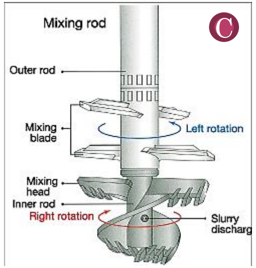
Source: https://www.keller-geoteknikk.no/en/en/expertise/techniques/permeation-grouting

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Chemical stabilization	Deep stabilization	Grouting Ⓐ Level = 3	Inject grout into ground to fill voids, densify soil, and have chemical reaction with soil particles to form a hardened mass	Increase strength and stiffness; reduce permeability, liquefaction, and ground heave potential	Different grout suitable for different geomaterial; mainly used for remedying measures or protective projects
		Jet grouting Level = 4 Ⓑ	Inject high-pressure cement-based fluid into ground to cut and then mix with geomaterial to form a hardened column by chemical reaction with soil particles	Increase strength, stiffness, and stability; reduce permeability, liquefaction, and ground heave potential	Suitable for a wide range of geomaterials; mainly used for remedying measures and protective projects to a typical depth of 30 m or less
		Deep mixing Level = 4* Ⓒ	Mix cement or lime from surface to depth with geomaterial by mechanical blade to have chemical reaction with soil particles after mixed to form a cementitious matrix	Increase strength, stiffness, and stability; reduce permeability, liquefaction, and ground heave potential	Suitable for a wide range of geomaterials; mainly used for foundation support, earth retaining during excavation, containment, and liquefaction mitigation

Source: http://www.bohn.hu/jet-grouting.htm



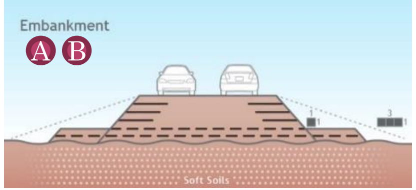
Source: http://www.spargrp.com/jet-grouting/



Source: https://www.asofoam.co.jp/english/jigyou/jiban/ras.html

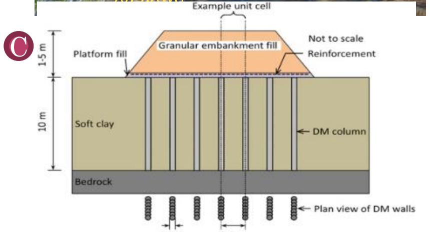
Source; http://menardcanada.ca/ground-improvement-solutions/deep-soil-mixing/

REINFORCEMENT:- FILL



Source: https://www.geogrid.com/en-us/applications/reinforced-steep-slopes

Source:
https://www.geosynt



Source:
http://www.vbmateriastextiles.com/2016/10/2
for-public-and-civil-works/

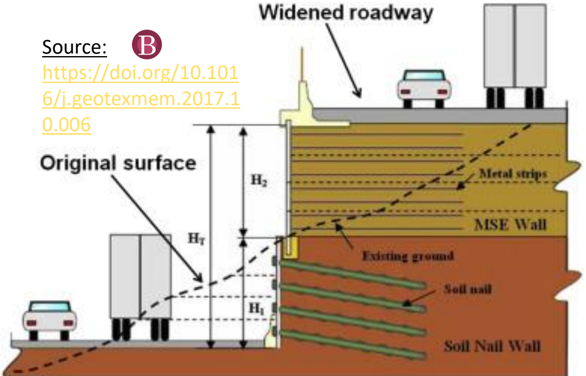
Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Reinforcement	Fill reinforcement	Geosynthetic-reinforced slopes Ⓐ Level = 5	Place geosynthetics in slope at different elevations during fill placement to provide tensile resistance	Increase stability	Suitable for low plasticity fill; mainly used for slope stability
		Geosynthetic-reinforced embankments Ⓑ Level = 5	Place high-strength geosynthetic at base of embankment to provide tensile resistance	Increase bearing capacity and stability	Suitable for embankments over soft foundation; mainly used for enhancing embankment stability
		Geosynthetic-reinforced column-supported embankments Ⓒ Level = 3	Place geosynthetic reinforcement over columns at base of embankment to support embankment load between columns	Reduce total and differential settlements; accelerate construction; increase stability	Suitable for embankments over soft foundation with strict settlement requirement and time constraint
		Mechanically stabilized earth walls Ⓓ Level = 5	Place geosynthetic or metallic reinforcements in wall at different elevations during fill placement to provide tensile resistance	Increase stability	Suitable for low plasticity free-draining fill
		Geosynthetic-reinforced foundations Ⓔ Level = 3*	Place geosynthetic reinforcements within fill under a footing to provide load support	Increase bearing capacity and reduce settlement	Suitable and economic for granular fill over soft soil with limited area and depth
		Geosynthetic-reinforced roads Ⓕ Level = 4	Place geosynthetic reinforcement on top of subgrade or within base course to provide lateral constraint	Increase bearing capacity and roadway life; reduce deformation and base thickness requirement	Suitable for granular bases over soft subgrade

REINFORCEMENT:- IN *SITU* GROUND

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Reinforcement	In-situ ground reinforcement	Ground anchors Ⓐ Level = 4*	Insert steel tendons with grout at end in existing ground to provide tensile resistance and prevent ground movement	Increase stability and resistance to uplift force	Suitable for granular soil or rock; used for temporary and permanent slopes and walls during excavation and substructures subjected to uplift force
		Soil nails Ⓑ Level = 4	Insert a steel bar with grout throughout the whole nail in existing ground to provide tensile resistance and prevent ground movement	Increase stability	Suitable for low plasticity stiff to hard clay, dense granular soil, and rock; used for temporary and permanent slopes and walls during excavation
		Micropiles Ⓒ Level = 4	Insert a steel reinforcing bar in a bored hole, grout in place to form a small diameter pile (<0.3 m) and provide vertical and lateral load capacities	Increase stability; protect existing, structures during ground movement	Suitable for a variety of geomaterials; used for slopes, walls, and unpinning of existing foundations

Source: www.platipus-anchors.com

Source: Ⓑ https://doi.org/10.1016/j.geotexmem.2017.10.006



Source: https://www.subsurfaceconstruction.com/services/micropiles/

THERMAL AND BIOLOGICAL TREATMENT

Category	Subcategory	Method and Level of Establishment[a]	General Description	Benefit	Application
Thermal and biological treatment		Ground freezing Level = 2 Ⓐ	Remove heat from ground to reduce soil temperature below freezing point and turn geomaterial into solid	Increase strength; reduce water flow and ground movement	Suitable for saturated clay and sand; used for temporary protection during excavation
		Biological treating Level = 1 Ⓑ	Utilize vegetation and roots to increase shear strength of soil or change soil properties by biomediated geochemical process, including mineral precipitation, gas generation, biofilm formation, and biopolymer generation	Increase strength and stiffness; reduce erodibility and liquefaction potential	Suitable for cohesive and cohesionless geomaterials; requires more research and field trial before it is adopted in practice

Source: https://tunnelingonline.com/soilfreeze-tsi-team-ground-freezing-solutions/

Source: http://www.dot.ca.gov/design/lap/landscape-design/erosion-control/plants/native_grass.html

PRELIMINARY SELECTION OF GROUND IMPROVEMENT METHODS

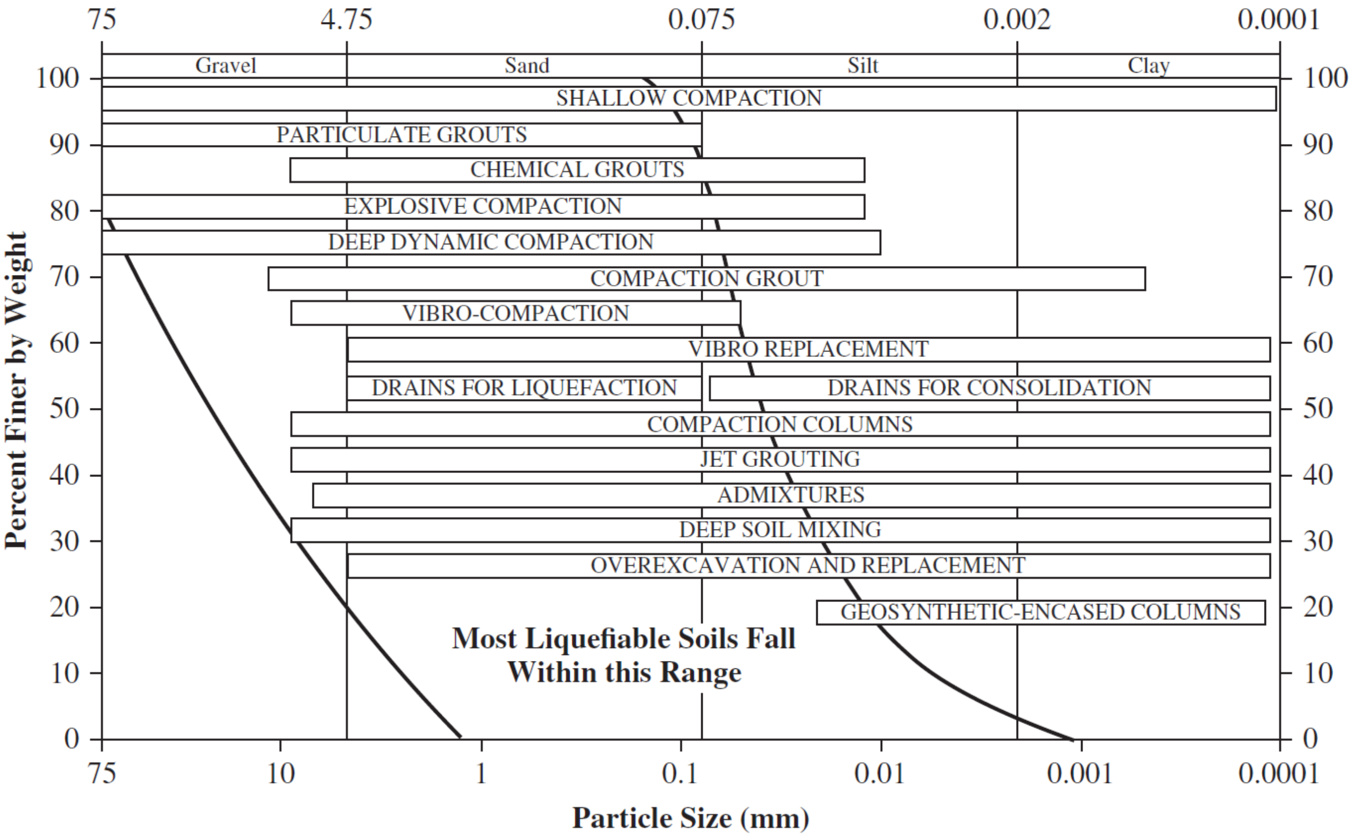


Figure 1.3 Available ground improvement methods for different soil types (modified from Schaefer et al., 2012).

FACTORS FOR SELECTING GROUND IMPROVEMENT METHOD

Structural Conditions	➢ type, shape, and dimension of structure and footing. ➢ Flexibility and ductility of structural and footing elements. ➢ Type, magnitude, and distribution of loads. ➢ Performance requirements (e.g., total and differential settlements, lateral movement, and minimum factor of safety).
Geotechnical Conditions	▪ Geologic formations and geographic landscape. ▪ Type, location, and thickness of problematic geomaterial. ▪ Possible end-bearing stratum. ▪ Groundwater table. ▪ Soil type and particle size distribution.
Environmental Constraints	o limited vibration, noise, traffic, water pollution, deformation to existing structures, spoil, and headspace.
Construction Conditions	❖ Site condition, ❖ Allowed construction time, ❖ Availability of construction material, ❖ Availability of construction equipment and qualified contractor, ❖ Construction cost.
Reliability and Durability	• The level of establishment, • Quality control and assurance. • For permanent structures, the durability of the construction material should be evaluated or considered in the design.

SELECTION PROCEDURE OF GROUND IMPROVEMENT METHOD

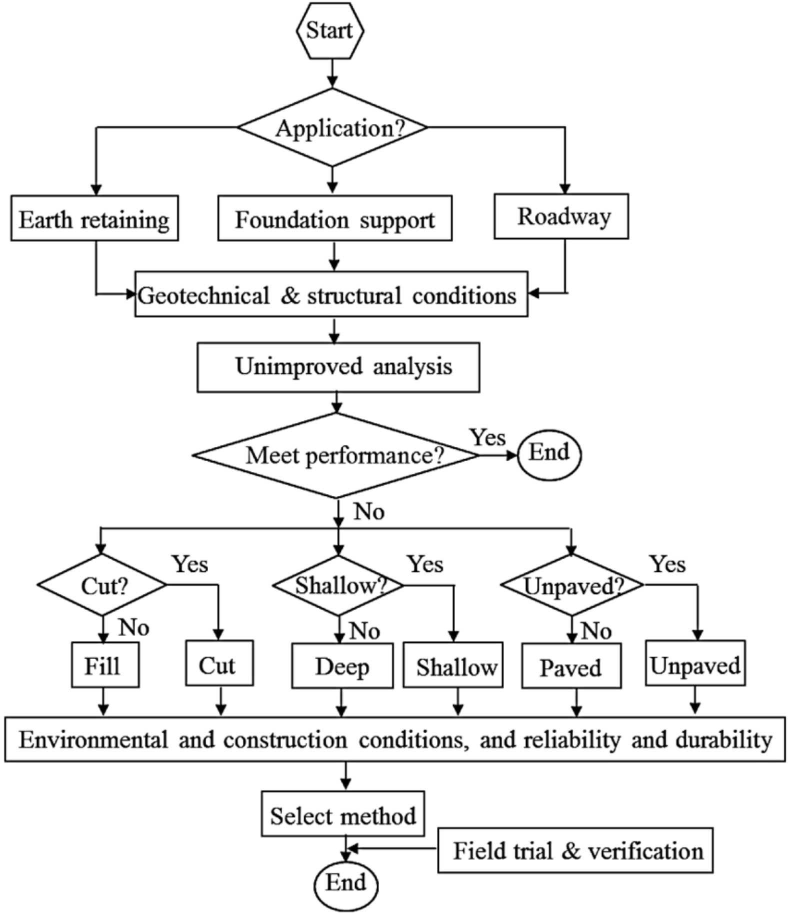


Figure 1.4 Flowchart for selection of ground improvement method.

SOIL MECHANICS II CVSM308

PROBLEMATIC SOILS & GROUND IMPROVEMENT

Topic #5 Shallow Compaction

Conventional compaction

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Image Source:
https://www.researchgate.net/publication/301608399_An_Investigation_of_Continuous_Compaction_Control_Systems

EFFECT OF COMPACTION ON GEOMATERIAL PROPERTIES

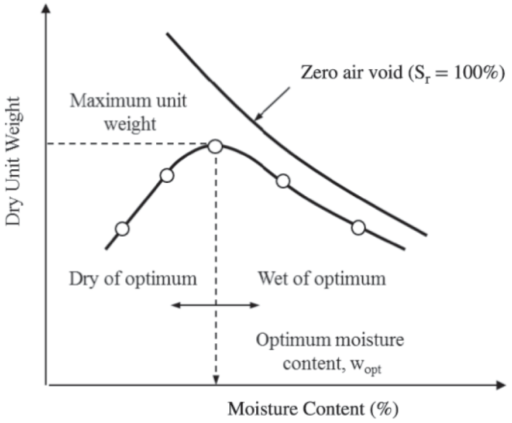


Figure 2.18 Typical compaction curve.

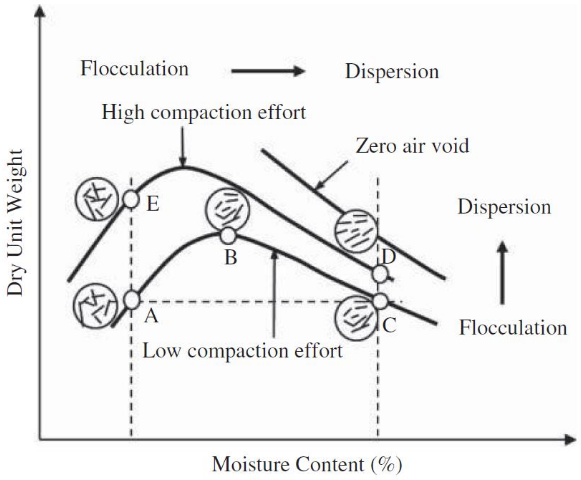


Figure 2.19 Soil fabrics at different moisture contents and compaction efforts (modified from Lambe, 1958).

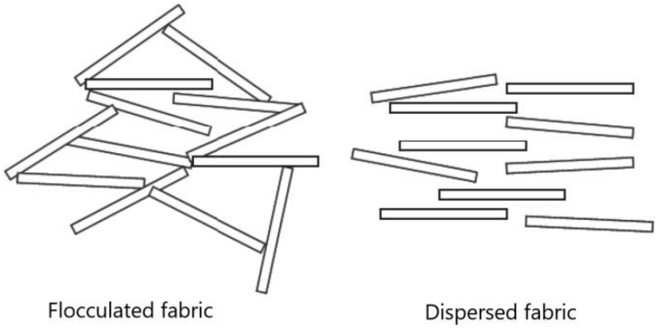


Figure 2.17 Clay fabric.

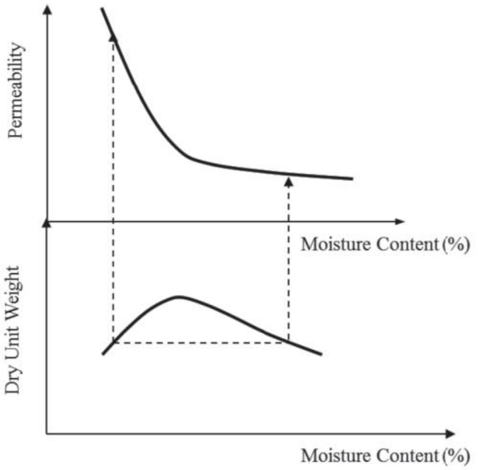


Figure 2.20 Effect on permeability (after Lambe, 1958).

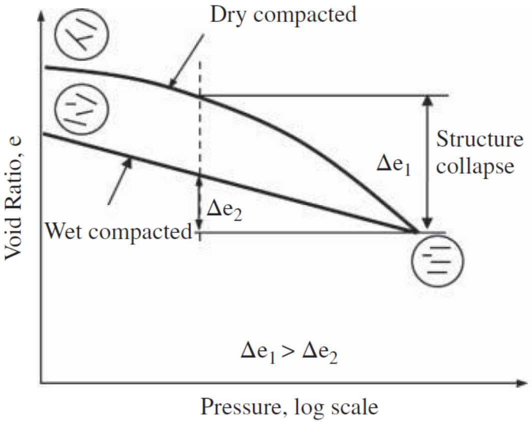


Figure 2.21 Effect on compressibility

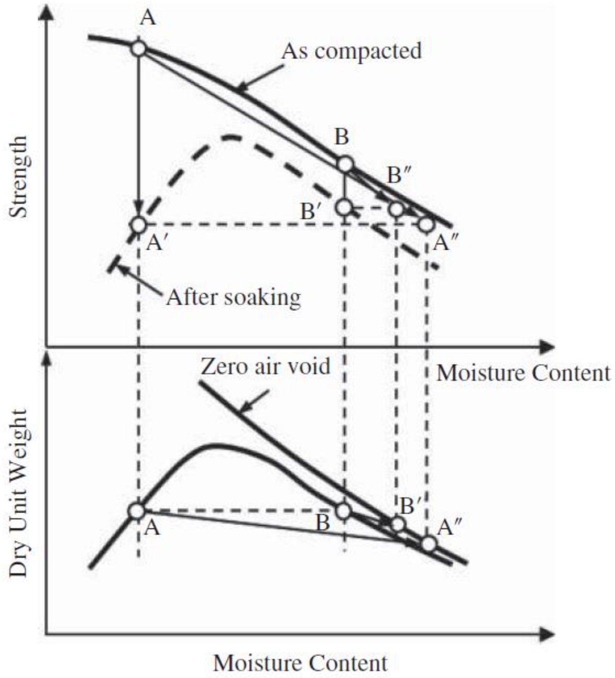


Figure 2.22 Effect of soaking on strength (modified from Lambe, 1958).

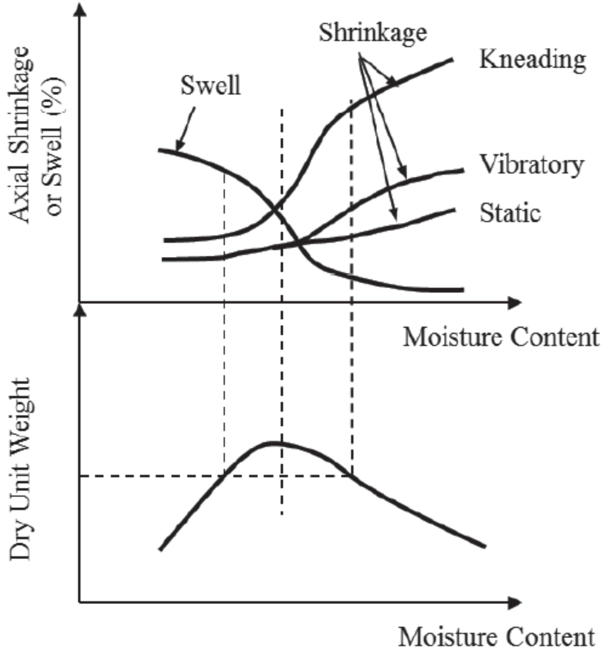


Figure 2.23 Effect on swell and shrinkage (after Seed and Chan, 1959).

DENSIFICATION PRINCIPLES

- The basic principle of densification is the rearrangement of particles into a denser state (i.e., the void ratio of geomaterial decreases).
- As a result, strength, and resistance to liquefaction of the geomaterial increase while the permeability and compressibility decrease.

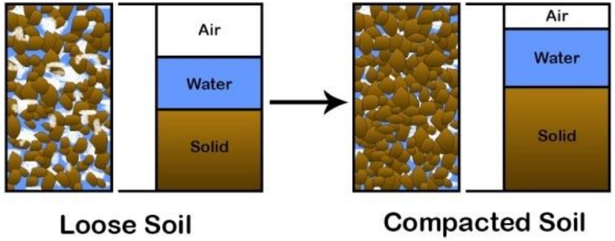
<u>Main mechanisms lead to fabric densification:</u>

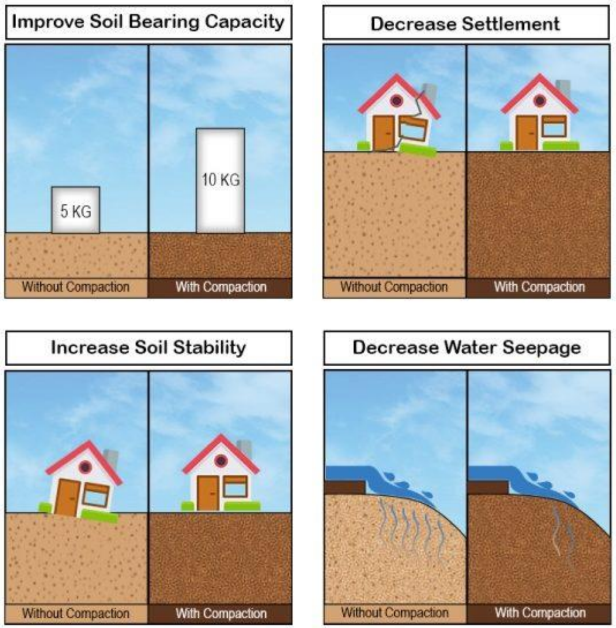
(1) static or kneading pressure → unsaturated cohesive geomaterial.

(2) dynamic loading (vibration or impact) → unsaturated cohesionless or collapsible geomaterial.

(3) Liquefaction → saturated cohesive and cohesionless geomaterial.

(4) consolidation → saturated cohesive soils.





Source: https://gharpedia.com/

CONVENTIONAL COMPACTION

Suitability

- Conventional compaction is used to densify cohesionsless and cohesive geomaterials in lifts.
- This occurs in earthworks, such as roads, embankments, dams, slopes, walls, parking lots, and sports fields.
- The lift thickness is typically limited to 300 mm.

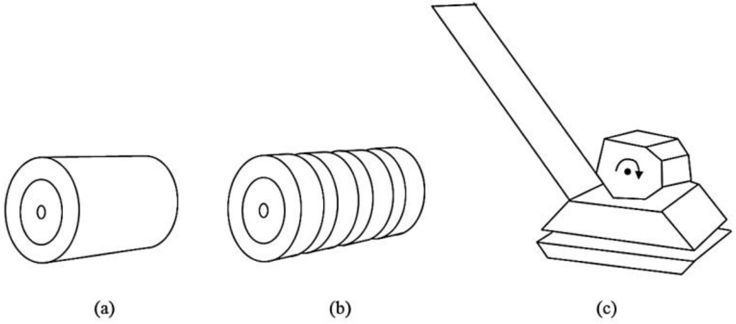


Figure 3.1 Different compaction equipment; (a) roller, (b) rubber tire compactor, and (c) vibrating plate compactor.

Relative Compaction (RC), is commonly used in the field to control and assure the quality of compaction:

$$RC = \frac{\gamma_d}{\gamma_{d,max}} \quad (3.1)$$

where γ_d = dry unit weight in field
$\gamma_{d,max}$ = maximum dry unit weight determined by standard or modified Proctor tests in laboratory

One-Point Method : to estimate the compactive energy used in the field and the maximum dry unit weight and its corresponding optimum moisture content of the fill under compaction.

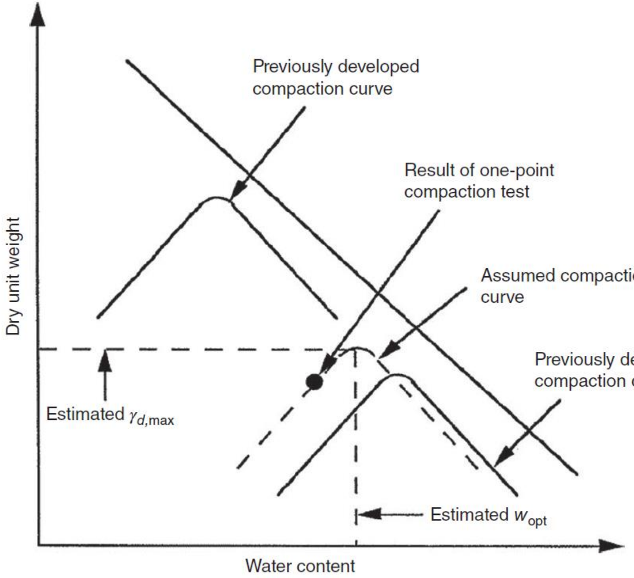


Figure 3.3 One-point method to estimate maximum dry unit weight and optimum moisture content in field.

Factors Influencing Field Compaction

- Geomaterial type
- Moisture content
- Compaction method, such as static pressure, kneading, vibration, and impact
- Compactive effort including applied energy, compactor size, lift thickness, and number of passes

✓ *In the figure, why near surface material has lower RD?*

Design Considerations

❑ ***Performance Requirements***

The relative compaction can be determined based on a specific application.

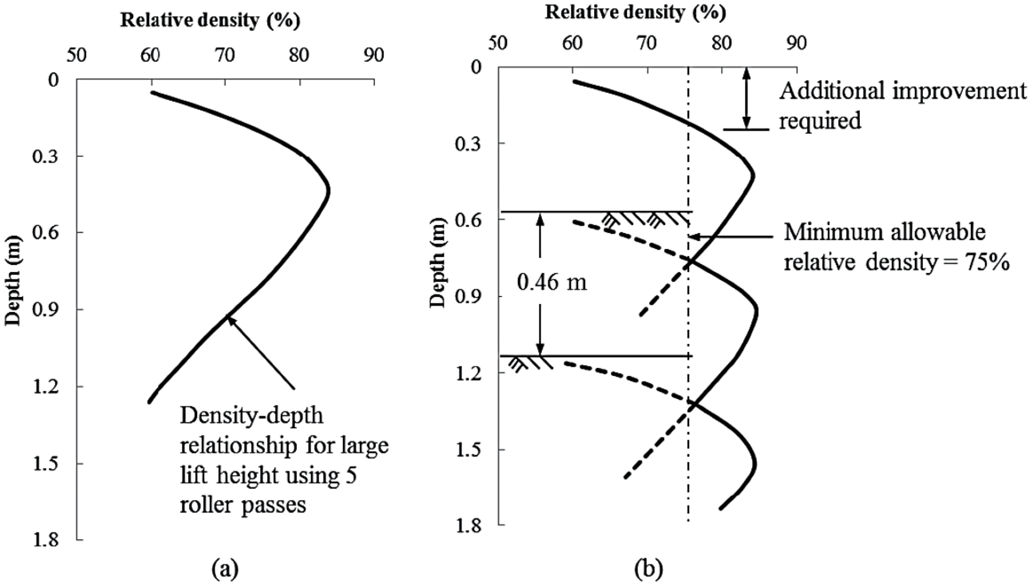


Figure 3.5 Approximate method to determine lift thickness: lifts (modified from D'Appolonia et al., 1969): (a) single lift and (b) multiple.

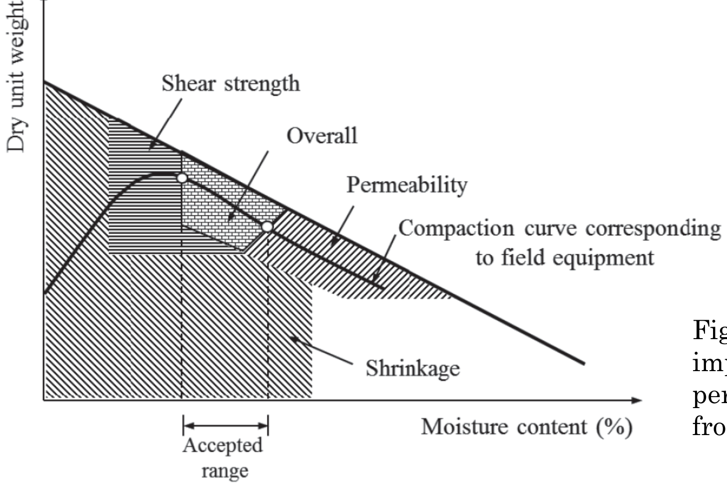


Figure 3.6 Accepted zone of improvement based on different performance requirements (modified from Daniel and Wu, 1993).

- ***Selection of Compaction Equipment***

Table 3.2 Recommended Type of Compaction Equipment

Geomaterial Type	First Choice	Second Choice	Comment
Rock fill	Vibratory roller	Rubber tire roller	—
Plastic soils—CH, MH	Sheepsfoot or pad foot roller	Rubber tire roller	Thin lifts usually needed
Low plasticity soils—CL, ML	Sheepsfoot or pad foot roller	Rubber tire vibratory roller	Moisture control often critical for silty soils
Plastic sands and gravels—GC, SC	Vibratory, pneumatic roller	Pad foot roller	—
Silty sands and gravels—SM, GM	Vibratory roller	Rubber tire, pad foot roller	Moisture control often critical
Clean sands—SW, SP	Vibratory roller	Impact, rubber tire roller	—
Clean gravels—GW, GP	Vibratory roller	Rubber tire, impact, grid roller	Grid useful for oversized particles

Source: Modified from Rollings and Rollings (1996).

Source: https://www.bomag.com

Source: https://www.coateshire.com.au

Source: https://www.cat.com

❑ *Lift Thickness and Number of Passes*

Source: https://www.constructionequipment.com/vibratory-plate-compactors

Source: http://eu.ironplanet.com

Source: https://tomahawk-power.com/

Table 3.3 Lift Thickness and Number of Passes for Different Compaction Equipment

Equipment Type	Applicability	Compacted Lift Thickness (mm)	Number of Passes
Sheepsfoot rollers	For fine-grained fills or coarse-grained fills with more than 20% fines	150	4–6 for fine-grained fills 6–8 for coarse-grained fills
Rubber tire roller	For clean, coarse-grained fills with 4–8% fines	250	3–5
	For fine-grained fills or well-graded coarse-grained fills with more than 8% fines	150–200	4–6
Smooth wheel rollers	Appropriate for subgrade or base course compaction of well-graded sand-gravel mixtures	200–300	4
	May be used for fine-grained fills other than earth dams	150–200	6
Vibrating sheepsfoot rollers	For coarse-grained fills and sand-gravel mixtures	200–300	3–5
Vibrating smooth drum rollers	For coarse-grained fills and sand-gravel mixtures—rock fills	200–300 (soil) to 900 (rock)	3–5 4–6
Vibrating plate compactors Ⓐ	For coarse-grained fills with less than 4–8% fines, placed thoroughly wet	200–250	3–4
Crawler tractor Ⓑ	Best suited for coarse-grained fills with less than 4–8% fines, placed thoroughly wet	150–250	3–4
Power tamper or rammer Ⓒ	For difficult access, trench backfill. Suitable for all inorganic fills	100–150 for silt or clay, 150 for coarse-grained fills	2

Source: Modified from U.S. Navy (1986).

❑ *Borrow Volume*

- The unit weight of geomaterial on a borrow site is often different from that on a construction site after compaction.
- Also considers weight loss in striping, waste, oversize, and transportation.
- The total borrow volume required for compacted fill can be estimated as follows (U.S. Navy, 1986):

$$V_b = \frac{\gamma_{d,f}}{\gamma_{d,b}} V_{f,r} + \frac{W_l}{\gamma_{d,b}} \qquad (3.7)$$

where V_b = borrow volume
$V_{f,r}$ = required fill volume
$\gamma_{d,f}$ = dry unit weight of fill
$\gamma_{d,b}$ = dry unit weight of borrow
W_l = dry weight loss in striping, waste, oversize, and transportation

Source: http://www.aggbusiness.com/sections/general/features/south-africas-quarry-industry-up-in-arms-against-borrow-pits/

Design Parameters

- Project requirement(s);
- Relative compaction;
- Area and thickness of compacted fill;
- Type and gradation of fill;
- Type of equipment;
- Optimum moisture content and maximum dry unit weight or minimum and maximum void ratios;
- Borrow volume;
- Thickness and number of lifts;
- Number of passes;

Table 3.5 Field Tests for Quality Assurance of Compaction

Test Method	Measurement	Standard
Sand cone	Density	ASTM D1556
Rubber balloon	Density	ASTM D2167
Nuclear gauge	Moisture content and density	ASTM D6938
Dynamic cone penetrometer	Penetration index	ASTM D6951
Soil stiffness gauge	Stiffness	ASTM D6758
Falling weight deflectometer	Stiffness	ASTM D4694
Light weight deflectometer	Stiffness	ASTM E2583
Electrical density gauge	Density	ASTM D7830
Time domain reflectometry	Moisture content	ASTM D6565

Source: http://www.brepllc.com/geotechnical/

Nuclear moisture density gauge
Source: https://www.matest.com/

Source: http://labmodules.soilweb.ca/time-domain-reflectometry/

Light weight defectometer, source: http://www.pcte.com.au/geotechnical-systems

SOIL MECHANICS II CVSM308

PROBLEMATIC SOILS & GROUND IMPROVEMENT

Topic #6 Deep Compaction

Deep Dynamic Compaction

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Image Source: https://www.cmwgeosciences.com/geotechnical-services/ground-improvement/dynamic-compaction

Basic Concept

- Deep dynamic compaction is a repeatedly drop of a weight (“tamper”) freely from a height onto the ground surface in a pattern to compact problematic geomaterial down to a depth of 10 m by reducing voids and thereby densifying the geomaterial.
- *Dynamic Densification…* When dynamic compaction is used on *unsaturated granular geomaterial*, the impact by a heavy tamper immediately displaces particles to a denser state, compresses or expels air out of voids, and reduces the volume of voids.
- A tamper typically has a weight of 5–40 tons and drops from a height of 10–40 m.

Suitability

- Loose and partially saturated fills
- Saturated free-drained soils
- Silts with plasticity index less than 8
- Clayey soil with a low degree of saturation (moisture content lower than plastic limit)

* not recommended for clayey soil with high plasticity index (greater than 8) and high degree of saturation, why?

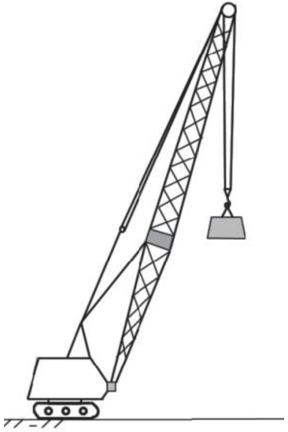


Figure 3.16 Dynamic compaction.

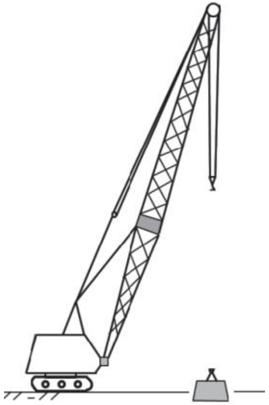


Figure 3.16 Dynamic compaction.

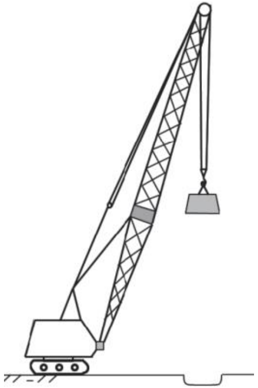


Figure 3.16 Dynamic compaction.

- *Drainage and/or dewatering?*
- *Excess pore water pressure?*
- *Time for dissipation of excess pore water pressure?*

Table 3.8 Adverse Situations for Dynamic Compaction

Adverse Situation	Possible Difficulty
Soft clays (undrained shear strength less than 30 kPa)	Insufficient resistance to transmit tamper impulse
High groundwater level	Need to dewater and to consider possible effects of subsequent recovery in water level
Vibration effects (may be worse if groundwater level is high)	Distance from closest structure to be of the order of 30 m or more
Clay surface	May be inadequate for heavy cranes and unsuitable for imprint backfilling
Clay fills	May be subject to collapse settlement if inundated later
Flying debris	Precautions for site and public safety
Voided ground or Karst features below treated ground	Treatment may not reach the voided zone or may make it less stable
Biologically degrading material	Compaction may create anaerobic conditions and regenerate or change the seat of the biological degradation

Source: Mitchell and Jardine (2002).

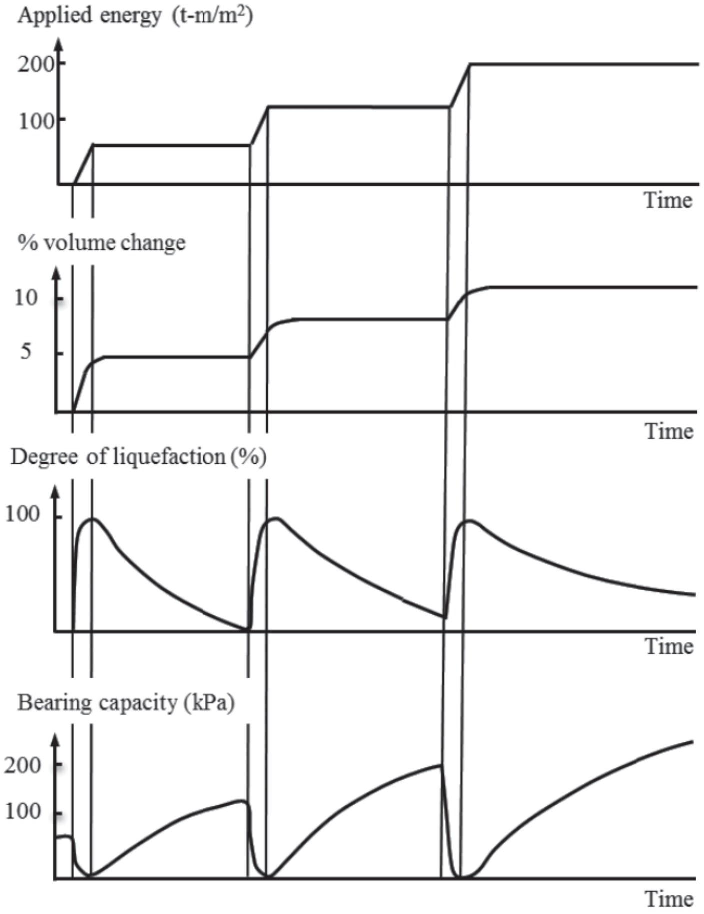


Figure 3.17 Variations of volume, excess pore water pressure, and soil strength during and after the tamping process (after Menerd and Broise, 1975).

Dynamic Replacement

Used when a clayey soil is too soft and has too low permeability.

The process of dynamic replacement involves:

- tamping,
- backfilling, and
- continued tamping until stone columns are formed.

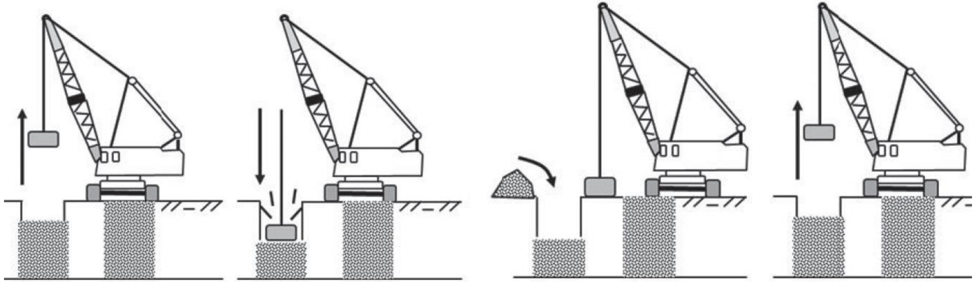


Figure 3.18 Dynamic replacement (after Yee and Ooi, 2010).

Design Considerations

❑ *Site Investigation*

To evaluate the site conditions, which include:

- Geomaterial profiles including geomaterial type, particle size, fine content, degree of saturation, and Atterberg limits
- Relative density of cohesionless geomaterial
- Groundwater level
- Possible voids
- Possible presence of hard lenses within the depth of improvement
- Possible sensitive soil

❑ ***Influence Factors*** :

- Geomaterial type
- Depth and area of improvement
- Tamper geometry and weight
- Drop height and energy
- Pattern and spacing of drops
- Depth of crater
- Number of drops and passes
- Degree of improvement
- Induced settlement
- Environmental impact (vibration, noise, and lateral ground movement)
- Presence of soft layer
- Presence of hard layer
- High groundwater table
- Elapsed time
- Pilot trial

❑ *Soil Type*

Soil that are suitable for dynamic compaction:

(1) pervious soil deposits—granular soil.

(2) semipervious deposit—primarily silts with plasticity index less than 8.

(3) semipervious deposit—primarily clayey soil with plasticity index greater than 8.

❑ *Depth and Area of Improvement*

An **<u>empirical formula</u>** developed based on field data:

$$D_i = n_c\sqrt{W_t H_d} \qquad (3.16)$$

where D_i = depth of improvement (m)

W_t = weight of tamper (ton)

H_d = height of drop (m)

n_c = constant, depending on soil type, degree of saturation, and speed of drop

Field data show that the depths of improvement for ***granular soils*** *are mostly up to* ***10 m*** *while those for* ***cohesive soils*** *and clay fills are limited to* ***5 m***.

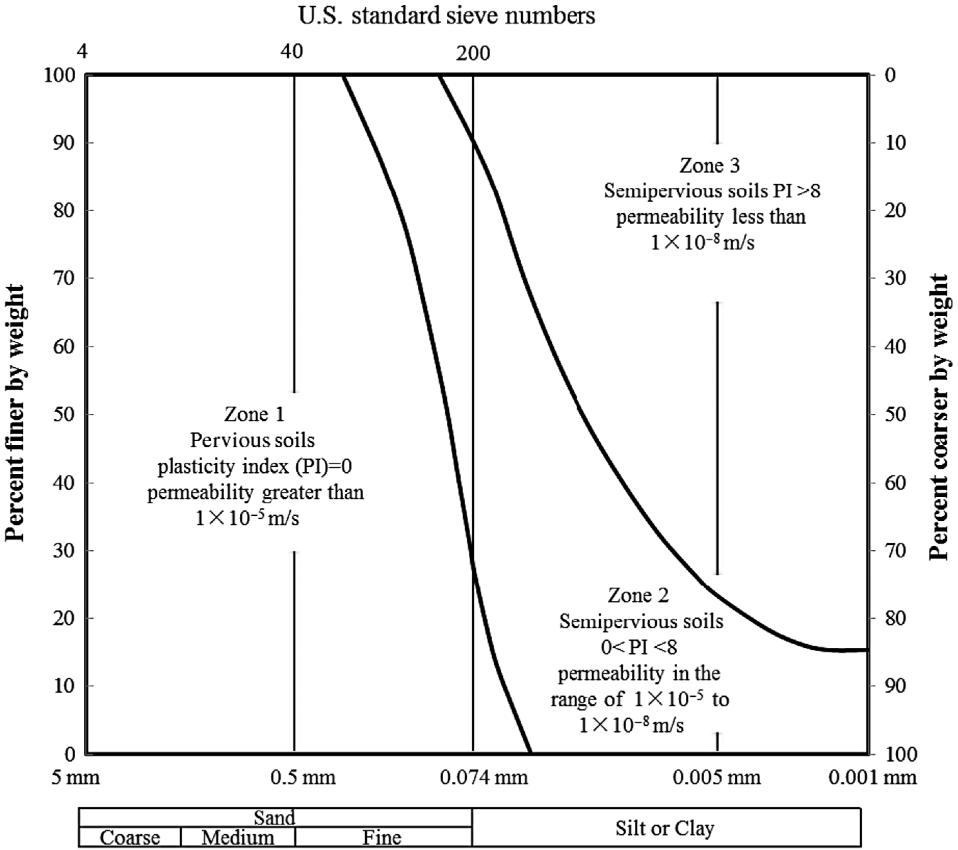


Figure 3.19 Soil types for dynamic compaction (Lukas, 1995).

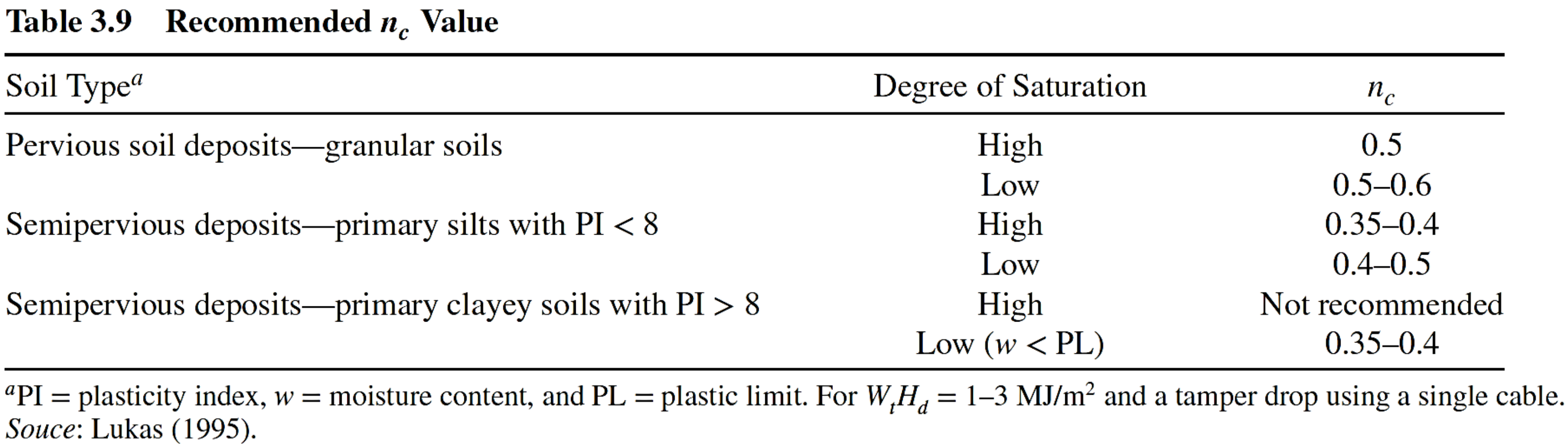


Table 3.9 Recommended n_c Value

Soil Type[a]	Degree of Saturation	n_c
Pervious soil deposits—granular soils	High	0.5
	Low	0.5–0.6
Semipervious deposits—primary silts with PI < 8	High	0.35–0.4
	Low	0.4–0.5
Semipervious deposits—primary clayey soils with PI > 8	High	Not recommended
	Low (w < PL)	0.35–0.4

[a] PI = plasticity index, w = moisture content, and PL = plastic limit. For $W_t H_d$ = 1–3 MJ/m^2 and a tamper drop using a single cable.

Souce: Lukas (1995).

❑ *Tamper Geometry and Weight*

-Most tampers are made of steel or steel shell filled with sand or concrete

- Have a circular or square base with an area of 3–6 m^2 or larger.
- Tampers with smaller base areas (3–4 m^2) are commonly used for granular soils while those with large base areas (larger than 6 m^2) are used for cohesive soils.
- The weight of a tamper typically ranges from 5 to 40 tons.

❑ *Drop Height and Energy*

- The height of tamper drop is typically 10–40 m.
- Based on Mayne et al. (1984), the energy per drop in practice mostly ranges from 800 to 8000 kN·m.

$$H_d = (W_t H_d)^{0.54} \qquad (3.17)$$

where $W_t H_d$= energy per drop of tamper (ton-m), which is determined from Equation (3.16) based on the required depth of improvement.

❑ *Pattern and Spacing of Drops*

* Square and triangular patterns of drops are commonly used.

- ➢ phase 1-1: only the deeper geomaterial is densified.
- ➢ Phase 1-2: further densifies the deeper geomaterial.
- ➢ Phase 2: densifies the geomaterial within the intermediate depth.
- ➢ Ironing phase with lower energy is to densify the loosened deposit to the depth of crater penetration.

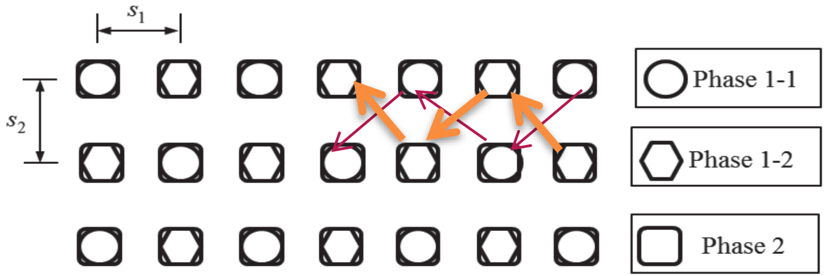


Figure 3.20 Layout of drop points.

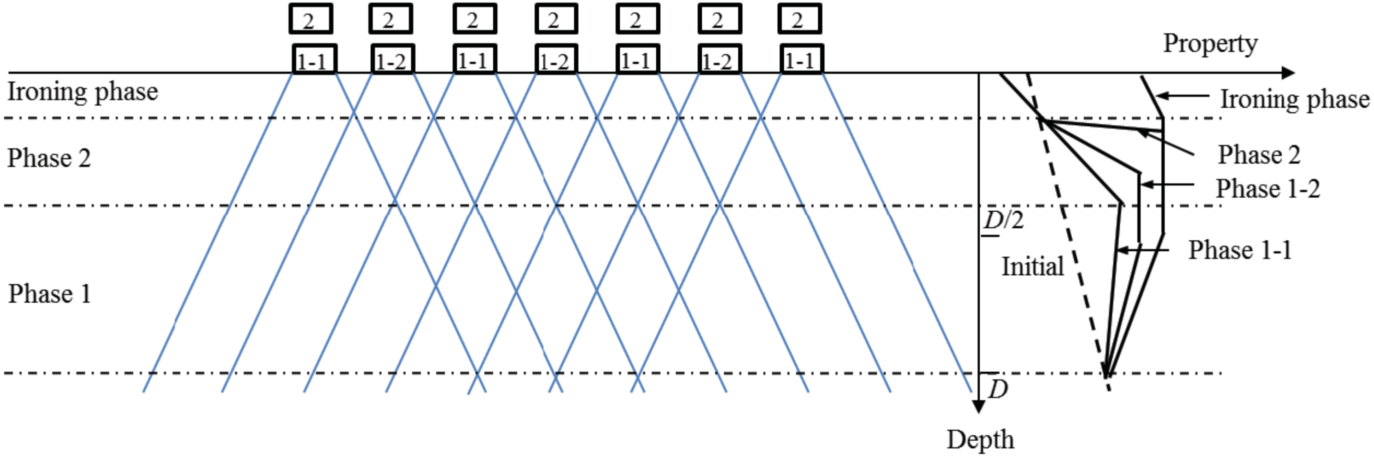
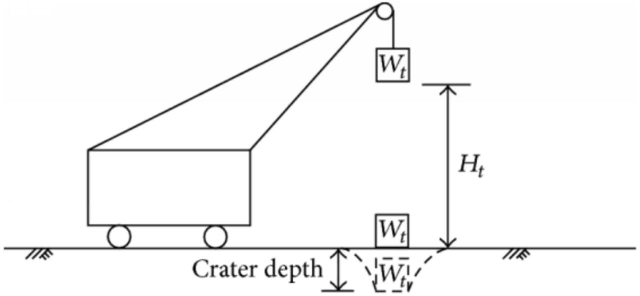


Figure 3.21 Depth of densification

- (s_1 or s_2) is ≈1.5–2.5 times the diameter or width of a tamper.
- s_1 and s_2 are often equal to create uniform compaction).
- The maximum improvement usually occurs between $D_i/3$ to $D_i/2$ (D_i is the maximum depth of improvement).

❑ *Depth of Crater*

- A crater is formed under each tamper drop and its depth increases with the number of drops.
- High-energy compaction can induce a crater of 1.0–1.5 m deep.
- The crater depth should be limited to the height of a tamper plus 0.3 m to ensure the safety and ease of compaction operation.



Source: http://dx.doi.org/10.1155/2015/127878

An empirical formulas to estimate **crater depth (d_{cd})** (Rollins and Kim (2010)):

For a rough estimate

$$d_{cd} = 0.028 N_d^{0.55} \sqrt{W_t H_d} \qquad (3.18)$$

This equation is useful for soils with a low degree of saturation after dynamic compaction

where H_d = drop height (m)
W_t = tamper weight (tons)
N_d = number of drops

Image Source: https://www.trevispa.com/en/Technologies/dynamic-compaction-heavy-tamping

❑ *Number of Drops and Passes*

- The **number of drops N_d** and passes can be estimated based on applied energy on a site.
- **Applied energy (AE)** at each drop point location can be calculated as follows:

$$AE = \frac{N_d W_t H_d}{A_e} \tag{3.20}$$

where
N_d = number of drops by one pass at each drop location (typically 5–10 drops)
W_t = weight of tamper
H_d = drop height
A_e = influence (equivalent) area of each impact point ($A_e = s^2$ for a square pattern or $0.867\ s^2$ for an equilateral triangular pattern)
s = drop spacing

- **Total applied energy (AE_{total})** is the sum of the energy applied during high-energy passes **(AE_{HIP})** plus ironing pass **(AE_{IP})** .
- **Unit applied energy (UAE)** is defined based on the depth of improvement as follows:

$$UAE = \frac{AE_{total}}{D_i} = \frac{AE_{HEP} N_p + AE_{IP}}{D_i} \tag{3.21}$$

where
AE_{HEP} = applied energy by a high-energy pass
AE_{IP} = applied energy by an ironing pass
N_p = number of passes
D_i = depth of improvement

Image Source: https://www.trevispa.com/en/Technologies/dynamic-compaction-heavy-tamping

Table 3.10 Required Unit Applied Energy[a]

Soil Type	Unit Applied Energy (kJ/m^3)	% Standard Proctor Energy
Pervious coarse-grained soil	200–250	33–41
Semi-impervious fine-grained soil	250–350	41–60
Landfill	600–1100	100–180

[a] Standard Proctor energy equals 600 kJ/m^3.

Source: Lukas (1995).

- The required applied energy for ironing compaction is estimated as follows:

$$AE_{IP} = UAE \cdot d_{cd} \qquad (3.22)$$

where d_{cd} is the depth of the crater.

- The number of drops for ironing pass can be determined using Equation (3.20) if the weight and drop height of the tamper and the area of the tamper (i.e. the influence area of each impact point) are known.
- When the number of drops at one location in a single pass is too large (greater than 10 passes) or the crater depth is too deep, the operation of compaction should be divided into two or multiple passes.

❑ *Degree of Improvement*

The actual degree of improvement should be evaluated by in situ testing after compaction.

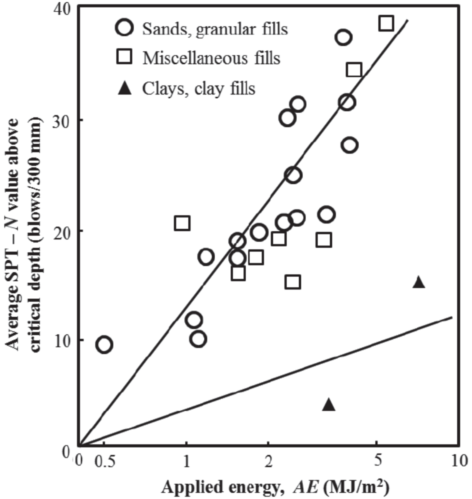


Figure 3.22 Average SPT *N* value after improvement (after Lukas, 1995).

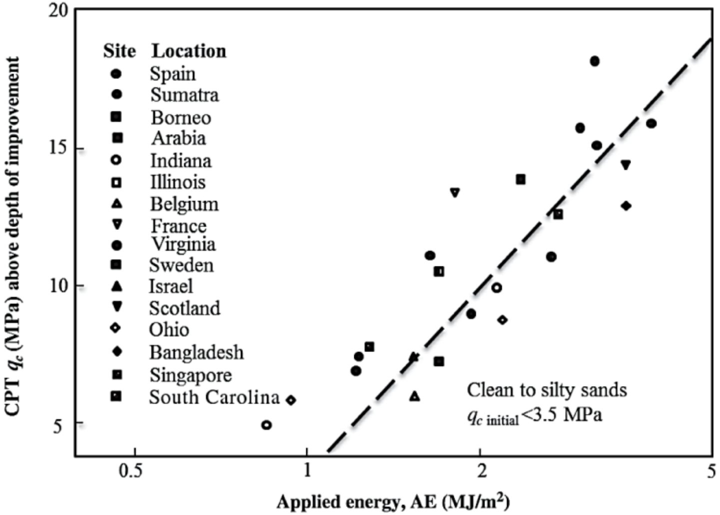


Figure 3.23 Average CPT q_c value after improvement (Lukas, 1995).

❑ *Induced Settlement*

- After each pass of dynamic compaction, construction equipment, most commonly bulldozers, is used to level the ground surface.
- Ground settlement (subsidence) is measured based on the current ground elevation as compared with the initial elevation.
- In unsaturated soil, the settlement occurs immediately after compaction.
- In saturated soil, however, the settlement increases gradually with time after the initial compression under each compaction.

Table 3.12 Approximate Induced Settlement as Percent of Improvement Depth

Soil Type	Percent of Depth
Natural clays	1–3
Clay fills	3–5
Natural sands	3–10
Granular fills	5–15
Uncontrolled fills	5–20

Source: Modified from Moseley and Kirsch (2004).

Further Reading

❑ *Environmental Impact*

- It is expected that applying high-energy impact on ground induces environmental impact, mostly vibration, noise, and lateral ground movement.
- Field measurements show that particle velocity depends on the scaled energy factor and the geomaterial density as shown in Figure 3.25. The scaled energy factor is defined in terms of the applied energy by a single drop and the distance from the point of impact to the point of interest.
- An increase of the scaled energy factor increases the particle velocity. A loose soil or fill typically generates lower particle velocity.
- Mayne et al. (1984) provided the following formula to estimate the upper limit of peak particle velocity (PPV) in terms of applied single-drop energy and distance to the drop point:

$$\text{PPV} = 70\left(\frac{\sqrt{W_t H_d}}{x_{dp}}\right)^{1.4} \qquad (3.23)$$

where PPV = peak particle velocity (mm/s)
W_t = tamper weight (ton)
H_d = drop height (m)
x_{dp} = distance to the drop point (m)

Table 3.13 Typical Threshold Particle Velocity

Structural Type	Velocity (mm/s)
Commercial, industrial	20–40
Residential	5–15
Sensitive	3–5

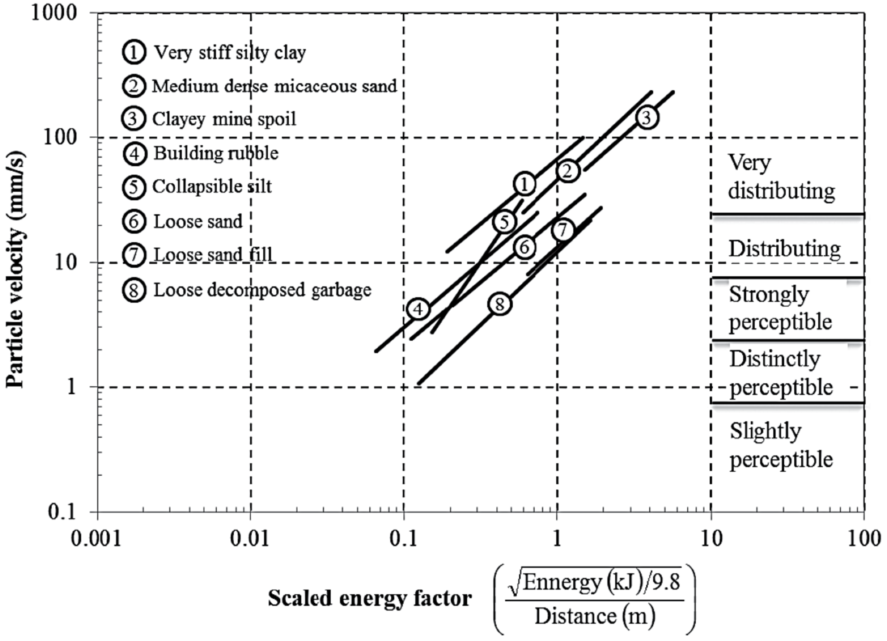


Figure 3.25 Scaled energy factor versus particle velocity (FHWA, 1986).

Table 3.13 provides typical values of threshold particle velocity based on the typical vibration frequency generated by deep dynamic compaction.

Design Parameters and Procedure

See Section 3.5.4 in
Han J., (2015), *Principles and Practices of Ground Improvement,* John Wiley & Sons, Inc., Hoboken, New Jersey.

SOIL MECHANICS II CVSM308

PROBLEMATIC SOILS & GROUND IMPROVEMENT

Topic #7 Shallow and Deep Compaction

Rapid Impact Compaction

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Image Source:
http://www.farrellinc.com/

RAPID IMPACT COMPACTION

Basic Concept

- It is an intermediate compaction method between conventional shallow compaction and deep dynamic compaction.
- It densifies geomaterial by repeatedly dropping a hydraulic hammer mounted on an excavator at a fast rate, see the figure below.
- The weight of hammer is typically 5–12 tons, which is dropped freely from a height of 1.2 m on a circular steel foot with a diameter of 1.0–1.5 m (the most common one is 1.5 m in diameter).
- The rapid compaction machine can generate 40–60 blows per minute, which is much faster than the deep dynamic compaction machine.
- The production rate of each machine is up to 500 m^2 improvement area per day.

Suitability

- This method is generally suitable for granular geomaterials, including gravel, sands, silts, uncontrolled fills (i.e., a mixture of sand, silt, and clay), and industrial and mine wastes.
- This method generally can improve geomaterials up to a depth of 6 m deep (mostly 3–4m).

Applications

- Used for increasing bearing capacity and stiffness of geomaterial to support building foundations, floor slabs, tanks, highways, railways, parking lots, and airport runways.
- Mitigating liquefaction.
- Reducing waste volume and collapsible potential.
- Compacting granular fills in large lifts (up to 3 m).

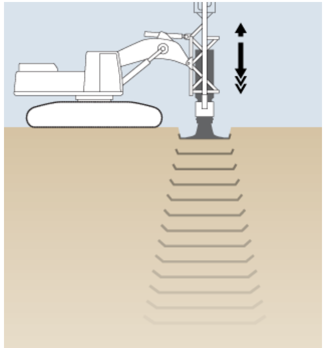


Image Source: http://www.farrellinc.com/

Source: http://www.bsp-if.com/

Rapid Impact Compaction vs Deep Dynamic Compaction

Advantages

- ✓ The operation of rapid impact compaction is fast and under a much controlled manner as compared with deep dynamic compaction.
- ✓ It induces smaller vibrations than deep dynamic compaction due to low impact energy; therefore, it can be operated at closer distances to existing structures.
- ✓ Because the impact foot is always in contact with the ground, it eliminates the risk of generating flying debris.
- ✓ Similar to deep dynamic compaction, it can detect weak areas during the construction.
- ✓ It has better mobility and works in areas with difficult access.

Limitations

- The depth of improvement is smaller than that of deep dynamic compaction.

Principles

- ❖ The general principle is dynamic densification.
- ❖ In rapid impact compaction, a dense soil plug is first formed under the steel foot by the first few blows.
- ❖ Further blows push the dense geomaterial plug as a rigid block deeper to densify the underlying geomaterial until no or little further penetration can be achieved.
- ❖ This is why rapid impact compaction can densify geomaterials at deeper depths even though its single-drop energy is much lower than that by deep dynamic compaction.

- *Close spacing are necessary because the densification occurs directly below the steel foot.*

Design Considerations

❑ *Depth of Improvement*

BRE (2003) and SAICE (2006) provide the guidelines to estimate the depth of improvement for rapid impact compaction as shown in Tables 3.15 and 3.16.

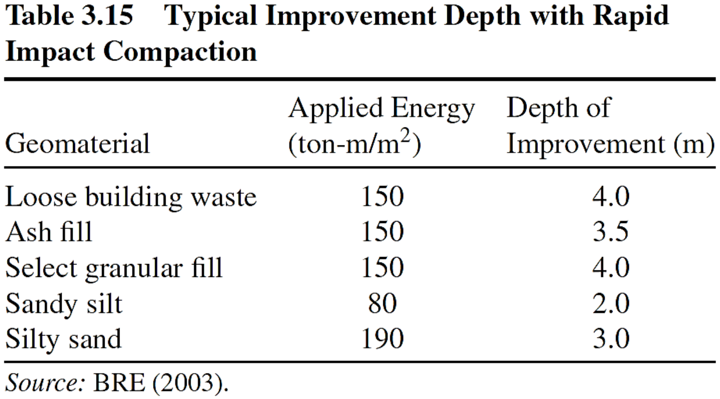


Table 3.15 Typical Improvement Depth with Rapid Impact Compaction

Geomaterial	Applied Energy (ton-m/m^2)	Depth of Improvement (m)
Loose building waste	150	4.0
Ash fill	150	3.5
Select granular fill	150	4.0
Sandy silt	80	2.0
Silty sand	190	3.0

Source: BRE (2003).

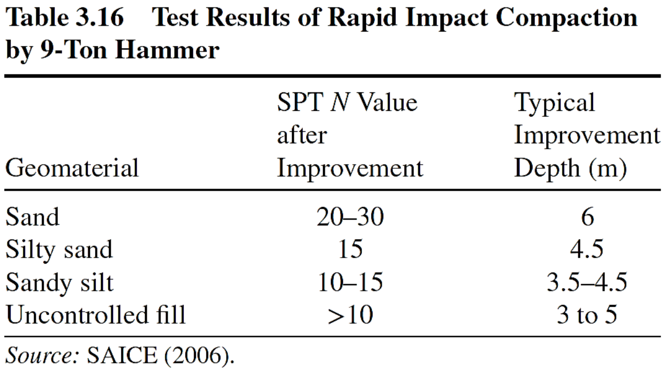


Table 3.16 Test Results of Rapid Impact Compaction by 9-Ton Hammer

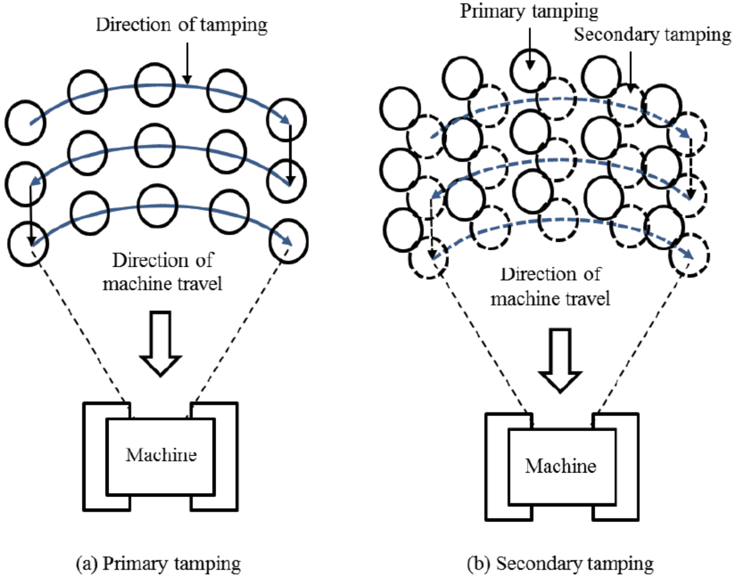
Geomaterial	SPT *N* Value after Improvement	Typical Improvement Depth (m)
Sand	20–30	6
Silty sand	15	4.5
Sandy silt	10–15	3.5–4.5
Uncontrolled fill	>10	3 to 5

Source: SAICE (2006).

For typical impact spacing (1.5 m × 1.5 m), 30 blows of 9-ton hammer with 1.2-m drop height generate about 150 ton-m/m^2 applied energy.

❑ *Patterns of Impact Points*

1. Arc pattern, that is, **primary impact points** are arranged in the arc around the center as shown in Figure 3.28. **Secondary impact points** are arranged between primary impact points.



(a) Primary tamping (b) Secondary tamping

Figure 3.28 Arc pattern of impact points: (a) primary and (b) secondary tamping (modified from Braithwaite and du Preez, 1997).

2. Square pattern, that is, primary impact points are arranged within a 6 m × 6 m or 9 m × 9 m area for each impact grid as shown in Figure 3.29. Within each impact zone, secondary and tertiary impact points are uniformly distributed between primary impact points.

3. Triangular pattern.

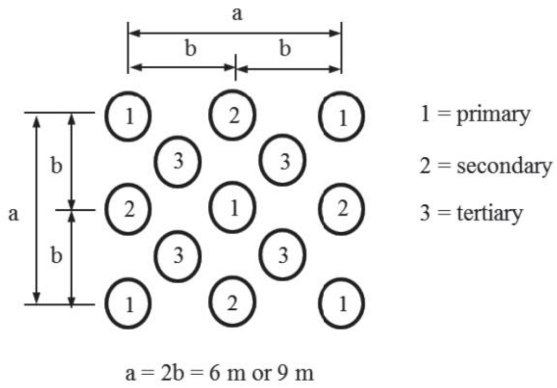
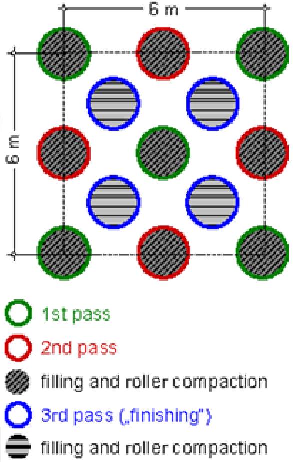


Figure 3.29 Square pattern of impact points (modified from SAICE, 2006).



https://www.semanticscholar.org/

 # No ironing pass is needed because rapid impact compaction is similar to ironing compaction with low energy and close spacing.

 # Surface compaction with rollers is often needed to densify shallow geomaterial and level the ground surface.

❑ *Number of Blows*

Number of blows on each point can be estimated using Equation (3.20) based on the required applied energy, weight of hammer, height of drop, and spacing of impact points. Number of blows typically ranges from 10 to 40.

$$\mathrm{AE} = \frac{N_d W_t H_d}{A_e} \tag{3.20}$$

where N_d = number of drops by one pass at each drop location (typically 5–10 drops)
W_t = weight of tamper
H_d = drop height
A_e = influence (equivalent) area of each impact point ($A_e = s^2$ for a square pattern or $0.867\ s^2$ for an equilateral triangular pattern)
s = drop spacing

❑ *Environmental Impact*

Becker (2011) obtained the following correlation for the peak particle velocity and the scaled energy factor by **rapid impact compaction:**

$$PPV = 188\left(\frac{\sqrt{W_t H_d}}{x_{dp}}\right)^{1.53} \quad \text{if} \quad \frac{\sqrt{W_t H_d}}{x_{dp}} \geq 0.1 \qquad (3.24)$$

$$PPV = 36\left(\frac{\sqrt{W_t H_d}}{x_{dp}}\right)^{0.79} \quad \text{if} \quad \frac{\sqrt{W_t H_d}}{x_{dp}} < 0.1 \qquad (3.25)$$

where PPV = peak particle velocity (mm/s)
W_t = weight of tamper (ton)
H_d = height of drop (m)
x_{dp} = distance from the center of the impact point (m)

- For most rapid impact compaction, the scaled energy factor is greater than 0.1 (ton-m)$^{0.5}$/m.
- The comparison between Equations (3.23) and (3.24) shows that rapid impact compaction produces greater peak particle velocity than deep dynamic compaction at the same scaled energy factor.
- The greater peak particle velocity transfers the impact energy to the ground more efficiently.
- However, the minimum allowable distance to existing structures for rapid impact compaction is typically larger than that for deep dynamic compaction because the energy per blow by rapid impact compaction is lower.
- Allen (1996) reported that rapid impact compaction induced the vibration frequencies ranging from 9 to 15 Hz, which are higher than those by deep dynamic compaction.
- Based on the vibration frequency and threshold particle velocity for different structures, Becker (2011) recommended the minimum allowable distance of rapid impact compaction to structures as shown in Table 3.17.
- *Shallow trenches can be excavated to minimize the vibration from the source.*

Table 3.17 Minimum Allowable Distance of Rapid Impact Compaction to Structures

Structure Type	Threshold Particle Velocity (mm/s)	Minimum Allowable Distance (m)
Drywall	19	14.5
Plaster	13	19.0
All others	51	7.5

Source: Modified from Becker (2011).

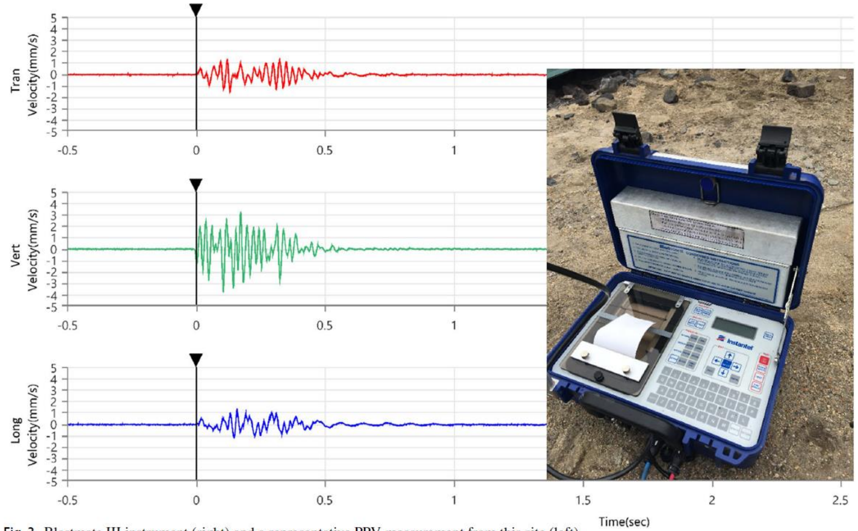
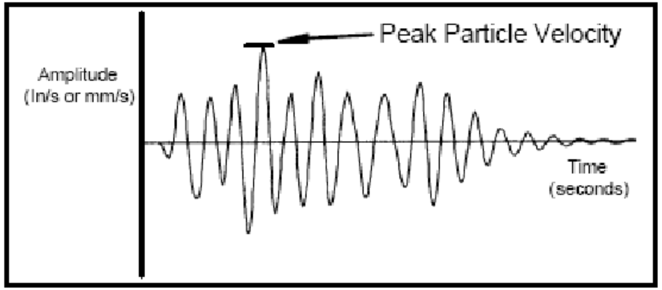


Fig. 3 Blastmate III instrument (right) and a representative PPV measurement from this site (left)

Source:
https://doi.org/10.1007/s12665-019-8491-x



Source:
https://www.researchgate.net/figure/Peak-particle-velocity-definition-From-Instantel-2001_fig1_265347764

❑ *Groundwater*

- The depth of groundwater table at 1 m is the minimum requirement for rapid impact compaction. If the groundwater table is too close to the ground surface, dewatering or additional fill should be implemented prior to compaction.

Design Parameters and Procedure

See Section 3.6.4 in
Han J., (2015), *Principles and Practices of Ground Improvement*, John Wiley & Sons, Inc., Hoboken, New Jersey.

Design Parameters

Design parameters for rapid impact compaction include:
- Geomaterial type
- Depth of groundwater table
- Weight of hammer
- Height of drop
- Diameter of steel foot
- Depth of improvement
- Pattern and spacing of impact points
- Number of blows
- Distance to existing structures or utility lines

SOIL MECHANICS II CVSM308

PROBLEMATIC SOILS & GROUND IMPROVEMENT

Topic #8 Shallow and Deep Compaction

Vibro-Compaction

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Image Source: https://nsccme.com/

VIBRO -COMPACTION

Source:
https://www.youtube.com/watch?v=fI54TqFbbgM&list=PLAjlFHAMA3GJuZcDphvSA1PrFVIoYLTFC&index=27

Basic Concept

- The vibrating probe, driven into the ground, generates lateral vibratory forces to rearrange particles into a dense state as shown in figure.

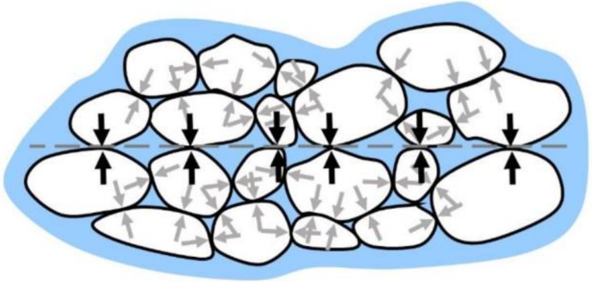
➢ The rearrangement of particles becomes possible only when the induced forces are higher than the interparticle friction.

➢ In saturated cohesionless geomaterial, vibration can generate excess pore water pressure, which reduces interparticle contact forces (i.e., effective stresses) so that the interparticle friction (i.e., shear strength) is reduced.

➢ As a result, the rearrangement of particles becomes easier.

➢ In dry cohesionless geomaterial, water can be injected to make the compaction easier.

- Backfill is also often used to improve the degree of densification.
- This technique, called the vibro-flotation method, was first developed in Germany in 1930s and has been successfully used worldwide.
- The probe for vibro-flotation is commonly referred to as a vibro-flot.



Source; https://www.researchgate.net/publication/311909145_State_of_the_Art_and_Practice_in_the_Assessment_of_Earthquake-Induced_Soil_Liquefaction_and_Its_Consequences

Source: http://www.atlasgcc.com/ground-improvement/

Suitability

It is suitable for densifying deep deposits of cohesionless geomaterial with up to 20% fines (preferably less than 10%) but less than 2–3% clay particles.

The 20% limit was developed based on the field evaluation shown in Figure 3.32.

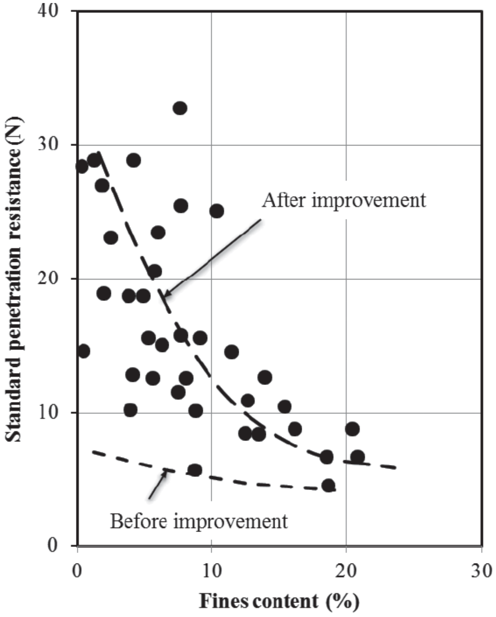
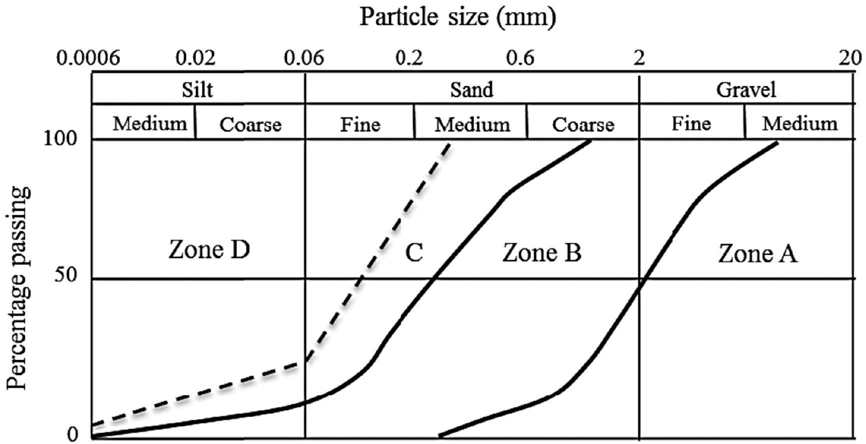


Figure 3.32 Effect of fine content on SPT *N* value (Saito, 1977).



Zone A: Vibro-compaction appropriate, but penetration difficult.
Zone B: Most suitable for vibro-compaction appropriate.
Zone C: Vibro-compaction feasible, but longer time required.
Zone D: Vibro-compaction not feasible - use stone columns.

Figure 3.33 Suitability for vibro-compaction (modified from Woodward, 2005).

 # Vibro-compaction method has been used to densify loose cohesionless soil up to a depth of 40 m (mostly within 20 m).

VIBRO -COMPACTION

Applications and Uses

Vibro-compaction has been mostly used when loose cohesionless geomaterial exists to

- increase bearing capacity
- reduce settlement
- mitigate liquefaction for a variety of projects.
- The examples of these projects are storage tanks, buildings, roadways, dams, and dikes or levees.

Acceleration

There is a critical acceleration of approximately 0.5 g, above which the dynamic stresses induced by dynamic compaction destroy the structure of granular soils.

- When the acceleration is increased to more than 1.5g, the shear strength of the soil is significantly reduced and the soil is fluidized. A further increase of acceleration exceeding 3.0g causes soil dilation.

Installation Process

- To minimize probe shaft resistance, penetration and extraction should be done at a high frequency.
- During the compaction, however, the preferable frequency is close to the resonance of the geomaterial mass so that more energy is transferred to the surrounding geomaterial to make the compaction efficient.

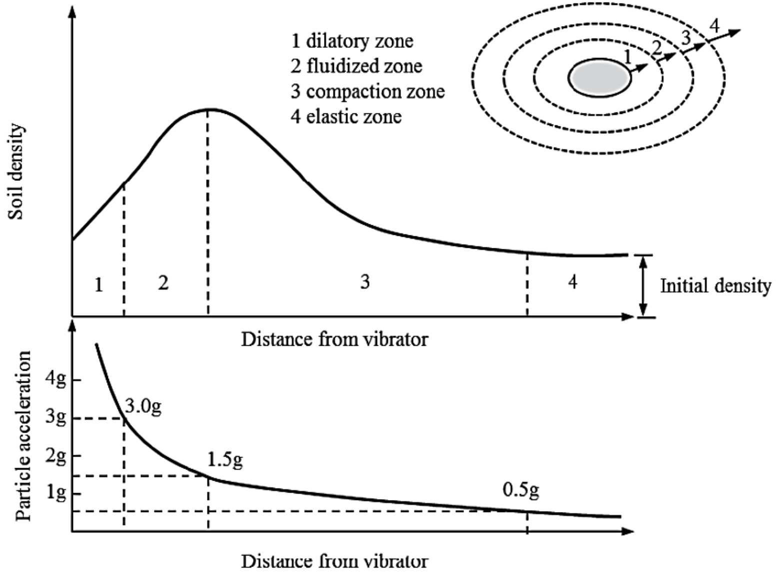


Figure 3.34 Idealized response of cohesionless soil around a vibrating probe (modified from Rodger, 1979).

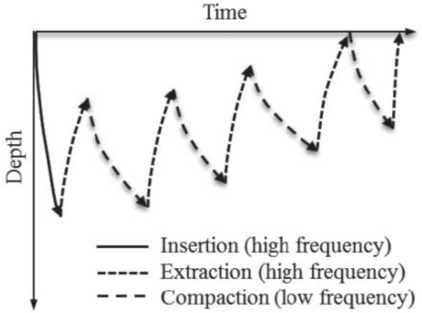
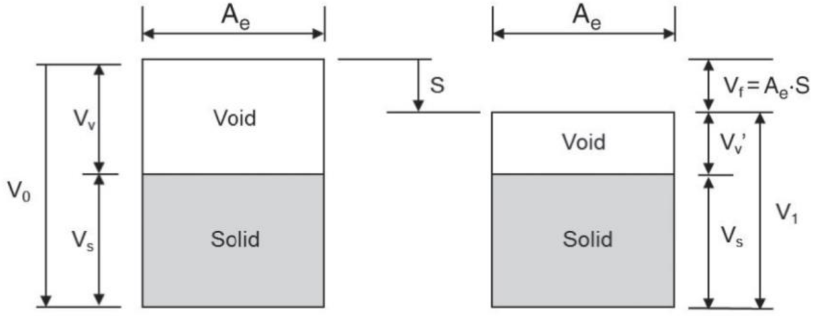


Figure 3.36 Penetration, compaction, and extraction process (Massarsch and Fellenius, 2005).

Volume Change without Backfill

Vibro-compaction without backfill often induces ground subsidence.



(a) Initial (b) After improvement

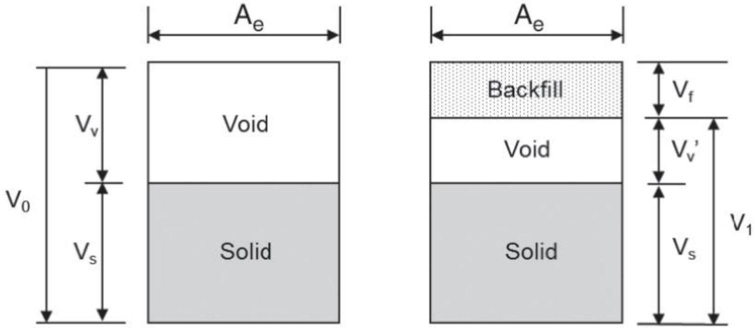
Figure 3.38 Volume changes during densification without backfill: (a) initial and (b) after improvement.

$$\frac{S}{h} = \frac{e_0 - e_1}{1 + e_0} \qquad (3.28)$$

where
e_0 =the void ratio before improvement (initial void ratio)
e_1= the void ratio after improvement,
h= the improvement depth
S= ground subsidence

Volume Change with Backfill

During vibro-compaction, backfill materials are sometimes added to help densify surrounding cohesionless geomaterial.



(a) Initial (b) After improvement

Figure 3.39 Volume changes during densification with backfill: (a) initial and (b) after improvement.

$$\frac{A_e h}{V_f} = \frac{1 + e_0}{e_0 - e_1} \qquad (3.30)$$

Considering the volume of backfill

$$V_f = \frac{\pi {d_{cl}}^2}{4} h \qquad (3.31)$$

where d_{cl} is the diameter of the column with backfill.

Improvement area by an individual column can be calculated as follows:

$$A_e = s^2 = \frac{\pi {d_{\mathrm{cl}}}^2}{4} \cdot \frac{1+e_0}{e_0 - e_1} \tag{3.32}$$

The spacing of columns, s, can be determined as follows:

$$s = 0.89 d_{\mathrm{cl}} \sqrt{\frac{1+e_0}{e_0 - e_1}} \quad \text{(square pattern)} \tag{3.33a}$$

$$s = 0.95 d_{\mathrm{cl}} \sqrt{\frac{1+e_0}{e_0 - e_1}} \quad \text{(triangular pattern)} \tag{3.33b}$$

If there is ground subsidence or heave after vibro-compaction, the required volume of backfill is

$$V_f = A_e H \frac{e_0 - e_1}{1+e_0} \pm A_e S = s^2 \left(h \frac{e_0 - e_1}{1+e_0} \pm S \right) \tag{3.34}$$

in which the + sign represents a ground heave condition while the – sign represents a ground subsidence condition.

Combining equations (3.31) and (3.34) yields the following equations:

$$s = 0.89 d_{\mathrm{cl}} \sqrt{\frac{(1+e_0)h}{(e_0 - e_1)h \pm (1+e_0)S}} \quad \text{(square pattern)} \tag{3.35a}$$

$$s = 0.95 d_{\mathrm{cl}} \sqrt{\frac{(1+e_0)h}{(e_0 - e_1)h \pm (1+e_0)S}} \quad \text{(triangular pattern)} \tag{3.35b}$$

Design Considerations

❑ *Performance Criteria*

For most vibro-compaction projects, the following performance criteria should be considered (Elias et al., 2004):

- Relative density of geomaterial, Dr ≥ 60% for floor slabs, flat bottom tanks, and embankments
- Dr ≥ 70–75% for column footings and bridge foundations
- Dr ≥ 80% for machinery and mat foundations.

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}}$$

❑ *Area and Depth of Improvement*

- In general, the area of improvement should be larger than footprints of foundations.
- Kirsch and Kirsch (2010) suggested typical arrangements of compaction probe points below isolated and strip footings as shown in Figure 3.40.
- Under a general condition, one to two rows of compaction points may be installed outside of a footing.

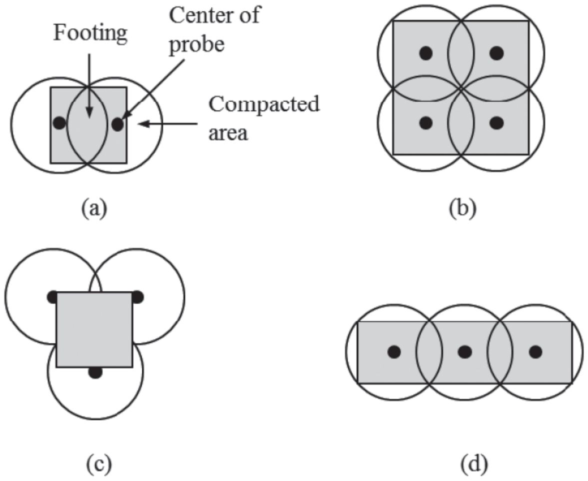


Figure 3.40 Typical arrangements of compaction probe points below isolated and strip footings (modified from Kirsch and Kirsch, 2010).

❑ *Grid Pattern and Spacing*

- Grid points for vibro-compaction can be in a square, rectangular or triangular pattern.
- Typical spacing for vibro-compaction ranges from 1.5 to 3.5 m, depending on type, initial density, and target density of the geomaterial and horsepower of the vibrator.
- Engineers have developed design charts to estimate the spacing of compaction points. Figure 3.41 is one such design chart.

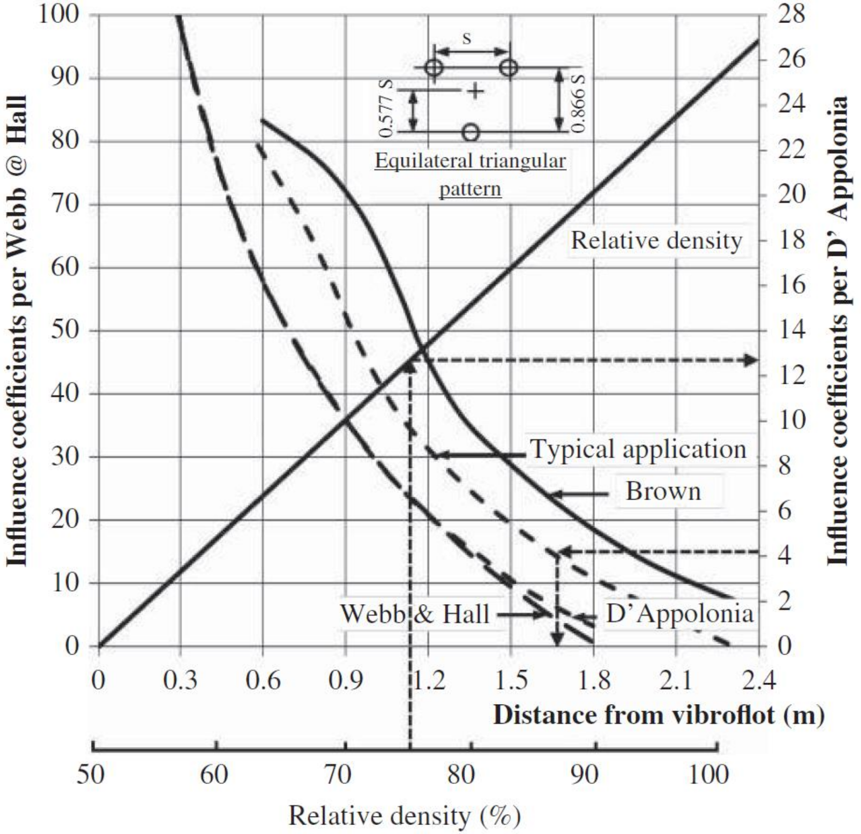


Figure 3.41 Design chart for compaction point spacing and relative density (Modified from Yee, 2013; Glover, 1982).

Another design chart as shown in Figure 3.42 has also been used in practice. Based on the soil type and the **target relative density**, the tributary area for each compaction point can be estimated from this figure. After the spacing of compaction points is determined, the average site subsidence can be estimated using Equation (3.28) without any backfill. If the ground subsidence is too large, backfill can be added to minimize ground subsidence.

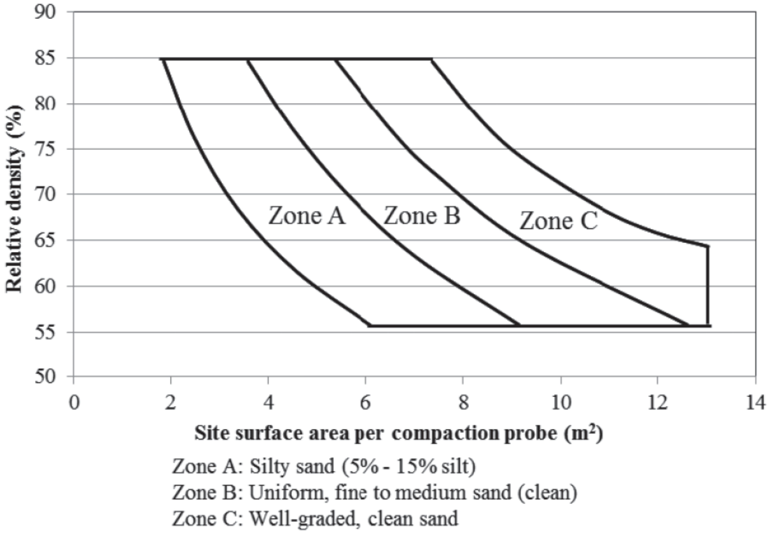


Figure 3.42 Tributary area of compaction point versus relative density of soil (Hayward Baker).

If backfill is used, Equation (3.35a) or (3.35b) can be used to estimate the required spacing of compaction points. If the spacing is fixed, the ground subsidence after adding backfill can be estimated. Based on a required allowable bearing capacity, the spacing of compaction points can also be estimated as shown in Figure 3.43.

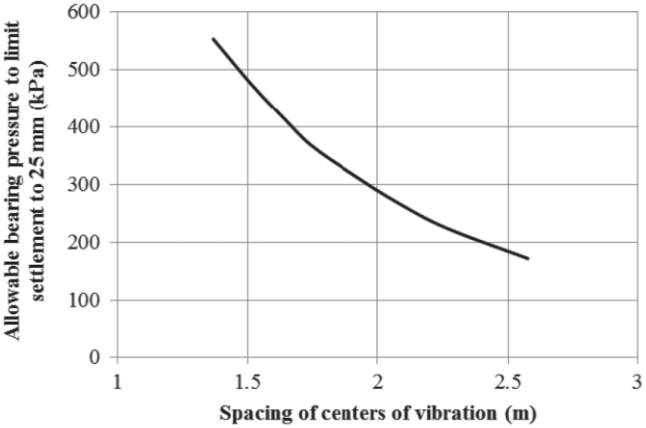


Figure 3.43 Allowable bearing capacity versus spacing of compaction points for footing width of 1–3 m (Thorburn, 1975).

VIBRO -COMPACTION

Design Parameters and Procedure

Design parameters for vibro-compaction include:

- Geomaterial type, fine content, and percent of clay particles
- Thickness and depth of problematic geomaterial
- Depth of groundwater table
- Initial void ratio or relative density of geomaterial
- Target void ratio or relative density of geomaterial
- Pattern and spacing of compaction points
- Area of improvement
- Equipment type and horsepower
- Frequency of penetration, compaction, and extraction
- Duration of compaction
- Ground subsidence
- Diameter of column if backfill is used