PDHonline Course C240 (3 PDH)

Ground Improvement Guidelines

Instructor: John Huang, Ph.D., PE and John Poullain, PE

2020

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

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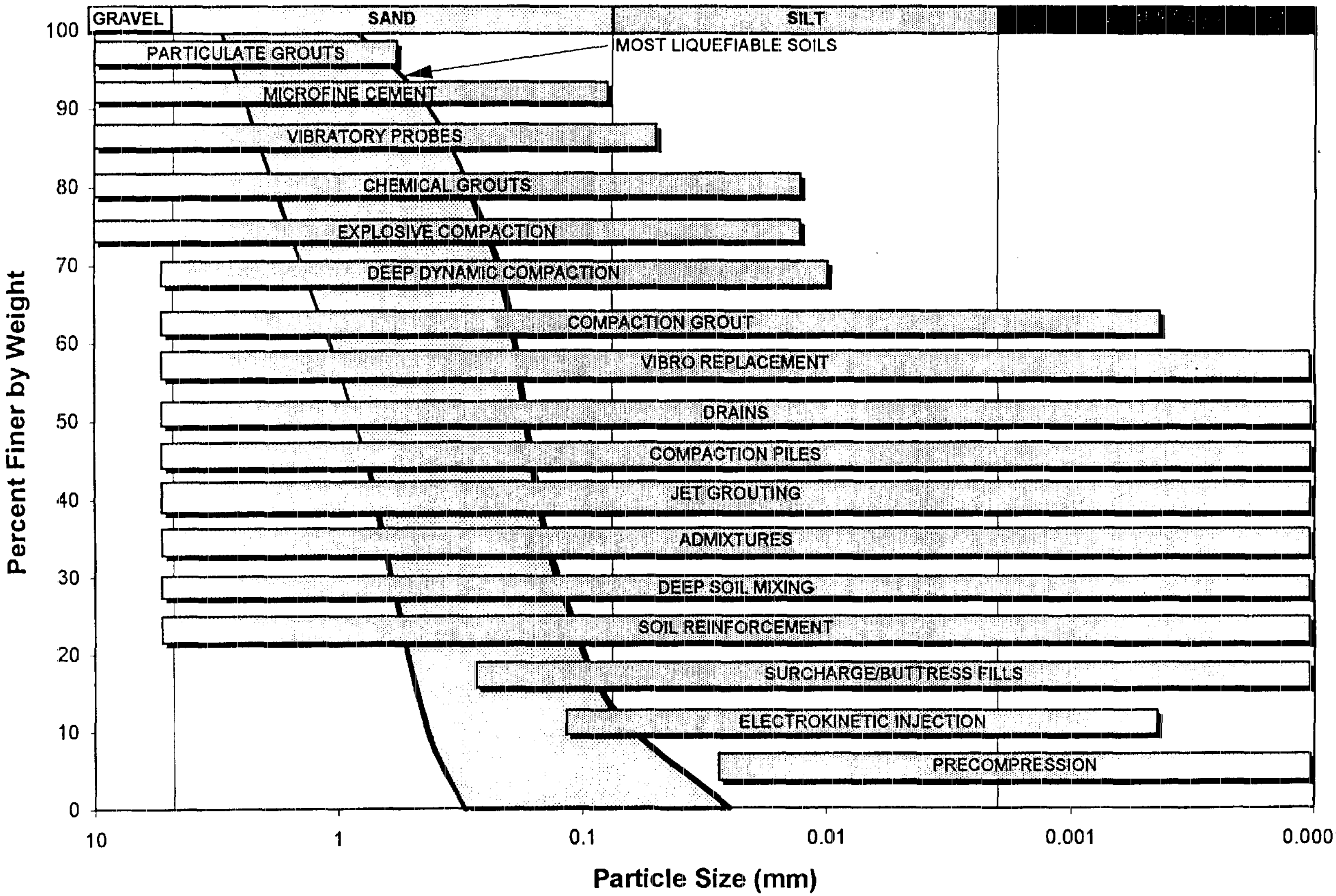
CHAPTER 3

IF GROUND IMPROVEMENT IS NECESSARY, WHAT METHODS ARE AVAILABLE?

Many methods for ground modification and improvement are available, including dewatering, compaction, preloading with and without vertical drains, admixture stabilization, grouting of several types, deep mixing, deep densification, and soil reinforcement. Many of these techniques, such as dewatering, compaction, precompression, and some types of grouting, have been used for many years. However, there have been rapid advances in the areas of deep densification (vibrocompaction, deep dynamic compaction, compaction piles, explosive densification), jet and compaction grouting, deep mixing, and stone column systems in recent years. These methods have become practical and economical alternatives for many ground improvement applications. While most of these technologies were originally developed for uses other than seismic risk mitigation, many of the recent advances in the areas of deep densification, jet and compaction grouting, and deep mixing methods have been spurred on by the need for practical and cost effective means for mitigating seismic risks. Many of these methods have been applied to increase the liquefaction resistance of loose, saturated, cohesionless soils.

Table 3 contains a list of potentially applicable ground improvement methods for civil works structures. Various purposes for ground improvement are indicated, along with methods that may be applicable for each purpose. Several different methods may be suitable for each potential application. Selection of the most appropriate method for a particular purpose will depend on many factors, including the type of soil to be improved, the level of improvement needed, the magnitude of improvement attainable by a method, and the required depth and areal extent of treatment. The applicable grain size ranges for various soil improvement methods are shown in Figure 27. The remaining factors are discussed further in subsequent chapters.

Figure 27. Applicable Grain Size Ranges For Soil Improvement Methods.



An important factor in selection of a suitable ground improvement method is the accessibility of the site, particularly if the site is already developed. When ground improvement is needed on large, open and undeveloped sites, there are typically more and less expensive options available than at sites that are small or have constraints such as existing structures or facilities. Ground improvement methods that are potentially suitable and economical for use on large, open, undeveloped sites are summarized in Table 4. A similar summary of ground improvement methods that may be applicable for use at constrained or developed sites is contained in Table 5. For each method, information is provided regarding suitable soil types, effective depth of treatment, typical layout and spacing, attainable improvement, advantages, limitations and prior experience. A summary of approximate costs for various ground improvement options is presented in Table 6.

Tables 3, 4, and 5 can be used to select options for ground improvement at a particular site. These options can then be narrowed down based on the design considerations presented in the next chapter. Table 6 can be used to estimate the approximate costs for various ground improvement methods.

Brief description of each of the methods are given below. More detailed discussions may be found in Mitchell (1981), FHWA (1983, 1986a, 1986c, 1996a, 1996b, 1998), Hausmann (1990), Mitchell and Christopher (1990), Narin van Court and Mitchell (1994, 1995), Hayward Baker (1996), and ASCE (1997).

Soil Replacement

Soil replacement involves excavating the soil that needs to be improved and replacing it. The excavated soil can sometimes be recompacted to a satisfactory state or it may be treated with admixtures and then be replaced in a controlled manner. It can also be replaced with a different soil with more suitable properties for the proposed application.

Admixture Stabilization

Admixture stabilization consists of mixing or injecting admixtures such as cement, lime, flyash or bentonite into a soil to improve its properties. Admixtures can be used to increase the strength, decrease the permeability or improve the workability of a soil. Admixtures can fill voids, bind particles, or break down soil particles and form cement. The general process of admixture stabilization consists of: (1) excavating and breaking up the soil, (2) adding the stabilizer and water, if necessary, (3) mixing thoroughly, and (4) compacting the soil and allowing it to cure. Admixture stabilization is discussed in detail in Hausmann (1990).

Roller Compacted Concrete

Roller compacted concrete (RCC) is a material that has useful applications for ground improvement. RCC is essentially no-slump concrete composed of a blend of coarse aggregate, fine aggregate, cement and water. It can be used to construct earth dams with steep slopes, to provide overtopping protection for existing earth dams, and to buttress existing slopes. It is placed and spread using conventional earth moving equipment, compacted with vibratory rollers and allowed to cure. During curing, the RCC hydrates and hardens into weak concrete. In recent years, many dams have either been constructed or rehabilitated using RCC. Use of RCC for embankment overtopping protection is discussed in *Roller Compacted Concrete III* (1992) and by McLean and Hansen (1993). Construction of dams using RCC is discussed in *Roller Compacted Concrete II* (1988) and *Roller Compacted Concrete III* (1992).

Deep Dynamic Compaction

Deep dynamic compaction (DDC), also called heavy tamping, consists of repeated dropping of heavy weights onto the ground surface to densify the soil at depth, as shown in Figure 28. For unsaturated soil, the process of DDC 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. A typical DDC program involves weights of 10 to 30 tons dropped from heights of 15 to 30 meters at grid spacings of 2 to 6 meters. A photograph of the DDC process is shown in Figure 28. DDC works best on 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. The relationship between the effective depth, the weight and the height of the drop can be expressed as:

$$D = (0.3 \text{ to } 0.7)*(WH)^{1/2}$$

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. DDC is discussed in greater detail in Mitchell (1981), FHWA (1986a), and Hayward Baker (1996).

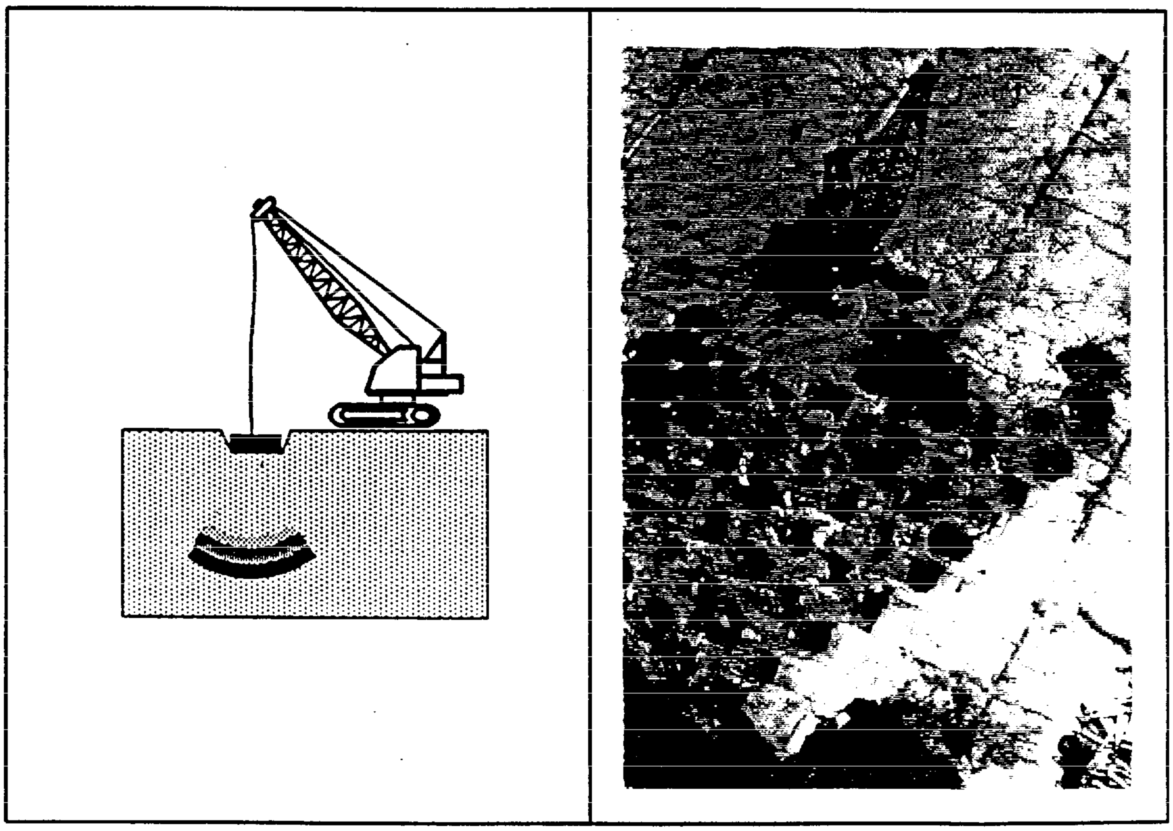


Figure 28. The dynamic compaction process (from Hayward Baker, 1996).

Vibrocompaction and Vibrorod

Vibrocompaction methods use vibrating probes (typically having a diameter of about 0.4 m) to densify the soil. A sketch showing the vibrocompaction process in shown in Figure 29. The probe is usually jetted into the ground to the desired depth of improvement and vibrated during withdrawal, causing densification. The soil densifies as the probe is repeatedly inserted and withdrawn in about 1 m increments. The cavity that forms at the surface is backfilled with sand or gravel to form a column of densified soil. Vibrocompaction methods are most effective for sands and gravels with less than about 20 percent fines, as shown in Figure 30.

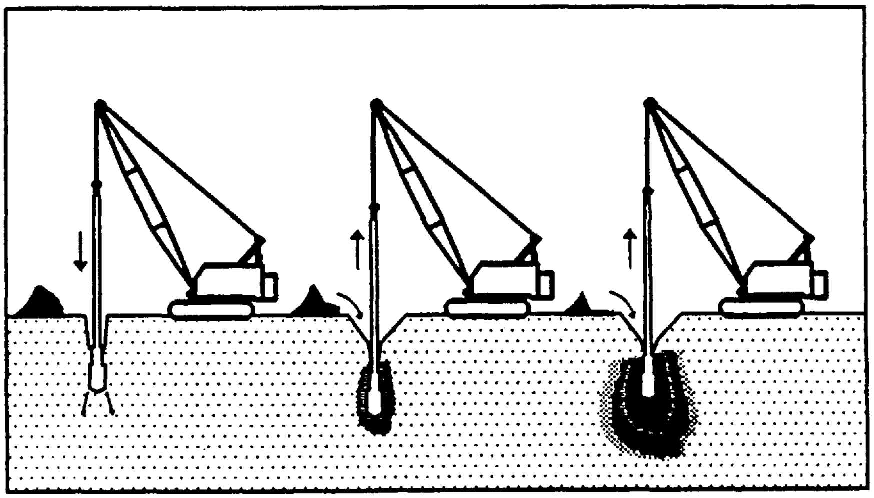


Figure 29. The vibrocompaction process (Hayward Baker, 1996)

When vibrocompaction is used for large areas, it is typically performed using either a triangular or rectangular grid pattern, with probe spacings in the range of 1.5 m to 3 m on centers. The spacing depends on several factors, including the soil type, backfill type, probe type and energy, and the level of improvement required. An approximate variation of relative density with effective area per compaction probe for a sand backfill is shown in Figure 31 (FHWA, 1983). While field tests are usually done to finalize the design, Figure 31 can be used for preliminary probe spacings. This figure can also be used for preliminary design of stone columns, which is discussed in the next section. Advantages of vibrocompaction are that the vibrations felt on or near the site are significantly less than caused by deep dynamic compaction or explosive compaction and more uniform densification is obtained. On the other hand, the cost is usually greater. Additional information is available in Mitchell (1981), Hausmann (1990), and Hayward Baker (1996).

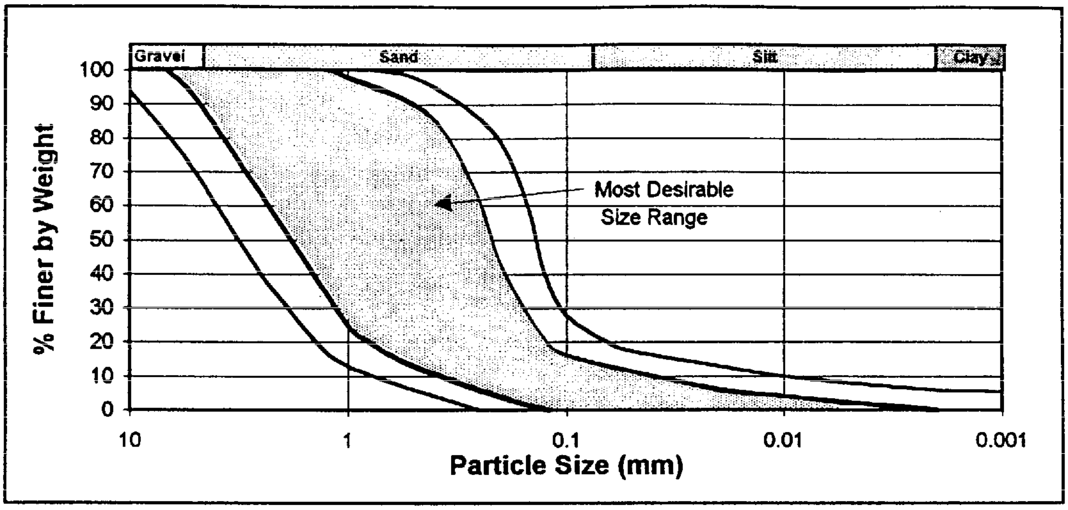


Figure 30. Range of particle size distributions suitable for densification by vibrocompaction.

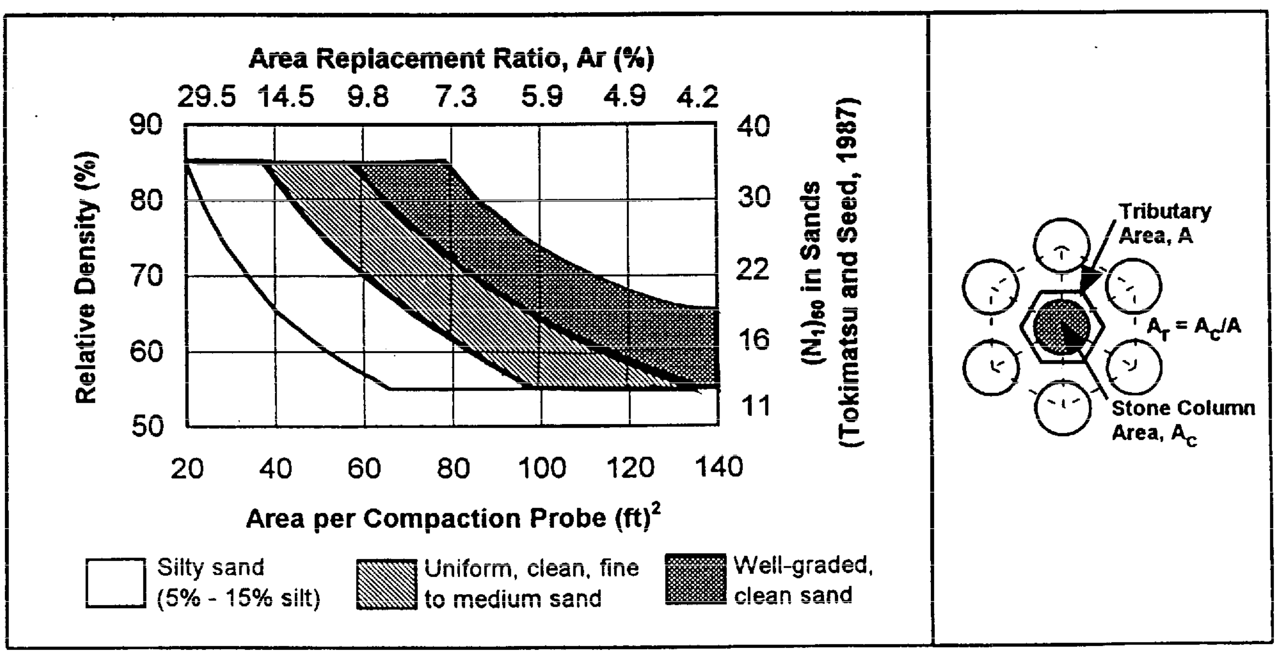


Figure 31. Approximate variation of relative density with tributary area or area replacement ratio (after FHWA, 1983).

Stone Columns (Vibroreplacement)

Stone columns are installed using a process similar to vibrocompaction, except that a gravel backfill is used, and they are usually installed in slightly cohesive soils or silty sands rather than clean sands. In the dry process, a cylindrical cavity is formed by the vibrator, that is filled from the bottom up with gravel or crushed rock. Compaction is by vibration and displacement during repeated 0.5± m withdrawals and insertions of the vibrator. Stone columns are usually about 1 m in diameter, depending on the soil conditions, equipment and construction procedures. They are usually installed in square or triangular grid patterns, but may also be used in clusters and rows to support footings and walls. Center-to-center column spacings of 1.5 to 3.5 m are typical. Figure 31 may be used for preliminary design using the area replacement ratio axis. The area replacement ratio is defined as the area of the stone column to the tributary area per stone column. For foundation applications, coverage should be extended beyond the perimeter of the structure to account for stress spread with depth. A drainage blanket of sand or gravel 0.3 m or more in thickness is usually placed over the top of the treatment area. This blanket also serves to distribute stresses from structures above. Additional details regarding stone columns are discussed in Mitchell (1981), Hausmann (1990), and Hayward Baker (1996).

Gravel Drains

Gravel drains are a type of stone column proposed for use in liquefiable soils to mitigate liquefaction risk by dissipation of excess pore water pressures generated during earthquakes (ASCE, 1997). They have been proposed for use in two ways: (1) as the sole treatment method for liquefiable zones and (2) as a perimeter treatment around improved zones to intercept pore pressure plumes from adjacent untreated ground. A typical layout for gravel drains is shown in Figure 32. Gravel drains are constructed in the same manner as stone columns, but are installed in cohesionless deposits. As the gravel is densified during vibro-replacement, there is mixing of the sand from the formation with the gravel in the drain. The degree of mixing has a strong influence on the final permeability of the gravel drain.

Seed and Booker (1977) first proposed design methods for gravel drains to prevent liquefaction of sands. They assumed that drainage would occur radially towards the center of the column if the drain permeability were at least 200 times the native soil permeability and that drain resistance could be neglected. In practice, however, seepage in the drain occurs vertically, so the drainage path length is much longer than originally assumed by Seed and Booker and drain resistance becomes an important factor in design. Design diagrams that consider the drainage path length and drain resistance were presented by Onoue (1988). Boulanger et al. (1998) performed designs using both methods and found that the methods agree when drain resistance is negligible. However, they also found that a drain permeability of 200 times the soil permeability was not sufficient to eliminate the effects of drain resistance. Therefore, they suggest that the diagrams presented by Onoue (1988) be used to include the effects of drain resistance in design of gravel drains.

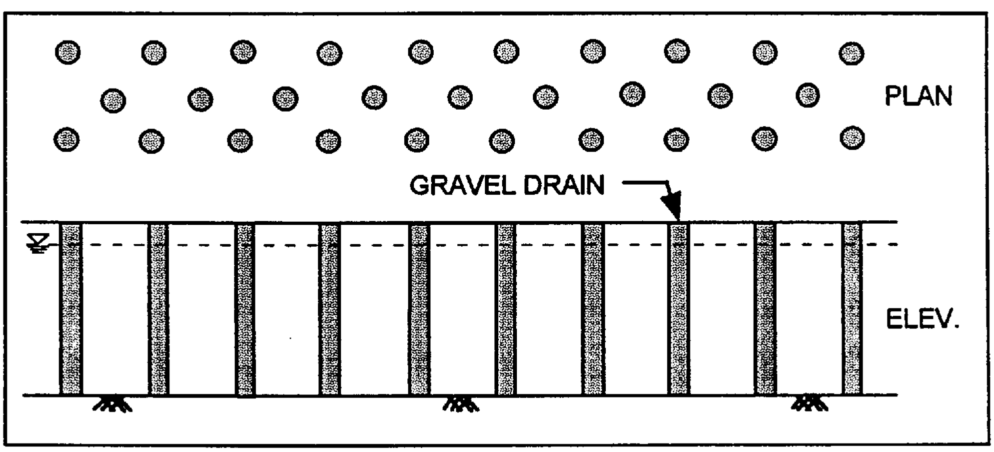


Figure 32. Arrangement of gravel drains (after Seed and Booker, 1977).

A detailed discussion of design and construction issues regarding gravel drains is presented by Boulanger et al. (1998). Intermixing of the native soil and the drain material can cause the permeability of the resultant drain to be less than 100 times the permeability of the native soil. Construction defects can result in zones of low permeability. Therefore, it is recommended that densification be the primary treatment goal when gravel columns are used and that drainage be considered a secondary benefit. It is noted, however, that row(s) of gravel drains used around the perimeter of a densified zone can be beneficial in intercepting excess pore pressure plumes from adjacent liquefied soil.

Sand and Gravel Compaction Piles

Compaction piles densify the soil by two mechanisms: (1) displacement of a volume of soil equal to the pile volume and (2) densification of the soil due to vibrations induced by the pile driving. They are typically spaced 1 to 3 m on center. For preliminary design in loose sand, the following guideline may be used. To increase the average density of loose sand from an initial void ratio e_o, to a void ratio e, assuming that installation of a sand pile causes compaction only in a lateral direction, the pile spacings may be determined using

$$S = d\left(\frac{\pi(1+e_o)}{e_o - e}\right)^{1/2}$$

for sand piles in a square pattern, Figure 33 (a) and

$$S = 1.08\,d\left(\frac{\pi(1+e_o)}{e_o - e}\right)^{1/2}$$

for piles in a triangular pattern, Figure 33 (b), in which d is the sand pile diameter (up to 800 mm) (Mitchell, 1981). Compaction piles are often slow to install and relatively expensive. A Franki pile is a type of compaction pile in which a falling weight is used to drive the backfill out the bottom of a large diameter pipe. Additional detail on sand and gravel compaction piles can be found in Mitchell (1981).

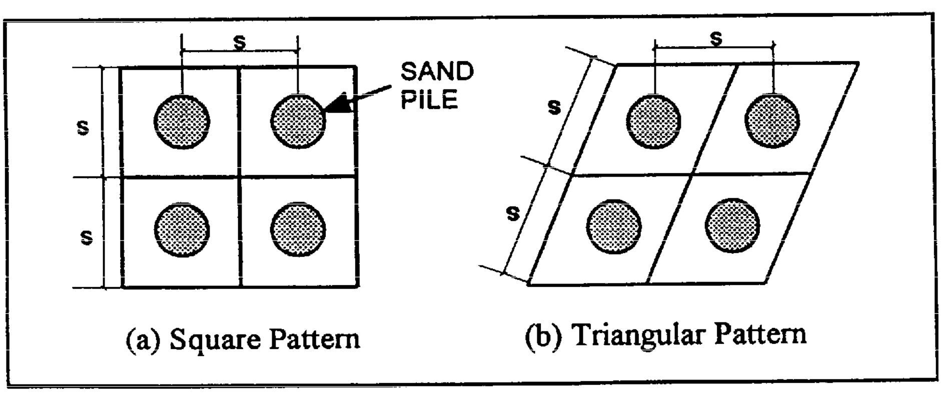


Figure 33. Usual compaction pile patterns.

Explosive Compaction

In explosive compaction, densification occurs after a charge is detonated below the ground surface. The detonation induces liquefaction in the soil, which then recompacts to a denser, more stable fabric under the pressures induced by both the blast and by gravity. If a partly saturated soil is prewetted before the charges are detonated, the process is termed hydroblasting. Hydroblasting is sometimes used to treat collapsible soils. A typical layout for explosive compaction is shown in Figure 34. Explosive compaction has an unlimited effective depth and is best suited for clean sands and silty sands with initial relative densities of less than about 50 to 60 percent. The post-densification improvement in strength and stiffness is usually time-dependent and may require several weeks to fully develop.

A typical blasting program consists of charges spaced at 3 to 8 m in developed areas and 8 to 15 meters in remote areas, with charge weights between 2 and 15 kilograms. The total explosive use is usually 40 to 80 g/m^3. For soil layers less than 10 m thick, the charges are usually placed at a depth between one-half and three-quarters the thickness of the layer to be treated, with a depth of two-thirds the layer thickness common. If a layer is more than 10 m thick, it is recommended that it be divided into sublayers, where each sublayer is treated separately with decked charges (Narin van Court and Mitchell, 1994). The charges in each sublayer can be set off in sequence from top to bottom or bottom to top, and there is no definitive evidence that one sequence is more effective than the other.

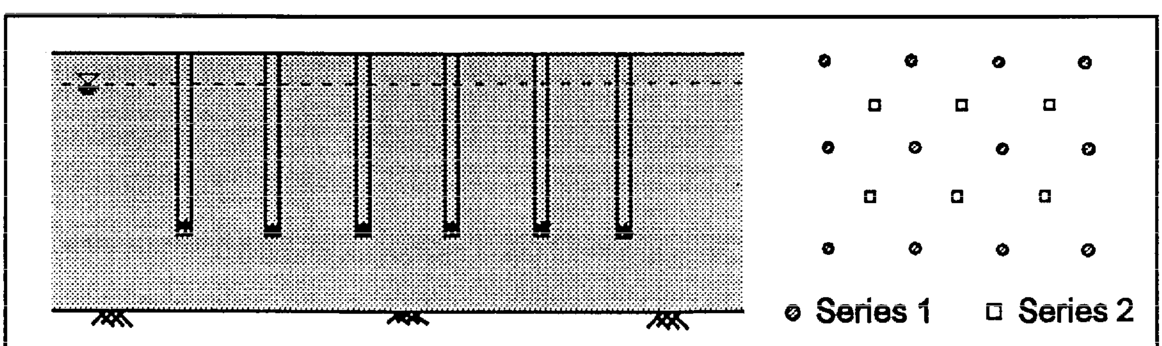


Figure 34. Typical layout for explosive compaction program.

For any layer thickness, the treatment area typically needs to be treated with 2 or 3 series of charges, with each series of charges separated by a period of hours or days. Surface settlement of 2 to 10 percent can be expected, depending on the amount of explosives used and the initial properties of the soil and site. A field testing program is usually performed for the final design. For additional information on explosive compaction, consult Narin van Court and Mitchell (1994, 1995).

Permeation Grouting

Permeation grouting is a process by which the pore spaces in soil or the joints in rock are filled with grout, as depicted in Figure 35. Injection pressures are usually limited to prevent fracture or volume change in the formation. One rule of thumb for maximum injection grouting pressures is 20 kPa per meter of depth (1 psi/ft). Either particulate or chemical grouts can be used. The process is limited to relatively coarse-grained soils, because the grout must be able to flow through the formation to replace the fluid in the void spaces or joints. Particulate grouts, such as cement or bentonite, are used for soils no finer than medium to coarse sands, since the particles in the grout must be able to penetrate the formation. Use of micro-fine cement enables penetration of somewhat finer-grained soil than can be treated using ordinary Portland cement. Chemical grouts, usually silicates, can be used in formations with smaller pore spaces, but are still limited to soils coarser than fine sands. The typical spacing for penetration grouting holes is between about 4 to 8 feet. For water cutoff applications, two or three rows of grout holes are usually required to form an effective seepage barrier. Penetration grouting can also be used for ground strengthening and liquefaction mitigation. Whereas seepage control requires essentially complete replacement of the pore water by grout, effective strengthening is possible with incomplete replacement. Additional references on permeation grouting include Karol (1990) and Xanthakos et al. (1994). Case histories on chemical grouting for mitigation of liquefaction risk can be found in Graf (1992b).

through friction or adhesion mobilized at the soil-nail interface. The second mechanism is the development of passive resistance against the face of the nail.

Soil nailing works best in dense granular soil and stiff, low plasticity silty clay soils. In stiff soils, the maximum facing displacement is about 0.3 percent. Current design procedures for soil nailed walls are included in FHWA (1996b).

Prefabricated Vertical (PV) Drains, with or without surcharge fills

Prefabricated vertical (PV) drains, also known as wick drains, are typically installed in soft, cohesive soil deposits to increase the rate of consolidation settlement and corresponding strength gain. The rate of consolidation settlement is proportional to the square of the length of the drainage path to the drain. Installing vertical drains shortens the drainage path, which causes an increase in the rate of settlement. Geocomposites are widely used as drains because they are relatively inexpensive, economical to install and have a high flow capacity. Geocomposite drains consist of a plastic waffle core which conveys the water and a geotextile filter to protect the core from clogging. In selecting a drain, it is important to choose one with enough capacity. Drains are typically spaced in a triangular or rectangular configuration. A sand blanket is usually placed on the surface of the consolidating layer to facilitate drainage. For additional information on engineering assessment and design of vertical drains, the 1986 FHWA publications titled *Prefabricated Vertical Drains* and *Geocomposite Drains* may be consulted. A discussion of the updates in PV drains in the past ten years can be found in ASCE (1997).

Surcharge preloading can be used in conjunction with vertical drains to increase the magnitude of settlement prior to construction, as shown in Figure 41. Surcharge preloading consists of placing a surcharge load over the footprint of the proposed facility prior to construction. The surcharge load causes consolidation settlement to occur. It can be accomplished with surcharge fills, water in tanks and ponds, by lowering the groundwater table or by electroosmosis.

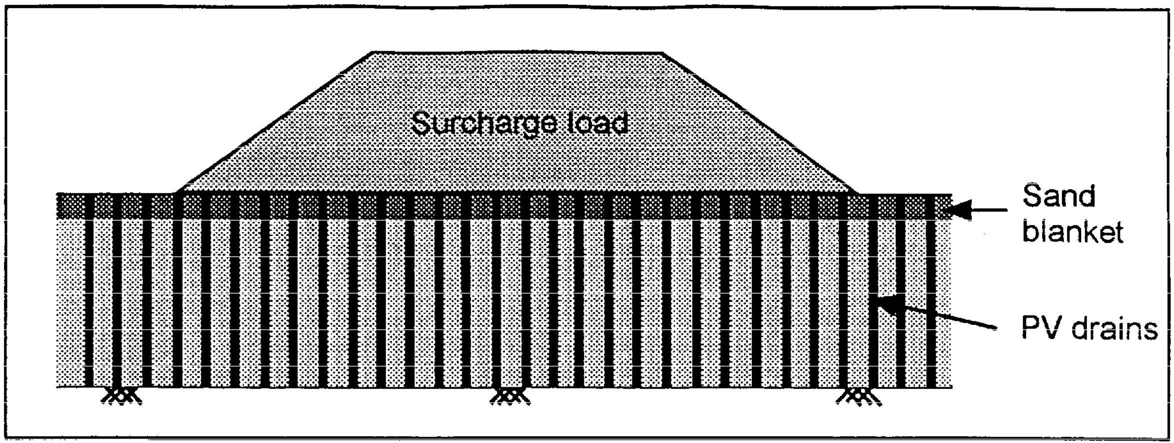


Figure 41. PV drains with surcharge load.

A new application for PV drains is in the area of mitigation of liquefaction risk (ASCE, 1997). PV drains have the potential to provide liquefaction resistance by improving drainage and/or adding reinforcement. PV drains were installed in conjunction with stone columns in a test section at Salmon Lake Dam in Washington (Luehring, 1997). The purpose of the installation was for liquefaction mitigation of non-plastic silty soils. The PV drains were used to improve drainage, provide relief of excess pore pressure and to prevent disturbance or fracturing of the foundation soils. The drains were installed prior to stone column construction. The columns were installed using the dry, bottom-feed method, which presents concerns with respect to disturbance or fracture of the foundation soils being treated, as well as the adjacent foundation soils. During construction of the stone columns, air and water were ejected from most of the wick drains. The study concluded that the wick drains relieved most of the excess air and water pressures during construction, thus protecting the dam and foundation materials immediately below the dam from disturbance.

Electroosmosis

If a DC electric potential is applied to a saturated clay soil, the cations will be attracted to the cathode and the anions will be attracted to the anode. The cations and anions will carry their water of hydration with them as they move and move additional water by viscous drag. Due

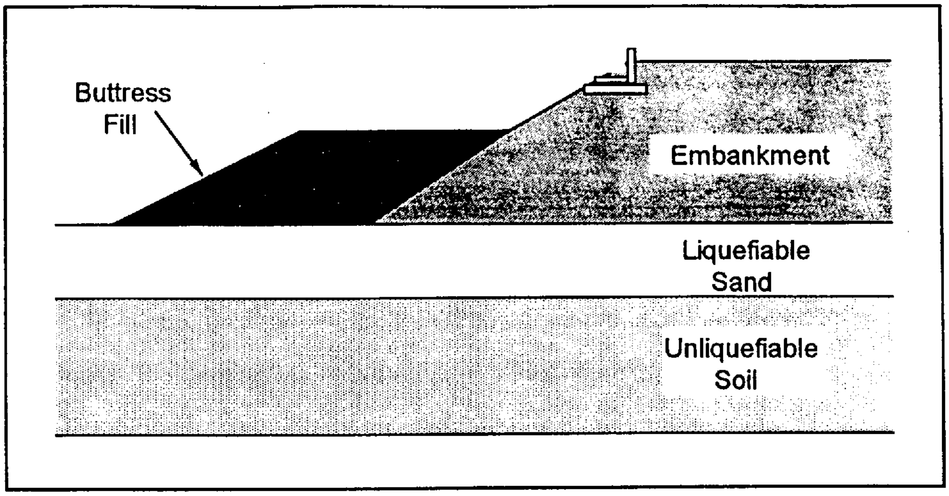


Figure 42. Buttress fill at toe of embankment.

to the net negative charge of the clay particles, there are more mobile cations than anions, so the net flow of pore water will be toward the cathode. If the cathode is a wellpoint, the water collected at the cathode can be removed and the soil between the electrodes will consolidate. Consolidation will be greatest at the anode and least near the cathode. No consolidation will occur at the cathode itself. The process of electroosmosis will result in a lower moisture content, lower compressibility and increased strength. There may be an additional increase in strength and a decrease in plasticity due to electrochemical hardening, which occurs when the application of a DC electric potential to a saturated clay causes electrode corrosion, ion exchange, and mineral alteration. Electroosmosis and electrochemical hardening are discussed by Mitchell (1993).

Buttress Fills

A buttress fill may be used to improve the stability of a slope or increase the resistance to liquefaction by adding weight to the system, as shown in Figure 42. For a slope, the buttress adds weight which increases the resisting force and increases the length of the failure surface. For ground susceptible to liquefaction, the buttress also serves to increase the confining pressure, thereby increasing the resistance to liquefaction.

Biotechnical Stabilization and Soil Bioengineering

Biotechnical stabilization and soil bioengineering can be used to stabilize slopes against erosion and shallow slope failures. The biotechnical stabilization method consists of using live vegetation in combination with inert structural or mechanical components, such as retaining structures, revetments and ground cover systems (ASCE, 1997). For example, plants can be established in the front openings of gabion walls and cellular grids or on the benches of tiered retaining walls. The vegetation and mechanical elements work together as an integrated system to provide erosion protection or slope stabilization. Soil bioengineering is the use of live plants alone to serve as soil reinforcement, hydraulic drains and barriers to earth movement. An example of slope stabilization by brush layering is shown in Figure 43. Bioetechnical stabilization and soil bioengineering are discussed in Gray and Sotir (1996). This method is applicable for river and stream banks. It should not be used as part of the physical flood protection (levees, etc.).

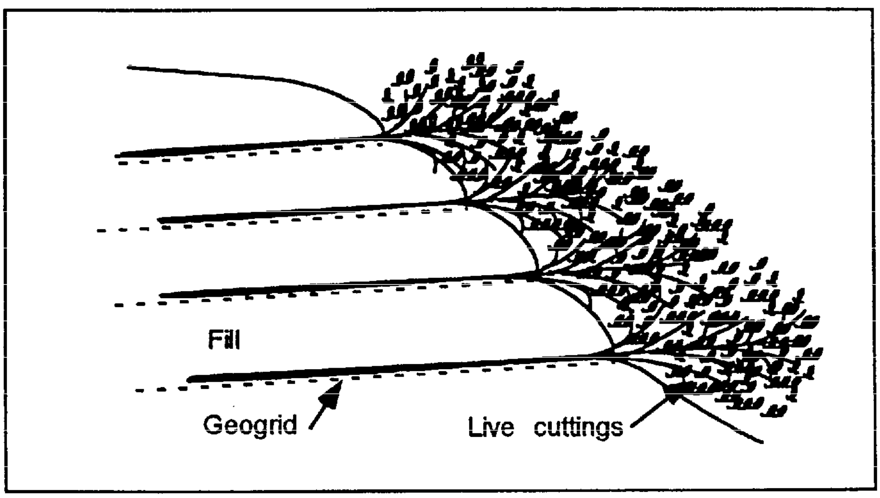


Figure 43. Biotechnical stabilization by brush layering (after Gray and Sotir, 1996).

Table 3 - Potentially Applicable Ground Improvement Methods for Civil Works Structures

Purpose	Method	
• Increase resistance to liquefaction • Reduce movements	• Vibrocompaction, vibrorod • Stone columns • Deep dynamic compaction • Explosive compaction • Gravel drains	• Deep soil mixing • Penetration grouting • Jet grouting • Compaction grouting • Sand and gravel compaction piles
• Stabilize structures that have undergone differential settlement	• Compaction grouting • Penetration grouting	• Jet grouting • Mini-piles
• Increase resistance to cracking, deformation and/or differential settlement	• Compaction grouting • Penetration grouting	• Jet grouting • Mini-piles
• Reduce immediate settlement	• Vibrocompaction, vibrorod • Deep dynamic compaction • Explosive compaction • Compaction grouting	• Deep soil mixing • Jet grouting • Sand and gravel compaction piles
• Reduce consolidation settlement	• Precompression • Jet grouting • Compaction grouting	• Stone columns • Deep soil mixing • Electro-osmosis
• Increase rate of consolidation settlement	• Vertical drains, with or without surcharge fills • Sand and gravel compaction piles	
• Improve stability of slopes	• Buttress fills • Gravel drains • Penetration grouting • Compaction grouting	• Jet grouting • Deep soil mixing • Soil nailing • Sand and gravel compaction piles
• Improve seepage barriers	• Jet grouting • Deep soil mixing	• Penetration grouting • Slurry trenches
• Strengthen and/or seal interfaces between embankments/abutments/foundations	• Penetration grouting	• Jet grouting

Table 3 (cont.) - Potentially Applicable Ground Improvement Methods for Civil Works Structures

Purpose	Method	
• Seal leaking conduits and/or reduce piping along conduits	• Penetration grouting	• Compaction grouting
• Reduce leakage through joints or cracks	• Penetration grouting	
• Increase erosion resistance	• Roller compacted concrete • Admixture stabilization	• Biotechnical stabilization
• Stabilize dispersive clays	• Add lime or cement during construction • Protective filters • For existing dams, add lime at upstream face to be conveyed into the dam by flowing water	
• Stabilize expansive soils	• Lime treatment • Cement treatment	• Soil replacement • Keep water out
• Stabilize collapsing soils	• Prewetting/hydroblasting • Deep dynamic compaction	• Vibrocompaction • Grouting

Table 4 – Summary of Ground Improvement Methods for Remediation of Large, Open, Undeveloped Sites

Method	Soil Type	Effective Depth	Typical Layout & Spacing	Attainable Improvement	Advantages	Limitations	Prior Experience
Deep Dynamic Compaction (DDC)	Saturated sands and silty sands; partly saturated sands	Up to 10 m	Square pattern, 2 to 6 m spacing	D_r = 80 % $(N_1)_{60}$ = 25 q_{c1} = 10-15 MPa	Low cost, Simple	Limited effective depth, Clearance required, Vibrations	Extensive
Vibrocompaction, Vibrorod	Sands, silty sands, gravelly sands < 20% fines	30 m	Square or triangular pattern, 1.5 to 3 m spacing	D_r = 80+ % $(N_1)_{60}$ = 25 q_{c1} = 10-15 MPa	Proven effectiveness, Uniformity with depth	Special equipment, Unsuitable in cobbles and boulders	Very extensive
Stone Columns (Vibroreplacement)	Soft, silty or clayey sands, silts, clayey silts	30 m	Square or triangular pattern, 1.5 to 3 m center to center column spacing	$(N_1)_{60}$ = 20 q_{c1} = 10-12 MPa	Proven effectiveness, Drainage, Reinforcement, Uniformity with depth, Bottom feed dry process puts fill where needed	Special equipment, Can't use in soil with cobbles and boulders	Very extensive
Sand and Gravel Compaction Piles	Can be used in most soil types	20 m	Square or triangular pattern, 1 to 3 m center to center spacing	Up to $(N_1)_{60}$ = 25-30, q_{c1} = 10-15 MPa, depending on soil type	Proven effectiveness, Reinforcement, Drainage, Uniformity with depth	Special equipment, Slow, Expensive	Very extensive
Gravel Drains	Sands, silty sands	20 m (?)	Spacing selected to minimize excess pore pressure ratio	Reduce pore pressure buildup, Intercept pore pressure plumes	Inexpensive, Does not require treatment of full area	May require very close spacing, Settlement not prevented	Some applications for interception of pore pressure plumes

Table 4 (cont.) – Summary of Ground Improvement Methods for Remediation of Large, Open, Undeveloped Sites

Method	Soil Type	Effective Depth	Typical Layout & Spacing	Attainable Improvement	Advantages	Limitations	Prior Experience
Explosive Compaction	Saturated sands, silty sands	Unlimited	Square or triangular pattern, 3 to 8 m spacing in developed areas, 8 to 15 m spacing in remote areas, vertical spacing varies with size of charge	D_r = 75 % $(N_1)_{60}$ = 20-25 q_{c1} = 10-12 MPa	Inexpensive, Simple technology	Vibrations, Psychological barriers	Extensive use; no EQ yet at improved sites
Buttress Fills (below and above ground)	All soil types	N/A	N/A	Site specific, Increases stability, Increased s_v' reduces liquefaction potential, Barriers against lateral spreading	Lower cost, Protection of existing embankments and large unimproved sites	Space needed for above ground buttresses, Liquefaction settlement in retained areas	Seismic retrofit of embankment dams and retention of liquefiable sites
Deep Soil Mixing	Most soil types	20 m	Select treatment pattern depending on application	Depends on size, strength and configuration of DSM elements	Positive ground reinforcement, Grid pattern contains liquefiable soil, High strength	Requires special equipment, Brittle elements	Excellent performance in 1995 Kobe EQ

Table 4 (cont.) – Summary of Ground Improvement Methods for Remediation of Large, Open, Undeveloped Sites

Method	Soil Type	Effective Depth	Typical Layout & Spacing	Attainable Improvement	Advantages	Limitations	Prior Experience
Prefabricated Vertical (PV) Drains (Wick Drains)	Moderately to highly compressible soils; clayey sands, silts, clays and their mixtures	Up to 65 m; over 20 m depth requires crane to install	Square or triangular pattern, spacing 1.5 to 6 m	Depends on final consolidation pressure	Proven effectiveness, Low cost, Simple	Unsuitable if obstructions exist above compressible layer	Very extensive
Prewetting	Collapsing soils such as loess, debris flows	Essentially unlimited, but not effective at shallow depths	N/A	When used alone, can reduce settlement due to existing overburden, When used with other methods, can reduce settlement due to additional load	Low cost, Simple	Usually not effective at shallow depths, Works best in combination with dynamic compaction, preloading, or explosive compaction	Extensive
Replacement	All soils	A few m	N/A	High density fills to cemented materials	Can design to desired improvement level	Expensive, Might require temporary support of existing structures	Very limited
Admixture Stabilization	Cement – sands and silty sands Lime – clays and clayey sands	A few m	N/A	High density fills to cemented materials	Can design to desired improvement level	Results depend on degree of mixing & compaction achieved in field	Extensive

Table 4 (cont.) – Summary of Ground Improvement Methods for Remediation of Large, Open, Undeveloped Sites

Method	Soil Type	Effective Depth	Typical Layout & Spacing	Attainable Improvement	Advantages	Limitations	Prior Experience
Roller Compacted Concrete	Sands and gravels, up to 15% fines	N/A	N/A	Cemented material	Can design steep slopes (0.7H:1V), Can place using conventional earth moving equipment	Bonding between lifts important, therefore, have to place quickly, keep lift surfaces clean	More than 25 new dams > 50 feet high in U.S. since early 1980's
Biotechnical Stabilization and Soil Bioengineering	All soils	A few m	Depends on application	Stabilize slopes, Prevent erosion	Cost effective, attractive treatment for shallow mass movement and erosion, Environmentally compatible, Blends in with natural surroundings, Can allow native plants to overtake treated area by succession	Keeping vegetation alive until established, Difficult to establish vegetation on slopes steeper than 1.5H:1V, Difficult to quantify reinforcement contribution of root systems	Extensive

Table 5 – Summary of Ground Improvement Methods for Remediation of Constrained and/or Developed Sites

Method	Soil Type	Effective Depth	Typical Lay-out & Spacing	Attainable Improvement	Advantages	Limitations	Prior Experience
Penetration Grouting	Sands and coarser materials	Unlimited	Triangular pattern, 1 to 2.5 m spacing	Void filling and solidification	No excess pore pressure or liquefaction, Can localize treatment area	High cost, Fines prevent use in many soils	Extensive
Compaction Grouting	Any rapidly consolidating, compressible soil including loose sands	Unlimited	Square or triangular pattern, 1 to 4.5 m spacing, with 1.5 to 2 m typical	Up to D_r=80+% $(N_1)_{60}$ = 25 q_{c1} = 10-15 MPa (Soil type dependent)	Controllable treatment zone, Useful in soils with fines	High cost, Post-treatment loss of prestress	Limited
Jet Grouting	Any soil; more difficult in highly plastic clays	Unlimited	Depends on application	Solidification of the ground – depends on size, strength and configuration of jetted elements	Controllable treatment zone, Useful in soils with fines, Slant drilling beneath structures	High cost	Limited; to date, in U.S. most applications have been for underpinning
Explosive Compaction	Sands, silty sands	Unlimited	Square or triangular pattern, 3 to 8 m spacing in developed areas, 8 to 15 m spacing in remote areas, vertical spacing varies with size of charge	D_r = 75 % $(N_1)_{60}$ = 20-25 q_{c1} = 10-12 MPa	Inexpensive, Simple technology, Can localize treatment zone, Slant drilling possible	Vibrations, Psychological barriers, Settlement	Limited use in U.S.

Table 5 (cont.) - Summary of Ground Improvement Methods for Remediation of Constrained and/or Developed Sites

Method	Soil Type	Effective Depth	Typical Layout & Spacing	Attainable Improvement	Advantages	Limitations	Prior Experience
Mini-Piles	Any drillable soil	Several m beneath existing structures	Depends on application	Transfers loads through weak soil	Structural support	Expensive, Potential settlement around structure	Deep foundations have performed well
Soil Nailing	Any drillable soil, except very soft clays	Unlimited	1 grouted nail per 1 to 5 m^2, 1 driven nail per 0.25 m^2	Stabilize cut slopes and excavations	Flexible system, Can tolerate large movements, Highly resistant to dynamic loading, Can install with small, mobile equipment, Reinforcement is redundant, so weak nail will not cause catastrophic failure	Excavation or cut slope must remian stable until nails are installed, Difficult to construct reliable drainage systems, May require underground easement on adjacent property	Used mainly in Europe until recently
Replacement	All soils	A few m	N/A	High density fills to cemented materials	Can design to desired improvement level	Expensive, Might require temporary support of existing structures	Very limited
Roller Compacted Concrete	Sands and gravels, up to 15% fines	N/A	N/A	Cemented material	Can design steep slopes (0.7H:1V), Can place using conventional earthmoving equipment	Bonding between lifts important, therefore, have to place quickly, keep lift surfaces clean	As of 1993, 30 projects have been modified using RCC

Table 6 – Summary of Approximate Costs for Various Ground Improvement Methods

Method	Relative Cost	Cost per m ($)	Cost per m^2 ground surface/wall face ($)	Cost per m^3 treated ground ($)	Reference	Comments
Deep Dynamic Compaction	Low	--	8 to 32	~5	FHWA (1998)	
Vibrocompaction, Vibrorod	Low to moderate	No backfill (B/F) - 15 Granular B/F - 25	--	1 to 4	FHWA (1998)	Plus mobilization of $15,000/rig
Stone Columns (Vibro-replacement)	Moderate	Starts at 45 to 60 if suitable B/F readily available	--	--	FHWA (1998)	Plus mobilization of $15,000/rig
Gravel Drains	Moderate	11 to 22	--	--	Ledbetter (1985)	
Explosive Compaction	Low	--	--	2 to 4	Adalier (1996)	
Compaction Grouting	Low to moderate	--	--	5 to 50	FHWA (1998)	Plus mobilization, pipe installation costs
Particulate Grouting (Permeation)	Moderate	--	--	3 to 30	Adalier (1996)	

Table 6 (cont.) – Summary of Approximate Costs for Various Ground Improvement Methods

Method	Relative Cost	Cost per m ($)	Cost per m^2 ground surface/wall face ($)	Cost per m^3 treated ground ($)	Reference	Comments
Chemical Grouting (Permeation)	High	--	--	150 to 400	Hayward Baker (1996)	If > 700 m^3 will be treated with sodium silicate grout, assume \$195/m^3 plus mobilization (\$10-50K) plus installation of grout pipes (\$65/m) (FHWA, 1998)
Jet Grouting	High to very high	Seepage control: 30 to 200 Underpinning, excavation support: 95 to 650	--	--	FHWA (1998)	Columns approximately 1 m diameter; if headroom is limited, assume high end of range
Soil Nailing	Moderate to high	--	Permanent: 165 to 775 Temporary: 160 to 400	--	FHWA (1998)	Permanent cost depends on type of facing
Deep Soil Mixing	High to very high	--	--	100 to 150	FHWA (1998)	Plus mobilization of \$100,000
Roller Compacted Concrete	--	--	--	New construction: 25 to 75 Overtopping protection: 65 to 130	Portland Cement Association (1992, 1997)	

Table 6 (cont.) – Summary of Approximate Costs for Various Ground Improvement Methods

Method	Relative Cost	Cost per m ($)	Cost per m^2 ground surface/wall face ($)	Cost per m^3 treated ground ($)	Reference	Comments
Prefabricated Vertical (PV) Drains (Wick Drains)	Low	<u>Drains only</u> Small projects (3 - 10,000 LM): 2.25 to 4.00 Medium projects (10,000 - 50,000 LM): 1.60 to 2.50 Large projects (> 50,000 LM): 1.20 to 2.00	--	--	FHWA (1998)	Plus mobilization of $7,000 to $15,000 Also need to consider costs of drainage blanket, surcharge, obstructions or dense soils, design, installation, and monitoring
Biotechnical Stabilization	Depends on application	Vegetated geogrid: 40 to 100	Live slope grating: 275 to 550 (of front face)	--	ASCE (1997)	
Replacement	--	--	--	10 to 20	Hayward Baker (1996)	