PDHonline Course C195 (3 PDH)

Ground Improvement Methods - Grouting

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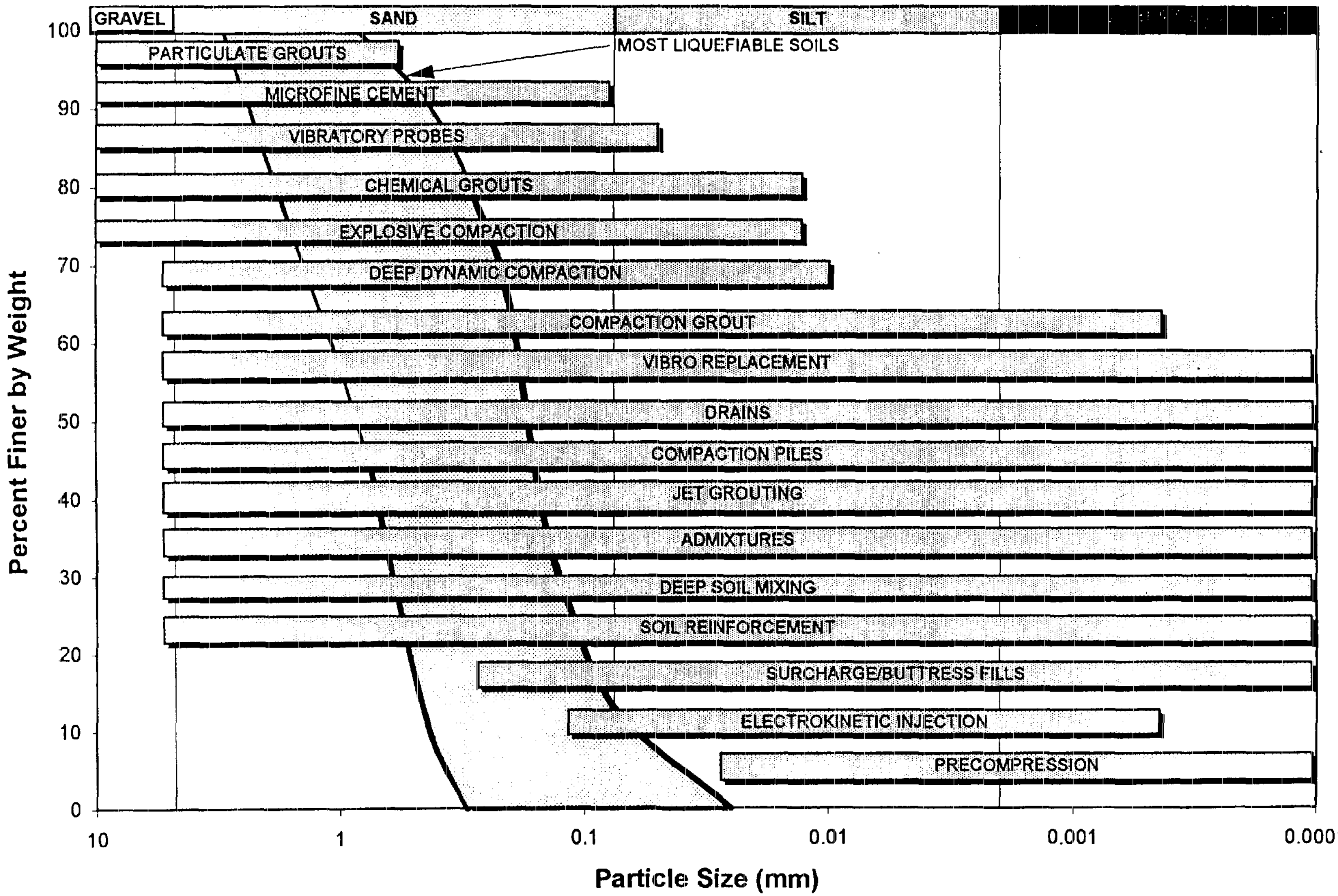
CHAPTER 3

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.

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).

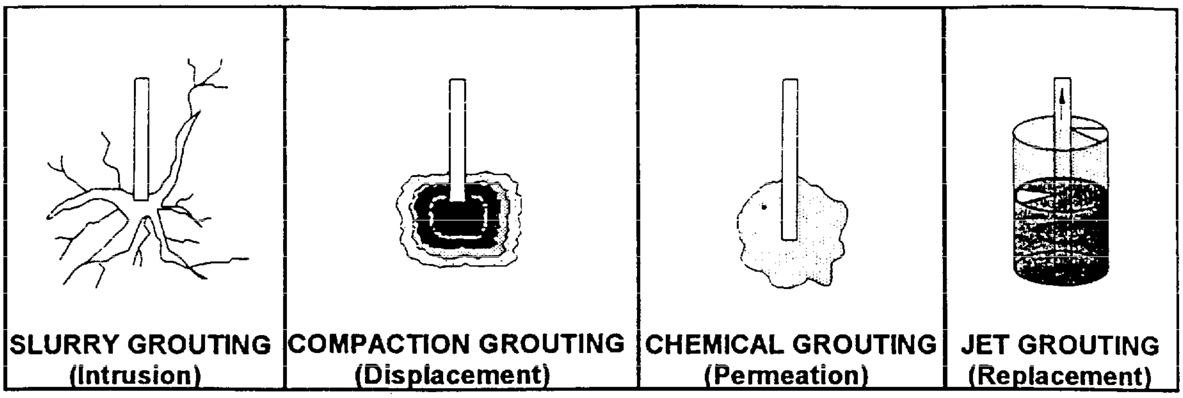


Figure 35. Types of grouting (Hayward Baker, 1996).

Compaction Grouting

Compaction grouting consists of injecting a very-low slump mortar into loose soils and cavities. The grout forms a bulb which expands against the surrounding soil, causing densification and displacement to occur (Figures 35 and 36). Unlike penetration grouting, the grout does not penetrate the soil pores in compaction grouting. The grout acts as a radial hydraulic jack to compress the surrounding soil. The grout is usually a mix of sandy soil with enough fines to bind the mix together, cement, and water. A typical compaction grout mix consists of about 3 parts sand to 1 part cement, although cement is not always used. The grout forms a bulb up to about 1 m in diameter, that is relatively strong and incompressible after it hardens. The process causes an overall decrease in the void ratio of the formation. Compaction grouting is most effective for loose granular soils, collapsible soils, and loose, unsaturated fine-grained soils.

A typical compaction grouting program consists of pipe spacings between 3 to 15 feet, with 5 to 7 feet spacing common. The pumping rate may vary from 0.5 to 10 cubic feet per minute, depending on the type of soil being treated. The replacement factor, which is the percentage of total ground volume that is filled with grout, ranges from about 3 to 12 percent. Additional information on compaction grouting can be found in Graf (1992a) and Warner et al. (1992). Details of compaction grouting for liquefaction mitigation can be found in Graf (1992b) and Boulanger and Hayden (1995).

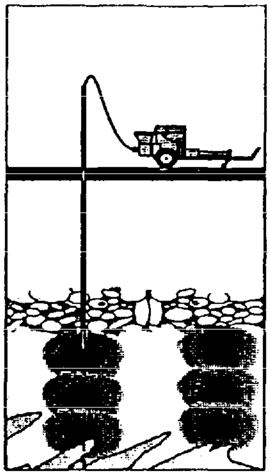


Figure 36. Compaction grout bulb construction (ASCE, 1997).

Jet Grouting

Jet grouting is a process in which a high-pressure water jet is used to erode the native soil and mix it or replace it with a stabilizer such cement or bentonite, as depicted in Figure 37. The grout-soil mixture forms high strength or low permeability columns, panels or sheets, depending on the orientation and rotation of the jets as they are withdrawn from the ground. Columns of up to about 1 m diameter are typical, although much larger columns are possible using special equipment. Jet grouting can be used in most soil types, although it works best in soils that are easily eroded, such as cohesionless soils. Cohesive soils, especially highly plastic clays, can be difficult to erode and can break up in chunks. The return velocity of the drilling fluid is usually not large enough to remove chunks of clay, so the quality of the grout-soil mixture could be compromised and hydrofracturing could occur in highly plastic clays (ASCE, 1997). A drawback of jet grouting is that it is very expensive and that special equipment is required. However, one advantage is that treatment can be restricted to the specific layer requiring improvement. Another advantage is that the injection rods can be inclined, so it is useful for grouting under structures or existing facilities. Burke and Welsh (1991) and Xanthakos et al. (1994) can be consulted for additional information regarding jet grouting.

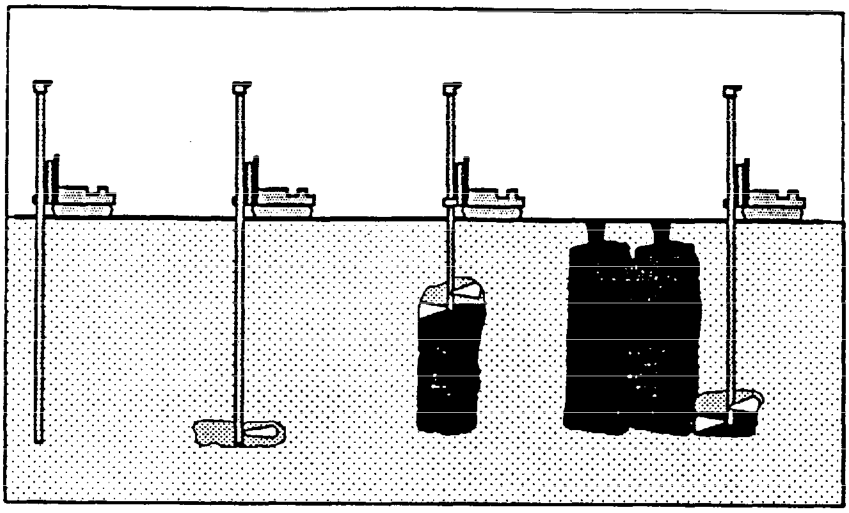


Figure 37. The jet grouting process (Hayward Baker, 1996).

Deep Soil Mixing

In the deep soil mixing technique, admixtures are injected into the soil at the treatment depth and mixed thoroughly using large-diameter single- or multiple-axis augers to form columns or panels of treated material. The mix-in-place columns can be up to 1 m or more in diameter. The treatment modifies the engineering properties of the soil by increasing strength, decreasing compressibility and decreasing permeability. Typical admixtures are cement and lime, but slag or other additives can also be used. The mix-in-place columns can be used alone, in groups to form piers, in lines to form walls, or in patterns to form cells. The process can be used to form soil-cement or soil-bentonite cutoff walls in coarse-grained soils, to construct excavation support walls, and to stabilize liquefiable ground. Deep mixing for mitigation of liquefaction risk at Jackson Lake Dam is illustrated in Figure 38. A detailed discussion of deep mixing is presented in ASCE (1997).

Mini-piles

Mini-piles, also known as micro-piles or root piles, are "small-diameter, bored, grouted-in-place piles incorporating steel reinforcement" (ASCE, 1997). Mini-piles can be used to with-

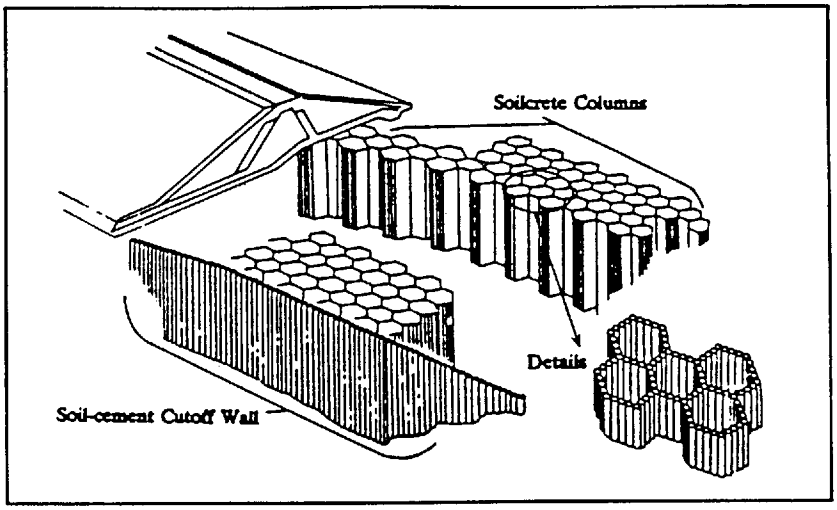


Figure 38. DSM for Jackson Lake Dam Modification Project (Taki and Yang, 1991).

stand axial loads and/or lateral loads, either for the support of structures or the stabilization of soil masses. Various applications for micro-piles are shown in Figure 39. Diameters are usually in the range of 100 to 250 mm, with lengths up to 20 to 30 m and capacities from about 100 to 300 kN (67 to 225 kips). Mini-piles can be installed both vertically and on a slant, so they can be used for underpinning of existing structures.

Conventional concrete cast-in-place piles generally rely on the concrete to resist the majority of the applied load. In contrast, mini-piles often contain high capacity steel elements that occupy up to 50 percent of the borehole volume. Therefore, the steel element is the primary

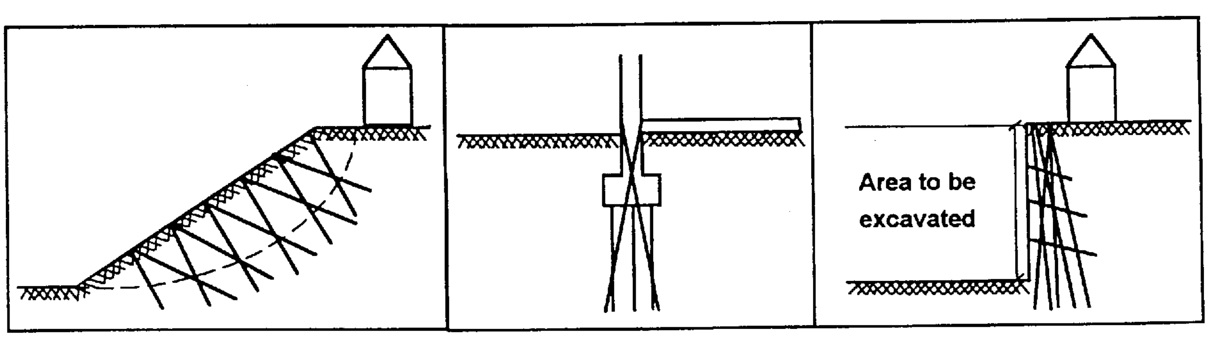


Figure 39. Mini-pile applications (modified from Lizzi, 1983).

load bearing component, and can develop high capacities, while the grout serves to transfer the load from the steel to the soil. Additional information on mini-piles can be obtained from Xanthakos et al. (1994). Case histories are discussed in Bruce (1991). Information on design can be found in Volume 2 of the FHWA State of Practice Report (1996a).

Soil Nailing

Soil nailing consists of a series of inclusions, usually steel rods, centered in a grout-filled hole about 6 inches in diameter in the ground to be supported. By spacing the inclusions closely, a composite structural entity can be formed. The "nails" are usually reinforcing bars 20-30 mm in diameter that are grouted into predrilled holes or driven using a percussion drilling device at an angle of 10 to 15 degrees down from the horizontal. Drainage from the soil is provided with strip drains and the face of the excavation is protected with a shotcrete layer.

The purpose of soil nailing is to improve the stability of slopes or to support slopes and excavations by intersecting potential failure planes. An example of soil nailing for excavation support is shown in Figure 41. There are two mechanisms involved in the stability of nailed soil structures (Mitchell and Christopher, 1990). Resisting tensile forces are generated in the nails in the active zone. These tensile forces must be transferred into the soil in the resisting zone

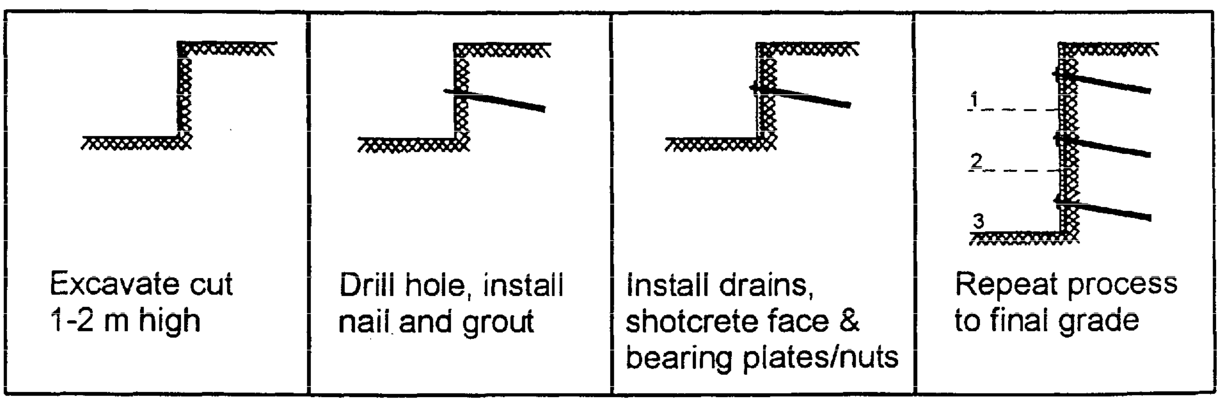


Figure 40. Soil nailing for excavation support (after Walkinshaw and Chassie, 1994).

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 (Vibro-replacement)	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 5 – 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
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 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)	