REMR TECHNICAL NOTE GT-SR-1.2

METHODS FOR IMPROVEMENT OF LIQUEFIABLE SOIL CONDITIONS

PURPOSE: To identify and summarize a source of information on methods that are considered potentially applicable for remedial treatment of liquefiable soils beneath and around existing structures.

REFERENCE: Improvement of liquefiable foundation conditions beneath existing structures. R. H. Ledbetter. US Army Engineer Waterways Experiment Station, Vicksburg, MS, Aug 1985. Technical Report REMR-GT-2. (NTIS No. AD A160 695.)

DESCRIPTION: The tables and figures in this Technical Note summarize methods that may be applicable for remedial treatment of liquefiable soils beneath and around existing structures. (These methods are discussed in detail in the above-referenced report.) The most important factors to consider in choosing an improvement method are the verifiability of improvement and stabilization, and whether or not the method will cause safety problems. Not only must the function or behavior of a method be verified at a field test location, but the final improvement product and results must be verified.

Table 1 summarizes possible courses of action for structures founded on liquefiable soil. These actions will either reduce the risk of failure or ensure that the consequences of a damaging earthquake will be tolerable. Table 2 summarizes methods for improving liquefiable soil. The methods are for direct in-situ improvement. However, combinations of these methods, including those in Table 1, can be used to indirectly improve liquefiable conditions and reduce damages by mitigating, confining, and preventing detrimental consequences.

In applying remedial methods to dams, the complex interrelationships must be considered within a dam concerning its core, shells, transition zones, filter zones, drains, and impermeable blankets as well as the interactions of the dam with its foundation, appurtenant structures, and reservoir margin. Extreme caution must be exercised to avoid creating a new defect in the process of applying remedial treatment methods to dams. Treatment methods and operations must be specified and monitored to prevent damage to dams. After remedial treatments, the stability and safety of a dam must be ensured under static and water loads. Table 3 presents precautions, for each remedial method of Table 2, that must be kept in mind when planning, designing, and executing treatment methods for a dam.

Figure 1 presents the applicable grain-size ranges for the liquefiable soil improvement methods. Also superimposed on Figure 1 is the grain-size range most sensitive to liquefaction. Effective ranges of soil-particle sizes for chemical groutability are shown in Figure 2 along with the most sensitive liquefaction region. References cited in the tables and figures are included under Additional References below.

ENVIRONMENTAL CONSIDERATIONS: Many of the methods outlined in this Technical Note involve the use of chemical grouts to stabilize the soil. Many of these grouts present both a short-term hazard to workers and an unknown long-term hazard to the environment. Reasonable caution should guide the preparation, application, and cleanup phases of any remedial activities involving potentially hazardous and toxic chemical substances. Manufacturer's recommendations to protect occupational health and environmental quality should be carefully followed. In instances where the effects of a chemical substance on occupational health or environmental quality are unknown, chemical substances should be treated as potentially hazardous and toxic materials.

ADDITIONAL REFERENCES:

a. Bhandari, R. K. M. 1981. Dynamic consolidation of liquefiable sands. International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Mo.

b. Broms, B. B., and Hansson, O. 1984. Deep compaction with the vibro-wing method. In: Ground Engineering, Vol 17, No. 5.

c. Hayward Baker Co. 1982. Ground modifacts. No. 3, Odenton, Md.

d. Menard, L., and Broise, Y. 1975. Theoretical and practical aspects of dynamic consolidation. In: Geotechnique, Vol 15, No. 1.

e. Mitchell, J. K. 1981. State-of-the-art report on soil improvement. In: Proceedings, International Conference on Soil Mechanics and Foundation Engineering, Stockholm.

f. Morrison, A. 1982. The booming business in wick drains. In: Civil Engineering, American Society of Civil Engineers, Vol 53, No. 3.

g. Nataraja, M. S., and Cook, B. E. 1983. Increase in SPT N-values due to displacement piles. In: Journal of the Geotechnical Engineering Division, American Society of Civil Engineers, Vol 109, No. 1.

h. Solymar, Z. V. 1984. Compaction of alluvial sands by deep blasting. In: Canadian Geotechnical Journal, Vol 21.

i. Solymar, Z. V., et al. 1984. Earth foundation treatment at Jebba Dam Site. In: Journal of the Geotechnical Engineering Division, American Society of Civil Engineers, Vol 110, No. 10.

POINT OF CONTACT: Richard H. Ledbetter

Phone Nos.: 601-634-3380
FTS 542-3380
AUTOVON 782-5011; then ask for 634-3380.

Address: Commander and Director
US Army Engineer Waterways Experiment Station
ATTN: CEWES-GH-R, Richard H. Ledbetter
PO Box 631
Vicksburg, MS 39180-0631

Table 1

Possible Courses of Action for Structures on Liquefiable Foundations

Method	Comments
No action	Public reaction would be strong in the case of a major structure such as a dam because the public is not prepared to accept risk-based designs and judgments. The data base is weak on earthquake potentials for risk analysis
Regulate access to the structure and areas that would be affected by a failure	For a dam, the public reaction would be strong and it is not practical in an urban area
For a dam, restrict reservoir level (a) Lower pool for a safe freeboard (b) Permanently empty the reservoir	Safety is improved and the risk of complete failure is reduced. Public reaction would probably be strong because of regional, social, and economic impact. The advantages and uses of the dam for navigation, recreation, and power generation may be lost
Construct buttresses (a) Earthen materials (b) Retaining walls above and below ground (1) Concrete (2) Sheet pile (3) Mixed in place with admixtures (4) Double wall system	Buttresses can be designed and placed against structures to prevent movement and slope failure. The liquefaction potential of the foundation material can be reduced beneath the buttress prior to construction. The weight of an earthen buttress additionally increases the liquefaction resistance by increasing effective confining pressures in the foundation. Buttresses can be constructed upstream and downstream against a dam
For a dam, increase the height	Additional freeboard of a dam can be obtained; however, effective freeboard remaining after deformation and/or a flow slide would be difficult to reliably predict at present

Table 1 (Concluded)

Method	Comments
For a dam, construct a detention dam downstream	Cost would be less than a new structure and in the event of a dam failure it would only need to serve as a levee to retain water for a few days or weeks until a safe pool lowering could be carried out. A potential stability problem for a detention dam exists if a tsunami-like wall of water impacts on the dam. No experience exists in designing for such an impact and the structure should have a very high freeboard. Public reaction may be strong
For a dam, construct a replacement structure at either the same or a new location	A new structure can be designed and constructed to resist almost any earthquake shaking except in epicentral regions of large earthquakes of magnitude 8.0 and larger. This approach would (a) be very expensive, (b) cause economic impact if no reservoir usage, and (c) require a new environmental impact statement. Public reaction would probably be strong
Improvement of liquefiable soil foundation conditions directly or indirectly to assure the safe performance of structures founded on them in the event of earthquake excitation	These methods are summarized in Table 2. The methods are for direct in-situ improvement of liquefiable soils. However, combinations of these methods, including the methods in this table, can be used to indirectly improve the liquefiable conditions by mitigating, confining, and preventing detrimental consequences, thereby assuring safe performance of structures. Site conditions have been classified into three cases; Case 1 is for beneath structures and the indirect improvement methods are most applicable, Case 2 is for the not-under-water free field adjacent to a structure and the indirect improvement methods are most applicable, and Case 3 is for the under-water free field adjacent to a structure and the direct improvement methods are most applicable

Table 2

Improvement of Liquefiable Soil Foundation Conditions

Method	Principle	Most Suitable Soil Conditions/ Types	Maximum Effective Treatment Depth	Economical Size of Treated Area	Ideal Properties of Treated Material*	Applications**	Case†	Relative Costs††
			In-Situ Deep Compaction					
(1) Blasting	Shock waves and vibrations cause limited liquefaction, displacement, remolding and settlement to higher density	Saturated, clean sands; partly saturated sands and silts after flooding	>40 m Solymar (1984)	Any size	Can obtain relative densities to 70-80%; may get variable density; time-dependent strength gain	Induce liquefaction in controlled and limited stages and increase relative density to potentially nonliquefiable range	2 3	Low ($2.00-$4.00/m^3)
(2) Vibratory probe (a) Terraprobe (b) Vibro-rods (c) Vibro-wing	Densification by vibration; liquefaction-induced settlement and settlement in dry soil under overburden to produce a higher density	Saturated or dry clean sand; sand	20 m routinely (ineffective above 3-4 m depth) >30 m sometimes Mitchell (1981) Vibro-wing-40 m Broms and Hansson (1984)	>1000 m^2	Can obtain relative densities of 80% or more. Ineffective in some sands	Induce liquefaction in controlled and limited stages and increase relative density to potentially nonliquefiable range. Has been shown effective in preventing liquefaction	2 3	Moderate ($6.00-$13.00/m^3)
(3) Vibro-compaction (a) Vibroflot (b) Vibro-Composer system (c) Soil Vibratory stabilizing method	Densification by vibration and compaction of backfill material of sand or gravel	Cohesionless soils with less than 20% fines	>30 m Solymar et al. (1984)	>1000 m^2	Can obtain high relative densities (over 85%), good uniformity	Induce liquefaction in controlled and limited stages and increase relative densities to nonliquefiable condition. Is used extensively to prevent liquefaction. The dense column of backfill provides (a) vertical support, (b) drains to relieve pore water pressure and (c) shear resistance in horizontal and inclined directions. Used to stabilize slopes and strengthen potential failure surfaces or slip circles	1 2 Δ‡	Low to moderate ($6,00-$9.00/m^3)
(4) Compaction piles	Densification by displacement of pile volume and by vibration during driving, increase in lateral effective earth pressure	Loose sandy soils; partly saturated clayey soils; loess	>20 m Nataraja and Cook (1983)	>1000 m^2	Can obtain high densities, good uniformity. Relative densities of more than 80%	Useful in soils with fines. Increases relative densities to nonliquefiable range. Is used to prevent liquefaction. Provides shear resistance in horizontal and inclined directions. Useful to stabilize slopes and strengthen potential failure surfaces or slip circles	1 2 3	Moderate to high
(5) Heavy tamping (dynamic compaction)	Repeated application of high-intensity impacts at surface	Cohesionless soils best, other types can also be improved	30 m (possibly deeper) Ménard and Broise (1975)	>3300 m^2	Can obtain high relative densities, reasonable uniformity. Relative densities of 80% or more	Suitable for some soils with fines; usable above and below water. In cohesionless soils, induces liquefaction in controlled and limited stages and increases relative density to potentially nonliquefiable range. Is used to prevent liquefaction	2 3	Low ($0.40-$6.00/m^3)

(Continued)

* SP, SW, or SM soils which have average relative density equal to or greater than 85 percent and the minimum relative density not less than 80 percent are in general not susceptible to liquefaction (TM 5-818-1). D'Appolonia (1970) stated that for soil within the zone of influence and confinement of the structure foundation, the relative density should not be less than 70 percent. Therefore, a criterion may be used that relative density increase into the 70-90 percent range is in general considered to prevent liquefaction. These properties of treated materials and applications occur only under ideal conditions of soil, moisture, and method application. The methods and properties achieved are not applicable and will not occur in all soils.

** Applications and results of the improvement methods are dependent on: (a) soil profiles, types, and conditions, (b) site conditions, (c) earthquake loading, (d) structure type and condition, and (e) material and equipment availability. Combinations of the methods will most likely provide the best and most stable solution.

† Site conditions have been classified into three cases; Case 1 is for beneath structures, Case 2 is for the not-under-water free field adjacent to a structure, and Case 3 is for the under-water free field adjacent to a structure.

†† The costs will vary depending on: (a) site working conditions, location, and environment, (b) the location, area, depth, and volume of soil involved, (c) soil type and properties, (d) materials (sand, gravel, admixtures, etc.) equipment, and skills available, and (e) environmental impact factors. The costs are average values based on: (a) verbal communication from companies providing the service, (b) current literature, and (c) literature reported costs updated for inflation.

‡ Δ means the method has potential use for Case 3 with special techniques required which would increase the cost.

(Sheet 1 of 4)

Table 2 (Continued)

Method	Principle	Most Suitable Soil Conditions/ Types	Maximum Effective Treatment Depth	Economical Size of Treated Area	Ideal Properties of Treated Material	Applications	Case	Relative Costs
(6) Displacement/compaction grout	Highly viscous grout acts as radial hydraulic jack when pumped in under high pressure	All soils	Unlimited	Small	Grout bulbs within compressed soil matrix. Soil mass as a whole is strengthened	Increase in soil relative density and horizontal effective stress. Reduce liquefaction potential Stabilize the ground against movement	1 2 3	Low to Moderate ($3.00-$15.00/m^3)
			Compression					
(7) Surcharge/buttress	The weight of a surcharge/buttress increases the liquefaction resistance by increasing the effective confining pressures in the foundation	Can be placed on any soil surface	---	>1000 m^2	Increase strength and reduce compressibility	Increase the effective confining pressure in a liquefiable layer. Can be used in conjunction with vertical and horizontal drains to relieve pore water pressure. Reduce liquefaction potential. Useful to prevent movements of a structure and for slope stability	2 3	Moderate if vertical drains used
			Pore-Water Pressure Relief					
(8) Drains (a) Gravel (b) Sand (c) Wick (d) Wells (for permanent dewatering)	Relief of excess pore-water pressure to prevent liquefaction. (Wick drains have comparable permeability to sand drains.) Primarily gravel drains; sand/wick may supplement gravel drain or relieve existing excess pore water pressure. Permanent dewatering with pumps	Sand, silt, clay	Gravel and sand >30 m Depth limited by vibratory equipment Wick >45 m Morrison (1982)	>1500 m^2 Any size for wick	Pore-water pressure relief will prevent liquefaction	Prevent liquefaction by gravel drains. Sand and gravel drains are installed vertically; however, wick drains can be installed at any angle. Dewatering will prevent liquefaction but not seismically induced settlements	Gravel and sand 2 Δ‡ Wick 1 2 3	Sand and gravel 0.1 m diam ($11.50-$21.50/m Wick $2.00-$4.00/m) Dewatering very expensive
			Injection and Grouting					
(9) Particulate grouting	Penetration grouting - fill soil pores with soil, cement, and/or clay	Medium to coarse sand and gravel	Unlimited	Small	Impervious, high strength with cement grout. Voids filled so they cannot collapse under cyclic loading	Eliminate liquefaction danger. Slope stabilization. Could potentially be used to confine an area of liquefiable soil so that liquefied soil could not flow out of the area	1 2 3	Lowest of grout methods ($3.00-$30.00/m^3)
(10) Chemical grouting	Solutions of two or more chemicals react in soil pores to form a gel or a solid precipitate	Medium silts and coarser	Unlimited	Small	Impervious, low to high strength. Voids filled so they cannot collapse under cyclic loading	Eliminate liquefaction danger. Slope stabilization. Could potentially be used to confine an area of liquefiable soil so that liquefied soil could not flow out of the area. Good water shutoff	1 2 3	High $75.00-$250.00/m^3
(11) Pressure-injected lime	Penetration grouting - fill soil pores with lime	Medium to coarse sand and gravel	Unlimited	Small	Impervious to some degree. No significant strength increase. Collapse of voids under cyclic loading reduced	Reduce liquefaction potential	1 2 3	Low $10.00/$m^3$

(Continued)

‡ Δ means the method has potential use for Case 3 with special techniques required which would increase the cost.

(Sheet 2 of 4)

Table 2 (Continued)

Method	Principle	Most Suitable Soil Conditions/ Types	Maximum Effective Treatment Depth	Economical Size of Treated Area	Ideal Properties of Treated Material	Applications	Case	Relative Costs
(12) Electrokinetic injection	Stabilizing chemicals move into and fill soil pores by electro-osmosis or colloids into pores by electro-phoresis	Saturated sands, silts, silty clays	Unknown	Small	Increased strength, reduced compressability, voids filled so they cannot collapse under cyclic loading	Reduce liquefaction potential	1 2 3	Expensive
(13) Jet grouting	High-speed jets at depth excavate, inject, and mix a stabilizer with soil to form columns or panels	Sands, silts, clays	Unknown	Small	Solidified columns and walls	Slope stabilization by providing shear resistance in horizontal and inclined directions which strengthens potential failure surfaces or slip circles. A wall could be used to confine an area of liquefiable soil so that liquefied soil could not flow out of the area	1 2 3	High $250.00- $650.00/m^3
			Admixture Stabilization					
(14) Mix-in-place piles and walls	Lime, cement, or asphalt introduced through rotating auger or special in-place mixer	Sand, silts, clays, all soft or loose inorganic soils	>20 m (60 m obtained in Japan) Mitchell (1981)	Small	Solidified soil piles or walls of relatively high strength	Slope stabilization by providing shear resistance in horizontal and inclined directions which strengthens potential failure surfaces or slip circles. A wall could be used to confine an area of liquefiable soil so that liquefied soil could not flow out of the area	1 2 3	High $250.00- $650.00/m^3
			Thermal Stabilization					
(15) In-situ vitrification	Melts soil in place to create an obsidianlike vitreous material	All soils and rock	>30 m Verbal from Battelle Laboratories	Unknown	Solidified soil piles or walls of high strength. Impervious; more durable than granite or marble; compressive strength, 9-11 ksi; splitting tensile strength, 1-2 ksi	Slope stabilization by providing shear resistance in horizontal and inclined directions which strengthens potential failure surfaces or slip circles. A wall could be used to confine an area of liquefiable soil so that liquefied soil could not flow out of the area	1 2 3	Moderate $53.00- $70.00/m^3
			Soil Reinforcement					
(16) Vibro-replacement stone and sand columns (a) Grouted (b) Not grouted	Hole jetted into fine-grained soil and backfilled with densely compacted gravel or sand hole formed in cohesionless soils by vibro techniques and compaction of backfilled gravel or sand. For grouted columns, voids filled with a grout	Sands, silts, clays	>30 m Limited by vibratory equipment	>1500 m^2 Fine-grained soils >1000 m^2	Increased vertical and horizontal load carrying capacity. Density increase in cohesionless soils. Shorter drainage paths	Provides; (a) vertical support, (b) drains to relieve pore water pressure, and (c) shear resistance in horizontal and inclined directions. Used to stabilize slopes and strengthen potential failure surfaces or slip circles	1 2 Δ‡	Moderate $11.00- $70.00/m^3

(Continued)

‡ Δ means the method has potential use for Case 3 with special techniques required which would increase the cost.

(Sheet 3 of 4)

Table 2 (Concluded)

Method	Principle	Most Suitable Soil Conditions/ Types	Maximum Effective Treatment Depth	Economical Size of Treated Area	Ideal Properties of Treated Material	Applications	Case	Relative Costs
						For grouted columns, no drainage provided but increased shear resistance. In cohesionless soil, density increase reduces liquefaction potential		
(17) Root piles, soil nailing	Small-diameter inclusions used to carry tension, shear, compression	All soils	Unknown	Unknown	Reinforced zone of soil behaves as a coherent mass	Slope stability by providing shear resistance in horizontal and inclined directions to strengthen potential failure surfaces or slip circles. Both vertical and angled placement of the piles and nails	1 2 3	Moderate to high

(Sheet 4 of 4)

Table 3

Potential Impacts of Remedial Methods on Dam Safety

Under Static and Water Loads Only

Method	Precautions
In-Situ Deep Compaction	
1. Blasting applicable to Cases 2 and 3*	When used near and beneath toe areas, potential hazards include induced sliding, slope failures, and damage to drains from motions and differential settlements
2. Vibratory probe applicable to Cases 2 and 3	When used near and beneath toe areas, potential hazards include: disturbance of and creation of new drainage paths; slides, slope failures, and damage to drains from differential settlements
3. Vibro-compaction applicable to Cases 1, 2, and 3	See method 2. For Case 1, damage can be caused to impermeable blankets, transition zones, filter zones, and drains. Holes can have rapid drawdown conditions and cause instability. These hazards can lead to piping and hydraulic fracturing
4. Compaction piles applicable to Cases 1, 2, and 3	See methods 2 and 3
5. Heavy tamping (dynamic compaction) applicable to Cases 2 and 3	See method 1
6. Displacement/compaction grout applicable to Cases 1, 2, and 3	For Case 1, holes can have the problems of methods 2 and 3; heavy differential movements, and fractures can cause damage to impermeable blankets, transition zones, filter zones, and drains. Drilling fluids can cause hydraulic fracturing. These hazards can lead to to piping and hydraulic fracturing
Compression	
7. Surcharge/buttress applicable to Cases 2 and 3	Differential settlements can damage impermeable blankets, transition zones, filter zones, and drains with results of piping and hydraulic fracturing

(Continued)

* Site conditions have been classified into three cases; Case 1 is for beneath structures, Case 2 is for the not-under-water free field adjacent to a structure, and Case 3 is for the under-water free field adjacent to a structure.

Table 3 (Concluded)

Method	Precaution
Pore Water Pressure Relief	
8. Drains applicable to Cases 1, 2, and 3	See methods 2 and 3
9. Particulate grouting applicable to Cases 1, 2, and 3	See method 6
10. Chemical grouting applicable to Cases 1, 2, and 3	See method 6
11. Pressure-injected lime applicable to Cases 1, 2, and 3	See method 6
12. Electrokinetic injection applicable to Cases 1, 2, and 3	Holes can have the problems of methods 2 and 3
13. Jet grouting applicable to Cases 1, 2, and 3	Holes and potential settlements can have the problems of methods 2 and 3
Admixture Stabilization	
14. Mix-in-place piles and move walls applicable to Cases 1, 2, and 3	Holes, trenches, and differential ments can have the problems of methods 2 and 3. Continuous mix-in-place walls near the toes can potentially cause slope instability
Thermal Stabilization	
15. In-Situ Vitrification applicable to cases 1, 2, and 3	Settlements due to decreased volume of voids could cause damage to impermeable blankets, transition zones, filter zones, zones, and drains which could lead to piping and hydraulic fracturing
Soil Reinforcement	
16. Vibro-replacement stone and sand columns applicable to Cases 1, 2, 3	See methods 2 and 3
17. Root piles, soil nailings applicable to Cases 1, 2, and 3	See methods 2 and 3

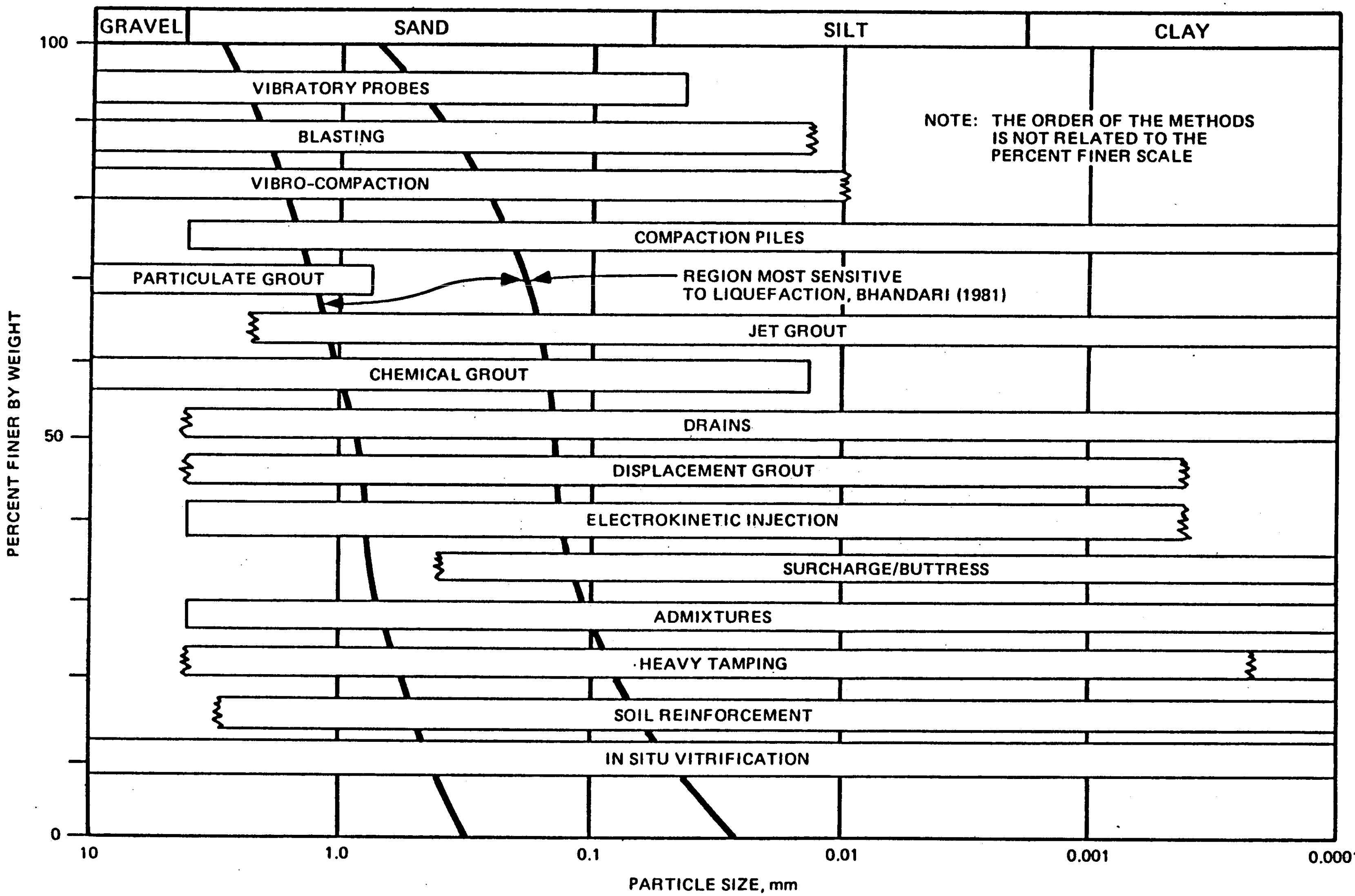

Figure 1. Applicable grain-size ranges for liquefiable soil improvement methods.

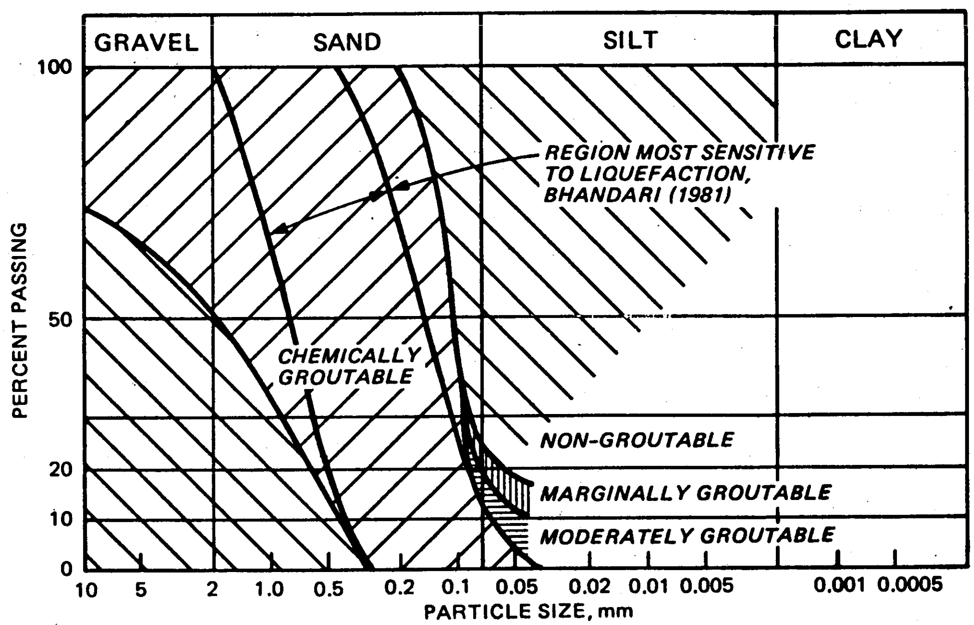

Figure 2. Effective ranges of soil particle sizes for chemical groutability (groutability data from Hayward Baker Co., 1982).