Introduction to Preparation of Foundations for Structures

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An Introduction to Preparation of Foundations for Structures

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The Figures, Tables and Symbols in this document are in some cases a little difficult to read, but they are the best available. **DO NOT PURCHASE THIS COURSE IF THE FIGURES, TABLES AND SYMBOLS ARE NOT ACCEPTABLE TO YOU.**

1. FOUNDATION EXCAVATION

1.1 GENERAL. In general, excavation for subsurface structures will consist of open excavation as well as shaft and tunnel excavation. Where excavation to great depths is required, a variety of soils and rock may be encountered at a single site. Soils may range through a wide spectrum of textures and water contents. Rock encountered may vary from soft rock, very similar to a firm soil in its excavation requirements, to extremely hard rock requiring extensive blasting operations for removal. Groundwater may or may not be present. The groundwater conditions and the adequacy of groundwater control measures are important factors in excavation, in maintaining a stable foundation, and in backfilling operations. The extent to which groundwater can be controlled also influences the slopes to which the open excavation can be cut, the bracing required to support shaft and tunnel excavation, and the handling of the excavated material.

1.2 GOOD CONSTRUCTION PRACTICES, AND PROBLEMS. A majority of the problems encountered during excavation are related to groundwater conditions, slope stability, and adverse weather conditions. Many of the problems can be anticipated and avoided by preconstruction planning and by following sound construction practices.

1.2.1 GROUNDWATER. Probably the greatest source of problems in excavation operations is groundwater. If the seepage of groundwater into an excavation is adequately controlled, other problems will generally be minor and can be easily handled. Several points should be recognized that, if kept in mind, will help to reduce problems attributable to groundwater. In some instances, groundwater conditions can be more severe than indicated by the original field exploration investigation since field explorations provide information only for selected locations and may not provide a true picture of the overall conditions. If groundwater seepage begins to exceed the capacity of the dewatering system, conditions should not be expected to improve unless the increased flow is known to be caused by a short-term condition such as heavy rain in the area. If seepage into the excavation becomes excessive, excavation operations should be halted until the necessary corrective measures are determined and affected. The design and evaluation of dewatering systems require considerable experience that the contractor or the owner's representative often does not possess, and the assistance of specialists in this field should be obtained. Groundwater without significant seepage flow can also be a problem since excess hydrostatic pressures can develop below relatively impervious strata and cause uplift and subsequent foundation or slope instability. Excess hydrostatic pressures can also occur behind sheet pile retaining walls and shoring and bracing in shaft and tunnel excavations. Visual observations should be made for indications of trouble, such as uncontrolled seepage flow, piping of material from the foundation or slope, development of soft wet areas, uplift of ground surface, or lateral movements. Accurate daily records should be kept of the quantity of water removed by the dewatering system and of the piezometric levels in the foundation and beneath excavation slopes. Separate records should be kept of the flow pumped by any sump-pump system required to augment the regular dewatering system to note any increase of flow into the excavation. Flowmeters or other measuring devices should be installed on the discharge of these systems for measurement purposes. These records can be invaluable in evaluating "Changed Condition" claims submitted by the contractor. The contractor should be required to have "standby" equipment in case the original equipment breaks down.

1.2.2 SURFACE WATER. Sources of water problems other than groundwater are surface runoff into the excavation and snow drifting into the excavation. A peripheral, surface-drainage system, such as a ditch and berm, should be required to collect surface water and divert it from the excavation. In good weather there is a tendency for the contractor to become lax in maintaining this system and for the inspection personnel to become lax in enforcing maintenance. The result can be a sudden filling of the excavation with water during a heavy rain and consequent delay in construction. The surface drainage system must be constantly maintained until the backfill is complete. Drifting snow is a seasonal and regional problem, which can best be controlled by snow fences placed at strategic locations around the excavation.

1.2.3 SLOPE INTEGRITY. Another area of concern during excavation is the integrity of the excavation slopes. The slopes may be either unsupported or supported by shoring and bracing. The lines and grades indicated in the plans should be strictly adhered to. The contractor may attempt to gain additional working room in the bottom of the excavation by steepening the slopes. This change in the plans must not be allowed.

- Where shoring and bracing are necessary to provide a stable excavation, and the plans and specifications do not provide details of these requirements, the contractor should be required to submit the plans in sufficient detail so that they can be easily followed and their adequacy checked. The first principle of excavation stabilization, using shoring and bracing, is that the placing of supports should proceed with excavation. The excavation cut should not be allowed to yield prior to placing of shoring and bracing since the lateral pressures to be supported would generally be considerably greater after yield of the unshored cut face than if no movement had occurred prior to placement of the shoring. Excavation support systems are discussed in Paragraph 8-1. All safety requirements for shoring and bracing as contained therein should be strictly enforced.
- The inspector must be familiar with stockpiling requirements regarding the distance from the crest of the excavation at which stockpiles can be established and heavy equipment operated without endangering the stability of the excavation slopes. He must also know the maximum height of stockpile or weight of equipment that can be allowed at this distance.
- Excessive erosion of the excavation slopes must not be permitted. In areas subject to heavy rainfall, it may be necessary to protect excavation slopes with polyethylene sheeting, straw, silt fences, or by other means to prevent erosion. Excavation slopes for large projects that will be exposed for several seasons should be vegetated and maintained to prevent erosion.

1.2.4 STOCKPILING EXCAVATED MATERIAL. Generally, procedures for stockpiling are left to the discretion of the contractor. Prior to construction, the contractor must submit his plans for stockpiling to the inspector for approval. In certain cases, such as where there are different contractors for the excavation and the backfill phases, it may be necessary to include the details for stockpiling operations in the specifications. In either case, it is important that the stockpiling procedures be conducive to the most advantageous use of the excavated materials. As the materials are excavated, they should be separated into classes of backfill and stockpiled accordingly. Thus the inspection personnel controlling the excavation should be qualified to classify the material and should be thoroughly familiar with backfill requirements. Also, as the materials are placed in stockpiles, water should be added or the materials should be aerated as required to approximate optimum water content for compaction. Field laboratory personnel can assist in determining the extent to which this is necessary. The requirements of shaping the stockpile to drain and seal it against the entrance of undesirable water by rolling with spreading equipment or covering with polyethylene sheeting should be enforced. This step is particularly important for cohesive soils that exhibit poor draining characteristics and tend to remain wet if once saturated by rains. Stockpiles must be located over an area that is large enough to permit processing and where they will not interfere with peripheral drainage around the excavation and will not overload the slopes of the excavation. In cases where significant energy and cost saving can be realized, special stockpiling requirements should be implemented. An example would be a large project consisting of a number of excavation and backfilling operations. The excavation material from the first excavation could be stockpiled for use as backfill in the last excavation. The material from the intermediate excavations could in turn be immediately used as backfill for the subsequent phases of the project and; thereby, eliminate double handling of excavated backfill for all but the first-phase excavation.

1.2.5 PROTECTION OF EXPOSED MATERIAL. If materials that are exposed in areas, such as walls of a silo shaft, foundation support, or any other area against which concrete will be placed, are susceptible to deterioration or swell when exposed to the weather, they should be properly protected after exposure as soon as possible. Depending on the material and protection requirements, this protection may be pneumatic concrete, asphalt spray, or plastic membrane In the case of a foundation area, the contractor is required to under-excavate leaving a cover for protection, as required, prior to placement of the structure foundation. Any frost-susceptible materials encountered during excavation should be protected if the excavation is to be left open during an extended period of freezing weather.

1.2.6 EXCAVATION RECORD. As the excavation progresses, the project engineer should keep a daily record of the type of material excavated and the progress made.

2. FOUNDATION PREPARATION

2.1 GOOD CONSTRUCTION PRACTICES AND PROBLEMS. As mentioned previously, the problems associated with foundation preparation are greatly reduced by following such proper excavation procedures as maintaining a dry excavation and planning ahead. The principles of good foundation preparation are simple, but enforcing the provisions of the specifications concerning the work is more difficult. Inspection personnel must recognize the importance of this phase of the work since, if not properly controlled, problems can result.

2.1.1 STABLE FOUNDATIONS. It is most important that a stable foundation be provided. Thus it may be necessary, particularly in the case of sensitive fine-grained materials, to require that the final excavation for footings be carefully done with hand tools and that no equipment is allowed to operate on the final cut surface. To provide a working platform on which to begin backfill placement on these sensitive materials, it may be necessary to place an initial layer of granular material.

2.1.2 FOUNDATIONS SUPPORTED ON ROCK. If the foundation is to be supported on rock, the soundness of the exposed rock should be checked by a slaking test (soaking a piece of the rock in water to determine the resulting degree of deterioration, and visual observation to determine if the rock is in a solid and unshattered condition). If removal of rock below the foundation level is required, the space should be filled with concrete. A qualified geological or soils engineer should inspect the area if it is suspected that the material will deteriorate or swell when exposed to the weather. If necessary, the materials must be protected from exposure.

- Before placement of any structure foundation is begun, the plans should be rechecked to ensure that all required utilities and conduits under or adjacent to the foundation have been placed, so that excavating under or undermining the foundation to place utilities and conduits will not become necessary later.
- Occasionally, it may be found upon completion of the excavation that if a structure was placed as shown on the plans, it would be supported on two materials with drastically different consolidation characteristics, such as rock and soil, rock and backfill, or undisturbed soil and backfill. This situation could occur because the pre-design subsurface information was inadequate, because the structure was relocated or reoriented by a subsequent change in the plans, because of an oversight of the design engineer, or because of the excavation procedures followed by the contractor. Regardless of the reason, measures such as over-excavation and placement of subsequent backfill should be taken, where possible, and in coordination with the design office to provide a foundation of uniform material. Otherwise, the design office should evaluate the differences in foundation conditions for possible changes to the structural foundation elements.
- Preparing the area to receive the backfill consists of cleaning, leveling, and compacting the bottom of the excavation if the foundation is in soil. All debris and foreign material, such as trash, broken concrete and rock, boulders, and forming lumber, should be removed from the excavation. All holes, depressions and trenches should be filled with the same material as that specified to be placed immediately above such a depression, unless

otherwise designated, and compacted to the density specified for the particular material used. If the depression is large enough to accommodate heavy compacting equipment, the sides of the depression should have a positive slope and be flat enough for proper operation of compaction equipment. After the area is brought to a generally level condition by compacting in lifts in accordance with specifications, the entire area to receive backfill should be sacrificed to the depth specified, the water content adjusted if necessary, and the area compacted as specified. If the foundation is in rock, the area should be leveled as much as possible and all loose material removed.

- All work in the excavation should be accomplished in the dry; therefore, the dewatering system should be operated for the duration of this work. Under no circumstances should the contractor be allowed to dry an area by dumping a thick layer of dry material over it to blot the excess water. If soil exists at the foundation level and becomes saturated, it cannot be compacted. The saturated soil will have to be removed and replaced or drained sufficiently so that it can be compacted. Any frozen material in the foundation should be removed before placement of concrete footings or compacted backfill.

2.2 PLACEMENT OF BACKFILL. Backfill construction is the refilling of previously excavated space with properly compacted material. The areas may be quite large, in which case the backfilling operation will be similar to embankment construction. On the other hand, the areas may be quite limited, such as confined areas around or between and beneath concrete or steel structures and areas in trenches excavated for utility lines. Prior to construction of the backfill, the inspection personnel should become thoroughly familiar with the various classes of backfill to be used. They should be able to readily identify the materials on sight, know where the various types of material should be placed, and be familiar with the compaction characteristics of the soil types. Problems with placement of backfill will vary from one construction project to another. The magnitude of the problems will depend on the type of materials available such as backfill, density requirements, and the configuration of the areas in which compaction is to be accomplished. Problems should be expected during the initial stages of backfill compaction unless the contractor is familiar with compaction characteristics of backfill materials. The inspector can be of great assistance to the contractor during this period by performing frequent water content and density checks. The information from these checks will show the contractor the effects of the compaction procedures being used and point out any changes that should be made.

2.2.1 BACKFILLING PROCEDURES. Problems associated with the compaction of backfill can be minimized by following good backfilling procedures. Good backfilling procedures include: processing the material before it is placed in the excavation; placing the material in a uniformly spread loose lift of the proper thickness suited to the compaction equipment and the type of material to be used; applying the necessary compaction effort to obtain the required densities; and ensuring that these operations are not performed during adverse weather. Proper bond should be provided between each lift and also between the backfill and the sides of the excavation.

2.2.2 COMPACTION EQUIPMENT, BACKFILL MATERIAL, AND ZONES. The type of compaction equipment used to achieve the required densities will usually depend upon the type of backfill material being compacted and the type of zone in which the material is placed.

- In open zones, coarse-grained soils that exhibit slight plasticity (clayey sands, silty sands, clayey gravels, and silty gravels) should be compacted with either sheepsfoot or rubber-tired rollers. Close control of water content is required where silt is present in substantial amounts. For sands and gravelly sands with little or no fines, good compaction results are obtained with tractor compaction. Good compaction can also be achieved in gravels and gravel-sand mixtures with either a crawler tractor or rubber-tired and steel-wheeled rollers. The addition of vibration to any of the means of compaction mentioned above will usually improve the compaction of soils in this category. In confined zones, adequate compaction of cohesionless soils in either the air-dried or saturated condition can be achieved by vibratory-plate compactors with a static weight of at least 100 pounds. If the material is compacted in the saturated condition, good compaction can be achieved by internal vibration (for example, by using concrete vibrators). Downward drainage is required to maintain seepage forces in a downward direction if the placed material is saturated to aid in compaction.

- Inorganic clays, inorganic silts, and very fine sands of low to medium plasticity are fairly easily compacted in open zones with sheepsfoot or rubber-tired rollers in the 67 kN (15,000 pound) and above wheel-load class. Some inorganic clays can be adequately compacted in confined zones using rammer or impact compactors with a static weight of at least 0.445 kN (100 pounds) provided close control of lift thickness and water content is maintained.
- Fine-grained, highly plastic materials, though not good backfill materials, can best be compacted in open zones with sheepsfoot rollers. Sheepsfoot rollers leave the surface of the backfill in a rough condition, which provides an excellent bond between lifts. In confined areas the best results, which are not considered good, are obtained with rammer or impact compactors.

2.2.3 LIFT THICKNESS. The loose-lift thickness will depend on the type of backfill material and the compaction equipment to be used.

- As a general rule, a loose-lift thickness that will result in a 0.15 m (6 in) lift when compacted can be allowed for most sheepsfoot and pneumatic-tired rollers. Cohesive soils placed in approximately 0.25 m (10 in) loose lifts will compact to approximately 0.15 m (6 in), and cohesionless soils placed in approximately 0.20 m (8 in) base lifts will compact to 0.15 m (6 in). Adequate compaction can be achieved in cohesionless materials of about

0.300 to 0.381 m (12 to 15 in) loose-lift thickness if heavy vibratory equipment is used. The addition of vibration to rolling equipment used for compacting cohesive soils generally has little effect on the lift thickness that can be compacted, although compaction to the desired density can sometimes be obtained by fewer coverages of the equipment.

- In confined zones where clean cohesionless backfill material is used, a loose-lift thickness of 0.100 to 0.150 m (4 to 6 in) and a vibratory plate or walk-behind, dual-drum vibratory roller for compaction is recommended. Where cohesive soils are used as backfill in confined zones, use of rammer compactors and a loose-lift thickness of not more than 100 mm (4 in) should be specified. Experience has shown that "two-by-four" wood rammers or single air tampers (commonly referred to as powder puffs" or "pogo sticks") do not produce sufficient compaction.

2.2.4 DENSITY REQUIREMENTS. In open areas of backfill where structures will not be constructed, compaction can be less than that required in more critical zones. Compaction to 90 percent of ASTM D 1557 maximum dry density should be adequate in these areas. If structures are to be constructed on or within the backfill, compaction of cohesionless soils to within 95 to 100 percent of ASTM D 1557 maximum dry density and of cohesive soils to at least 95 percent of ASTM D 1557 should be required for the full depth of backfill beneath these structures. The specified degree of compaction should be commensurate with the tolerable amount of settlement, and the compaction equipment used should be commensurate with the allowable lateral pressure on the structure. Drainage blankets and filters having special gradation requirements should be compacted to within 95 to 100 percent of ASTM D 1557 maximum dry density. Table 1 gives a summary of the type of compaction equipment, coverage and lift thickness for the specified degree of compaction of various soil types.

2.2.5 COLD WEATHER. In areas where freezing temperatures either hamper or halt construction during the winter, certain precautions can, and should, be taken to prevent damage from frost penetration and subsequent thaw. Some of these precautions are presented below.

- Placement of permanent backfill should be deferred until favorable weather conditions prevail. However, if placement is an absolute necessity during freezing temperatures, either dry, cohesionless, non frost-susceptible materials or material containing additives, such as calcium chloride, to lower the freezing temperature of the soil water should be used. Each lift should be checked for frozen material after compaction and before construction of the next lift is begun. If frozen material is found, it should be removed; it should not be disked in place. Additives should not be used indiscriminately since they will ordinarily change compaction and water content requirements. Prior laboratory investigation should be conducted to determine additive requirements and the effect on the compaction characteristics of the backfill material.

- Under no circumstances should frozen material from stockpile or borrow pit be placed in backfill that is to be compacted to a specified density.

- Prior to halting construction during the winter, the peripheral surface drainage system should be checked and reworked where necessary to provide positive drainage of surface water away from the excavation.

- Foundations beneath structures and backfill around structures should not be allowed to freeze because structural damage will invariably develop. Structures should be enclosed as much as possible and heated if necessary. Construction should be scheduled so as to minimize the amount of reinforcing steel protruding from a partially completed structure since steel will conduct freezing temperatures into the foundation.

- Permanent backfill should be protected from freezing. Records should be made of all temporary coverings that must be removed before backfilling operations are resumed. A checklist should be maintained to ensure that all temporary coverings are removed at the beginning of the next construction season.

- During freezing weather, records should be kept of the elevation of all critical structures to which there is the remotest possibility of damage or movement due to frost heave and subsequent thaw. It is important that frost-free benchmarks be established to which movement of any structure can be referenced. Benchmarks also should be established on the structures at strategic locations prior to freezing weather.
- At the beginning of the following construction season and after the temporary insulating coverings are removed, the backfill should be checked for frozen material and ice lenses, and the density of the compacted material should be checked carefully before backfilling operations are resumed. If any backfill has lost its specified density because of freezing, it should be removed.

2.2.6 ZONES HAVING PARTICULAR GRADATION REQUIREMENTS. Zones that have particular gradation requirements include those needed to conduct and control seepage, such as drainage blankets, filters, and zones susceptible to frost penetration. Drainage zones are often extremely important to the satisfactory construction and subsequent performance of the structure. To maintain the proper functioning of these zones, care must be taken to ensure that the material placed has the correct gradation and is compacted according to specifications.

Soil Group	Soil Types	Degree of Compaction		Fill and Backfill: Typical Equipment and Procedures for Compaction: Equipment	No. of Passes or Coverages	Comp. Lift Thickness mm (in)	Placement Water Content	Field Control
Pervious (Free Draining)	GW GP SW SP	Compacted	90 – 95% of CE 55 maximum density 75 – 85% of relative density	Vibratory Rollers Rubber Tired Roller[b] Crawler Type Tractor[c] Power Hand Tamper[d]	Indefinite 2-5 Coverages 2-5 Coverages Indefinite	Indefinite 300 (12) 200 (8) 150 (6)	Saturate by Flooding	Control tests at intervals to determine degree of compaction or relative density
		Semi-Compacted	85 to 90% of CE 55 maximum density 65 to 75% of relative density	Rubber Tired Roller[b] Crawler Type Tractor[c] Power Hand Tamper[d] Controlled routing of construction equipment	2-5 Coverages 1-2 Coverages Indefinite Indefinite	360 (14) 250 (10) 200 (8) 200–250 (8-10)	Saturate by Flooding	Control tests at intervals to determine degree of compaction or relative density, if needed

Note: The above requirements will be adequate in most construction venues. In special cases where tolerable settlements are unusually small, it may be necessary to employ additional compaction equivalents to 95-100% of compaction effort. A coverage consists of one application of the wheel of a rubber tired roller or the treads of a crawler type tractor over each point in the area being compacted. For a sheepsfoot roller , one pass consists of one movement of a sheepsfoot roller drum over the area being compacted.

a) From TM 5-818-1

b) Rubber – tired rollers having a wheel load between 80 and 111 kN (18,000 and 25,000 lb) with a tire pressure between 552-689 kPa (80-100 psi).

c) Crawler type tractors weighing not < 89 kN (20,000 lbs) / exerting a foot pressure not < 4.5 kPa (6.5psi).

d) Power hand tampers weighing more than 0.44 kN (100 lbs) / pneumatic or gasoline powered.

e) Sheepsfoot roller with a foot pressure between 1724-3448 kPa (250-500 psi)/ tamping feet 180-250 mm (7-10 in) long/ face area between 4500-10300 mm^2 (7-16 sq. in.)

Table 1

Summary of Compaction Criteria

Soil Group	Soil Types	Degree of Compaction		Fill and Backfill: Typical Equipment and Procedures for Compaction: Equipment	No. of Passes or Coverages	Comp. Lift Thickness mm (in)	Placement Water Content	Field Control
Semi-Pervious and Impervious	CM CC SM SC ML CL OL OH MH CH	Compacted	90 to 95% of CE55 maximum density	Rubber tired Roller[b] Sheepsfoot Roller [e] Power hand Tamper[d]	2-5 Coverages 4-8 Passes Indefinite	200 (8) 150 (6) 100 (4)	Optimum water content	Control tests at intervals to determine degrees of compaction
		Semi-Compacted	85 to 90% of CE55 maximum density	Rubber tired rollers[b] Sheepsfoot Roller[e] Crawler-type Tractor[c] Power hand tamper[d] Controlled routing of construction equipment'	2-4 coverages 4-8 passes 3 coverages Indefinite Indefinite	250 (10) 200 (8) 150 (6) 150 (6) 150-200 (6-8)	(A) Optimum water content (B) Observation: wet side maximum water content at which material can satisfactorily operate; dry side minimum water content required to bond particles; must not result in voids or honey-combed materials.	(A) Control tests as shown (B) Field control via visual inspection of process

Note: The above requirements will be adequate in most construction venues. In special cases where tolerable settlements are unusually small, it may be necessary to employ additional compaction equivalents to 95-100% of compaction effort. A coverage consists of one application of the wheel of a rubber tired roller or the treads of a crawler type tractor over each point in the area being compacted. For a sheepsfoot roller , one pass consists of one movement of a sheepsfoot roller drum over the area being compacted.

e) From TM 5-818-1

f) Rubber – tired rollers having a wheel load between 80 and 111 kN (18,000 and 25,000 lb) with a tire pressure between 552-689 kPa (80-100 psi).

g) Crawler type tractors weighing not < 89 kN (20,000 lbs) / exerting a foot pressure not < 4.5 kPa (6.5psi).

h) Power hand tampers weighing more than 0.44 kN (100 lbs) / pneumatic or gasoline powered.

e) Sheepsfoot roller with a foot pressure between 1724-3448 kPa (250-500 psi)/ tamping feet 180-250 mm (7-10 in) long/ face area between 4500-10300 mm^2 (7-16 sq. in.)

Table 1 (continued)

Summary of Compaction Criteria

2.3 SPECIAL PROBLEMS. In open zones, compaction of backfill will not generally present any particular problems if proper compaction procedures normally associated with the compaction of soils are exercised and the materials available for use, such as backfill, are not unusually difficult to compact. The majority of the problems associated with backfill will occur in confined zones where only small compaction equipment producing a low compaction effort can be used or where because of the confined nature of the backfill zone even small compaction equipment cannot be operated effectively. Considerable latitude exists in the various types of small compaction equipment available. Unfortunately, very little reliable information is available on the capabilities of the various pieces of equipment. Depending upon the soil type and working room, it may be necessary to establish lift thickness and compaction effort based essentially on trial and error in the field. For this reason, close control must be maintained particularly during the initial stages of the backfill until adequate compaction procedures are established.

2.3.1 DIFFICULT STRUCTURES. Circular, elliptical and arched walled structures are particularly difficult to adequately compact backfill beneath the under side of haunches because of limited working space. Generally, the smaller the structure, the more difficult it is to achieve required densities. Rock, where encountered, must be removed to a depth of at least 0.15 m (6 in) below the bottom of the structure and the over-depth backfilled with suitable material before foundation bedding for the structure is placed. Some alternate bedding and backfill placement methods are discussed below.

- One method is to bring the backfill to the planned elevation of the spring line using conventional heavy compaction equipment and methods. A template in the shape of the structure to be bedded is then used to re-excavate to conform to the bottom contours of the structure. If the structure is made of corrugated metal, allowance should be made in the grade for penetration of the corrugation crests into the backfill upon application of load. Success of this method of bedding is highly dependent on rigid control of grade during re-excavation using the template. This procedure is probably the most applicable where it is necessary to use a cohesive backfill.

- Another method of bedding placement is to sluice a clean granular backfill material into the bed after the structure is in place. This method is particularly adapted to areas containing a maze of pipes or conduits. Adequate downward drainage, generally essential to the success of this method, can be provided by sump pumps or, if necessary, by pumping from well points. Sluicing should be accompanied by vibrating to ensure adequate soil density. Concrete vibrators have been used successfully for this purpose. This method should be restricted to areas where conduits or pipes have been placed by trenching, or in an excavation that provides confining sides. Also, this method should not be used below the groundwater table in seismic zones, since achieving densities high enough to assure stability in a seismic zone is difficult.

- Another method is to place clean, granular bedding material with pneumatic concrete equipment under the haunches of pipes, tunnels, and tanks. The material is placed wet and should have an in-place water content of approximately 15 to 18 percent. A nozzle pressure of 40 pounds per square inch is required to obtain proper density. Considerable rebound of material (as much as 25 percent by volume when placed with the hose nozzle pointed vertically downward and 50 percent with the nozzle pointed horizontally) occurs at this pressure. Rebound is the material that bounces off the surface and falls back in a loose state. However, the method is very satisfactory if all rebound material is removed. The material can be effectively removed from the backfill by dragging the surface in the area where material is being placed with a flat-end shovel. Two or three men will be needed for each gunite hose operated.

- For structures and pipes that can tolerate little or no settlement, lean grouts containing granular material and various cementing agents, such as portland cement or fly ash, can be used. This grout may be placed by either method discussed above. However, grouts may develop hard spots (particularly where the sluice method is used that could cause segregation of the granular material and the cementing agent) which could generate stress concentrations in rigid structures such as concrete pipes. Stress concentrations may be severe enough to cause structural distress. If lean grouts are used as backfill around a rigid structure, the structure must be designed to withstand any additional stress generated by possible hard spots.

2.4 INSTALLATION OF INSTRUMENTS. Installation of instrumentation devices should be supervised, if not actually done, by experienced personnel or by firms that specialize in instrumentation installation. The resident engineer staff must be familiar with the planned locations of all instruments and necessary apparatus or structures (such as trenches and terminal houses) so that necessary arrangements and a schedule for installation can be made with the contractor and with the office or firm that will install the devices. Inspectors should inspect any instrumentation furnished and installed by the contractor. Records must be made of the exact locations and procedures used for installation and initial observations. Inspectors should ensure that necessary extensions are added for the apparatus (such as lead lines and piezometer tubes) installed within the backfill as the backfill is constructed to higher elevations. Care must be used in placing and compacting backfill around instruments that are installed within or through backfill. Where necessary to prevent damage to instruments, backfill must be placed manually and compacted with small compaction equipment such as rammers or vibratory plates.

2.5 POST-CONSTRUCTION DISTRESS. Good backfill construction practices and control will minimize the potential for post-construction distress. Nevertheless, the possibility of distress occurring is real, and measures must be taken to correct any problems before they become so critical as to cause functional problems with the facility. Therefore, early detection of distress is essential. Some early signs of possible distress include: settlement or swelling of the backfill around the structure; sudden or gradual change of instrumentation data; development of cracks in structural walls; and adverse seepage problems. Detailed construction records are important for defining potential distress areas and assessing the mechanisms causing the distress.

2.6 SPECIFICATION PROVISIONS

2.6.1 GENERAL. The plans and specifications define the project in detail and show how it is to be constructed. They are the basis of the contractor's estimate and of the construction contract itself. The drawings show the physical characteristics of the structure, and the specifications cover the quality of materials, workmanship, and technical requirements. Together they form the guide and standard of performance that will be required in the construction of the project. Once the contract is let, the plans and specifications are binding on both the Owner's Representative and the contractor, and are changed only by written agreement. For this reason, it is essential that the contractor and the Owner's Representative anticipate and resolve differences that may arise in interpreting the intent and requirements of the specifications. The ease with which this can be accomplished will depend on the clarity of the specifications and the background and experience of the individuals concerned. Understanding of requirements and working coordination can be improved if unusual requirements are brought to the attention of prospective bidders and meetings for discussion are held prior to construction. Situations will undoubtedly arise that are not covered by the specifications or conditions may occur that are different from those anticipated. Close cooperation is required between the contractor and the inspection personnel in resolving situations of this nature. If necessary, a change order should be issued.

2.6.2 PREPARATION OF CONTRACT SPECIFICATIONS. Preparation of contract specifications is easier if an outline of the general requirements is available to the specification writer. However, it would be virtually impossible to prepare a guide specification that anticipates all problems that may occur on all projects. Therefore, contract specifications must be written to satisfy the specific requirement of each project. Some alternate specification requirements that might be considered for some projects are discussed below.

2.6.2.1 EXCAVATION. The section of the specifications dealing with excavation contains information on drainage, shoring and bracing, removal and stockpiling, as well as other items, and refers to the plans for grade requirements and slope lines to be followed in excavating overburden soils and rock.

2.6.2.2 DRAINAGE. For some projects the specifications will require the contractor to submit a plan of his excavation operations to the Inspector for review. The plans and specifications will require that the excavation and subsequent construction and backfill be carried out in the dry. To meet this requirement, a dewatering system based on the results of groundwater studies may be included in the plans. Also, for some projects the specifications may require the contractor to submit his plan for controlling groundwater conditions. The specifications should likewise indicate the possibility of groundwater conditions being different from those shown in the subsurface investigation report due to seasonal or unusual variations or insufficient information, since the contractor will be held responsible for controlling the groundwater flow into the excavation regardless of the amount. To this end, the specifications should provide for requiring the contractor to submit a revised dewatering plan for review where the original dewatering plan is found to be inadequate.

2.6.2.3 SHORING AND BRACING. The specifications either will require the contractor to submit for review his plans for the shoring and bracing required for excavation or will specify shoring and bracing required by subsurface and groundwater conditions and details of the lines and grades of the excavation. In the latter case, the contractor may be given the option to submit alternate plans for shoring and bracing for review by the Contracting Officer. The plans will present the necessary information for the design of such a system if the contractor is allowed this option.

2.6.2.4 STOCKPILING. Provisions for stockpiling materials from required excavation according to type of backfill may or may not be included in the specifications. Generally, procedures for stockpiling are left to the discretion of the contractor, and a thorough study should be made to substantiate the need for stockpiling before such procedures are specified. There are several conditions under which inclusion of stockpiling procedures in the specifications would be desirable and justified. Two such conditions are discussed in the following paragraphs.

- Under certain conditions, where time was an important factor, it may be necessary or desirable to award contracts for the work in phases. As a result, one contractor may do the excavating and another place the backfill. It is probable that the excavation contractor will have little or no interest in stockpiling the excavated materials in a manner conducive to good backfilling procedures. When such a situation can be foreseen, the specifications should set forth stockpiling procedures. The justification for such requirements would be economy and optimum use of materials available from required excavation as backfill.
- The specifications will contain provisions for removing, segregating, and stockpiling or disposing of material from the excavation and will refer to the plans for locations of the stockpiles. The subsoil conditions and engineering characteristics requirements may state that the specifications must be quite definite concerning segregation and stockpiling procedures so that the excavated materials can be used most advantageously in the backfill. The specification may require that water be added to the material or the material be aerated as it is stockpiled to approximate optimum water content; that the stockpile be shaped to drain and be sealed from accumulation of excess water; and that the end dumping of material on the stockpile be prohibited to prevent segregation of material size or type along the length of the stockpile.

An alternative to this latter action would be to specify the various classes of backfill required and leave the procedure for stockpiling the materials by type to the discretion of the contractor. In this case, the contractor should be required to submit a detailed plan for excavating and stockpiling the material. The plan should indicate the location of stockpiles for various classes of backfill so that the material can be tested for compliance with the specifications. The contractor may elect to obtain backfill material from borrow or commercial sources rather than to separate and process excavated materials. Then the specifications should require that stockpiles of the various classes of needed backfill be established at the construction site in sufficient quantity and far enough in advance of their use to allow for the necessary testing for approval, unless conditions are such that approval of the supplier's stockpile or borrow source can be given.

2.6.3 FOUNDATION PREPARATION. The provisions for preparation for structures will generally not be grouped together in the specifications but will appear throughout the earthwork section of the specifications where requirements for excavation, protection of foundation materials, backfill construction and concrete placement are discussed. When a structure is to be founded on rock, the specifications will require that the rock be firm, unshattered by blasting operations, and not deteriorated from exposure to the weather. The contractor will be required to remove shattered or weathered rock and to fill the space with concrete.

2.6.3.1 STRUCTURES ON SOIL. Specifications for structures founded on soil require the removal of all loose material and all unsuitable material, such as organic clay or silt, below the foundation grade. When doubt exists as to the suitability of the foundation materials, a soils engineer should inspect the area and his recommendations should be followed. When removal of rock material below the planned foundation level is required, the over-excavation will usually require filling with concrete. The specifications also require dewatering to the extent that no backfill or structural foundation is placed in the wet. Specifications for the preparation of the soil foundation to receive backfill require removing all debris and foreign matter, making the area generally level, and scarifying, moistening, and compacting the foundation to a specified depth, generally 305 mm (12 in). Specific provisions may or may not be given with respect to leveling procedures.

2.6.4 BACKFILL OPERATIONS. The specifications define the type or types of material to be used for backfill construction and provide specific instructions as to where these materials will be used in the backfill. The percentage of ASTM D 1557 maximum dry density to be obtained, determined-by a designated standard laboratory compaction procedure, will be specified for the various zones of backfill. The maximum loose-lift thickness for placement will also be specified. Because of the shape of the compaction curve, the degree of compaction specified can be achieved only within a certain range of water contents for a particular compaction effort. Though not generally specified in military construction, the range of water contents is an important factor affecting compaction.

2.6.4.1 COMPACTING. The specifications sometimes stipulate the characteristics and general type of compaction equipment to be used for each of the various types of backfill. Sheepsfoot or rubber-tired rollers, rammer or impact compactors, or other suitable equipment are specified for fine-grained, plastic materials. Non-cohesive, free draining materials are compacted by saturating the material and operating crawler-type tractor, surface or internal vibrators, vibratory compactors, or other similar suitable equipment. The specifications generally will prohibit the use of rock or rock-soil mixtures as backfill in this type of construction. However, when the use of backfill containing rock is permitted, the maximum size of the rock is given in the specifications along with maximum lift thickness, loading, hauling, dumping, and spreading procedures, type of compaction equipment, and method of equipment operation. The specifications should prohibit the use of rock or rock-soil mixtures as backfill in areas where heavy equipment cannot operate. Rock/soil mixtures having greater than 8 to 10 percent binder should be prohibited in all areas. In the case of backfill containing rock, the density is not generally specified. Obtaining adequate density is usually achieved by specifying the compaction procedures. The specifications may require that these procedures be developed in field test sections. Specifications may also require specific equipment and procedures to ensure adequate bedding for round-bottom structures such as tunnels, culverts, conduits, and tanks.

2.6.4.2 BACKFILL AGAINST STRUCTURES. The specifications will state when backfill may be placed against permanent concrete construction with respect to the time after completion; this time period is usually from 7 to 14 days. To provide adequate protection of the structures during backfill construction, the specifications require that the backfill be built up symmetrically on all sides and that the area of operation of heavy equipment adjacent to a structure is limited. Also, the minimum thickness of compacted materials to be placed over the structures by small compaction equipment, such as vibratory plate or rammer type, will be specified before heavy equipment is allowed to operate over the structure. The specifications require that the surface of the backfill be sloped to drain at all times when necessary to prevent ponding of water on the fill. The specifications also provide for groundwater control, so that all compacted backfill will be constructed in the dry. Where select, freedraining, cohesionless soils of high permeability are required in areas where compaction is critical, the specifications list gradation requirements. Gradation requirements are also specified for materials used for drains and filters. Unusually severe specification requirements may be necessary for backfill operations in confined areas. The requirements may include strict backfill material type limitation, placement procedures, and compaction equipment.

2.6.4.3 PROTECTION FROM FREEZING. To ensure that adequate protection is provided, it may be necessary to specify that the contractor submit detailed plans for approval for such protection.

2.7 STABILIZATION OF SUBGRADE SOILS

2.7.1 GENERAL . The applicability and essential features of foundation soil treatments are summarized in Tables 2 and 3. The depth of stabilization generally must be sufficient to absorb most of the foundation pressure bulb. The relative benefits of vibrocompaction, vibrodisplacement compaction, and precompression increase as load intensity decreases and size of loaded area increases. Soft, cohesive soils treated in place are generally suitable only for low-intensity loadings. Soil stabilization of wet, soft soils may be accomplished by the addition of lime; grout to control water flow into excavations to reduce lateral support requirements or to reduce liquefaction or settlement caused by adjacent pile driving; seepage control by electro osmosis; and temporary stabilization by freezing. The range of soil grain sizes for which each stabilization method is most applicable is discussed in J. K. Mitchell, "Innovations in Ground Stabilization," Chicago Soil Mechanics Lecture Series, Innovations in Foundation Construction, Illinois Section, 1972.

2.7.2 VIBROCOMPACTION. Vibrocompaction methods (blasting, terraprobe, and vibratory rollers) can be used for rapid densification of saturated cohesionless soils (Figure 1.) The ranges of grain-size distributions suitable for treatment by vibrocompaction, as well as vibroflotation, is discussed in J. K. Mitchell, "Innovations in Ground Stabilization," Chicago Soil Mechanics Lecture Series, Innovations in Foundation Construction, Illinois Section, 1972. The effectiveness of these methods is greatly reduced if the percent finer than the 0.075 Micron (No. 200) sieve exceeds about 20 percent or if more than about 5 percent is finer than 0.002 millimeter, primarily because the hydraulic conductivity of such materials is too low to prevent rapid drainage following liquefaction. The usefulness of these methods in partly saturated sands is limited because the lack of an increase of pore water pressure impedes liquefaction. Lack of complete saturation is less of a restriction to use of blasting because the high-intensity shock wave accompanying detonation displaces soil, leaving depressions that later can be backfilled.

2.7.2.1 BLASTING. Theoretical design procedures for densification by blasting are not available and continuous onsite supervision by experienced engineers having authority to modify procedures as required is essential if this treatment method is used. A surface heave of about 150 mm (6 in) will be observed for proper charge sizes and placement depths. Surface cratering should be avoided. Charge sizes of less than 1.8 to more than 27 kg (4 to more than 60 lb) have been used. The effective radius of influence for charges using (M = lb) 60 percent dynamite is as follows:

$$R = 3M^{1/3} \text{ (feet)}$$

2.7.2.1.1 CHARGE SPACINGS. Charge spacings of 3 to 7.62 m (10 to 25 ft) are typical. The center of charges should be located at a depth of about two thirds the thickness of the layer to be densified, and three to five successive detonations of several spaced charges each are likely to be more effective than a single large blast. Little densification is likely to result above about a 1-m (3-ft) depth, and loosened material may remain around blast points. Firing patterns should be established to avoid the "boxing in" of pore water. Free-water escape on at least two sides is desirable.

2.7.2.1.2 PRE-FLOODING. If blasting is used in partly saturated sands or loess, pre-flooding of the site is desirable. In one technique, blast holes about 76 to 88 mm (3 to 3 ½ in) in diameter are drilled to the desired depth of treatment, then small charges connected by the prima cord are strung the full depth of the hole. Each hole is detonated in succession and the resulting large diameter holes formed by lateral displacement are backfilled. A sluiced-in cohesionless backfill will densify under the action of vibrations from subsequent blasts. Finer grained backfills can be densified by tamping.

2.7.2.2 VIBRATING PROBE (TERRAPROBE). A 30-in-outside-diameter, open-ended pipe pile with 9.5 mm (3/8-in) wall thickness is suspended from a vibratory pile driver operating at 15 Hz. A probe length from 3.05 to 4.57 m (10 to 15 ft) greater than the soil depth to be stabilized is used. Vibrations of 9.5 mm to 25.4 mm (3/8 to 1 in) amplitude are applied in a vertical mode. Probes are made at a spacing of between 0.91 and 3.05 m (3 to 10 ft). After the soil sinks to the desired depth, the probe is held for 30 to 60 seconds before extraction. The total time required per probe is typically 2½, to 4 minutes. Effective treatment has been accomplished at depths of 3.66 to 18.29 m (12 to 60 ft). Areas in the range of 376 to 585 m^2 (450 to 700 sq yd) may be treated per machine per 8-hour shift. Test sections about 9.1 to 18.3 m (30 to 60 ft) on a side are desirable to evaluate the effectiveness and required probe spacing. The grain-size range of treated soil should fall within recommended limits. A square pattern is often used, with a fifth probe at the center of each square giving more effective increased densification than a reduced spacing. Saturated soil conditions are necessary as underlying soft clay layers may dampen vibrations.

2.7.2.3 VIBRATORY ROLLERS. Where cohesionless deposits are of limited thickness, e.g., less than 2 m (6 ft), or where cohesionless fills are being placed, vibratory rollers are likely to be the best and most economical means for achieving high density and strength. They should be used with flooding where a source of water is available. The effective depth of densification may be 2 m (6 ft) or more for heaviest vibratory rollers or a fill placed in successive lifts with a density-depth distribution similar to that in Figure 1. It is essential that the lift thickness, soil type, and roller type be matched. Properly matched systems can yield compacted layers at a relative density of 85 to 90 percent or more.

2.7.3 VIBRODISPLACEMENT COMPACTION. The methods in this group are similar to those described in the preceding section except that the vibrations are supplemented by active displacement of the soil and, in the case of vibroflotation and compaction piles, by backfilling the zones from which the soil has been displaced.

2.7.3.1 COMPACTION PILES. Partly saturated or freely draining soils can be effectively densified and strengthened by this method, which involves driving displacement piles at close spacings, usually 1 to 2 m (3 to 6 ft) on centers. One effective procedure is to cap temporarily the end of a pipe pile (e.g., by a detachable plate) and drive it to the desired depth which may be up to 18 m (60 ft). Either an impact hammer or a vibratory driver can be used. Sand or other backfill material is introduced in lifts with each lift compacted concurrently with the withdrawal of the pipe pile. In this way, not only is the backfill compacted, but the compacted column has also expanded laterally below the pipe tip forming a caisson pile.

2.7.3.2 HEAVY TAMPING (DYNAMIC CONSOLIDATION). Repeated impacts of a very heavy weight (up to 356 kN (80 kips)) dropped from a height of 15 to 40 m (50 to 130 ft) are applied to points spaced 4.5 to 9.0 m (15 to 30 ft) apart over the area to be densified. In the case of cohesionless soils, the impact energy causes liquefaction followed by settlement as water drains. Radial fissures that form around the impact points, in some soils, facilitate drainage. The method has been used successfully to treat soils both above and below the water table. The product of tamper mass and height of fall should exceed the square of the thickness of layer to be densified. A total tamping energy of 2 to 3 blows per square meter or square yard is used. Increased efficiency is obtained if the impact velocity exceeds the wave velocity in the liquefying soil. One crane and tamper can treat from 293 to 627 m^2 (350 to 750 sq yd) per day. Economical use of the method in sands requires a minimum treatment area of 2,671 m^2 (7,500 sq yd). Relative densities of 70 to 90 percent are obtained. Bearing capacity increases of 200 to 400 percent are usual for sands and marls, with a corresponding increase in deformation modulus. The cost is reported as low as one-fourth to one-third that of vibroflotation. Because of the high-amplitude, low-frequency vibrations (2-12 Rz), minimum distances should be maintained from adjacent facilities as follows:

Piles or bridge abutment 4.6 – 6.1 m (15 – 20 ft)
Liquid storage tanks 9.1 m (30 ft)
Reinforced concrete buildings 15.2 m (50 ft)
Dwellings 30.5 m (100 ft)
Computers (not isolated) 91.4 m (300 ft)

2.7.3.3 VIBROFLOTATION. A cylindrical penetrator about 381 mm (15 in) in diameter and 1.8 m (6 ft) long, called a vibroflot, is attached to an adapter section containing lead wires and hoses. A crane handles the whole assembly. A rotating eccentric weight inside the vibroflot develops a horizontal centrifugal force of about 89 kN (10 tons) at 1800 revolutions per minute. Total weight is about 18 kN (2 tons). To sink the vibroflot to the desired treatment depth, a water jet at the tip is opened and sets in conjunction with the vibrations so that a hole can be advanced at a rate of about 1.2 m (3.6 ft) per minute; then the bottom jet is closed, and the vibroflot is withdrawn at a rate of about 30 mm (0.1 ft) per minute. Newer, heavier vibroflots operating at 100 horsepower can be withdrawn at twice this rate and have a greater effective penetration depth. Concurrently, a cohesionless sand or gravel backfill is dumped in from the ground surface and densified. Backfill consumption is at a rate of about .62 to 1.77 m3 per m2 (0.7 to 2 cubic yards per square yard) of surface. In partly saturated sands, water jets at the top of the vibroflot can be opened to facilitate liquefaction and densification of the surrounding ground. Liquefaction occurs to a radial distance of 305 mm to 610 mm (1 to

2 ft) from the surface of the vibroflot. Most vibroflotation applications have been to depths less than 18 m (60 ft), although depths of 27 m (90 ft) have been attained successfully. A relationship between probable relative density and vibroflot hold spacings is given in Figure 2. Newer vibroflots result in greater relative densities. Figure 3 shows relationships between allowable bearing pressure to limit settlements to 25.4 mm (1 in) and vibroflot spacing. Allowable pressures for "essentially cohesionless fills" are less than for clean sand deposits because such fills invariably contain some fines and are harder to densify. Continuous square or triangular patterns are often used over a building site. Alternatively, it may be desired to improve the soil only at the locations of individual spread footings. Patterns and spacings required for an allowable pressure of 287 kPa (3 tons per sq ft) and square footings are given in Table 4.

	Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth meters (ft)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Material	Special Advantages and Limitations	Relative Costs (1976)
Vibro-Compaction	Blasting	Shock waves and vibrations causes liquefaction, displacement	Saturated, clean sands, partially saturated sands and silts after flooding	18 M (60 ft)	Small areas can be treated economically	Explosives; backfill to plug drill holes	Jetting or drilling machinery	Can obtain relative densities to 70-80%; may get variable density	Rapid, inexpensive; can treat small areas, variable properties; no improvement near surface dangerous	Low $0.50 to $1.00 per cubic meter (cubic yard)
	Terraprobe	Densification by vibrations, liquefaction induced settlement under overburden	Saturated or clean dry sand	18 M (60 ft) (ineffective 3.6 M (12 ft) depth and above)	1000M^2 >1200yd^2	None	Vibratory pile driver and 75mm diameter open steel pipe	Can obtain relative densities of 80% or more	Rapid, simple; good underwater and w/ soft underlayers; difficult to penetrate stiff upper layers; not good in poorly saturated soils.	Moderate; $1.50-.$3.25/cubic meter (cubic yd) $2.00 cubic meter (cubic yd) average
	Vibratory Rollers	Densification by vibration, liquefaction induced settlement under roller weight	Cohesion-less soils	1.8-3 M (6-10 ft)	Any size	None	Vibratory roller	Can obtain very high relative densities	Best method for thin layers and lifts	Low

Table 2

Stabilization of Soils for the Foundations of Structures

	Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth (feet)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Material	Special Advantages and Limitations	Relative Costs (1976)
Vibro-Displacement Compaction	Compaction piles	Densification by displacement of pile volume and vibration during drilling	Loose sandy soils, partly saturated clay like soils; loess	1.8 M (60ft)	Small to moderate	Pile material (often sand or soil + cement	Pile driver	Can obtain high densities; good uniformity	Useful in soils w/ fines, uniform compactioneasy to check results, slow, limited improvement in upper 300 – 600 mm (1-2 ft)	High
	Heavy Tamping (Dynamic consolidation)	Repeated application of high intensity impacts @ surface.	Cohesionless best; other types can also be improved	15- 18 M (50-60 ft)	>3344 M^2 (4000 yd^2)	None	Tamper of 10-40 tons; high capacity crane	Can obtain high relative densities; reasonable uniformity	Simple, rapid; suitable for some soils w/ fines; usable above and below water; requires control; must be away from existing structures.	Less than vibro-floatation.
	Vibrofloatation	Densification by vibration and compaction of backfill material	Cohesionless soils with less than 20%	90ft	>1000 M^2 (1200 yd^2)	Granular backfill	Vibroflot; crane	Can obtain high relative densities; good uniformity	Useful in saturated and partially saturated soils; uniformity	$10.00-$25.00/m^2 (yd^2); $1.00/$m^2$ (yd^2); may cost about half of compaction or concrete piles.

Table 2 (continued)

Stabilization of Soils for the Foundations of Structures

	Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth (feet)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Materials	Special Advantages and Limitations	Relative Costs (1976)
Grouting and Injection	Particulate Grouting	Penetration grouting; fill soil pores w/ cement and/or clay	Medium to coarse sand and gravel	Unlimited	Small	Grout, water	Mirrors, tanks, pumps, hoses	Impervious, high strength with cement grout; eliminates liquefaction danger	Low cost grouts, high strength: limited to coarse grained soils hard to evaluate	Lowest of the grout systems
	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	Grout, water	Mirrors, tanks, pumps, hoses	Impervious, low to high strength; eliminate liquefaction danger	Low viscosity, controllable gel time, good water shut-off; high cost, hard to evaluate	High to very high $30/m^2$-$80/m^2$ typical
	Pressure Injected Lime	Lime slurry injected to shallow depths under high pressure	Expansive clays	Unlimited; but 2-3 m usual	Small	Lime, water, surfactant	Slurry tanks, agitators, injectors	Lime encapsulated zones formed by chemicals resulting from cracks, root holes, hydraulic fracture.	Rapid and economical treatment for foundation soils under light structures.	$2.50-$3.00/m of ground surface area.

Table 2 (continued)

Stabilization of Soils for the Foundations of Structures

Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth (feet)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Materials	Special Advantages and Limitations	Relative Costs (1976)
Grouting and Injection (Continued)									
Displacement Grout	Highly viscous grout acts as radial hydraulic jack when pumped in under high pressure	Soft, fine grained soils; foundation soils with large voids or cavaties	Unlimited, but a few, as usual	Small	Soil, cement, water	Batching equipment, high pressure pumps and hoses	Grout bulbs within compressed soil matrix	Good for correction of differential settlements, filling large voids; careful control required	Low for materials; high for injection process.

Table 2 (continued)

Stabilization of Soils for the Foundations of Structures

	Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth (feet)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Material	Special Advantages and Limitations	Relative Costs (1976)
Precompression	Preloading	Load is applied sufficiently in advance of construction so that compression of soft soils is completed prior to site development	Normally consolidated soft clays, silts, organic deposits, completed sanitary landfills	-----	>1000m^2	Earth fill or other material for loading the site; sand or gravel for drainage blanket.	Earth moving equipment; large H_2O tanks or vacuum drainage systems may be used; settlement markers; piezometers	Reduced water content and void ratio/ increased strength	Easy, theory well developed, consistent and uniform; requires long time (sand drains or wicks can be used to reduce consolidation time	Low / moderate if vertical drains are required.
	Surcharge fills	Fill in excess of that required permanently is applied to achieve a given amt of settlement in a shorter time; excess fill then removed	Normally consolidated soft clays, silts, organic deposits: completed sanitary landfills	-----	>1000m^2	Earth fill / other material for loading/ sand or gravel as drainage blanket	Earth moving equipment; settlement markers; piezometers	Reduced H_2O content, void ratios and compressibility: increased strength	Faster than preloading w/o surcharge; theory well developed; extra material handing; use sand drains/ wicks	Moderate/ Sand drains moderate cost

Table 2 (continued)

Stabilization of Soils for the Foundations of Structures

	Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth (feet)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Material	Special Advantages and Limitations	Relative Costs (1976)
Precompression (Continued)	Dynamic Consolidation	High energy impacts compress and dissolve gas in pores to give immediate settlement; increased pore pressure gives subsequent drainage.	Partly saturated fine grained soils; quarternary clays clays w/ 1-4 gas in micro – bubbles	30 m	>15000-30000 m^2	>15000-30000 m^2	Tamper of 10-40 tons, high capacity cranes	Reduced water content, void ratio and compressability; Increased strength	Faster than preloading, economical on large areas; uncertain mechanism in clays; less uniformity than preloading	< preload fills w/ sand drains
	Electro-osmosis	DC current causes H_2O to flow from anode to cathode where it is then removed	Normally consolidated silts and silty clays	10-20m	Small	Anodes (rebar or aluminum) Cathodes (well points or rebar)	D/C power supply, wiring, metering system	Reduced water content and compressibility; increased strength, electrochemical hardening	No fill loading required, can use in confined areas, relatively fast, non-uniform properties between electrodes; useless in highly conductive soils	High

Table 2 (continued)

Stabilization of Soils for the Foundations of Structures

	Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth (feet)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Material	Special Advantages and Limitations	Relative Costs (1976)
Reinforcement	Mix in Place Piles and Walls	Lime, cement or asphalt introduced through rotating auger or special in-place mixer	All soft or loose inorganic soils	>20m	Small	Cement, lime, or chemical stabilization.	Drill rig, rotating cutting and mixing head, additive proportioning equipment	Modified soil piles or walls of relatively high strength.	Does native soil, reduced lateral support requirements during excavation; difficult to exert quality control.	Moderate to high
	Strips and Membranes	Horizontal toenails or membranes buried in soil under footings	All	A few meters	Small	Metal or plastic strips, polyethylene, polypropylene, or polyester fabrics	Excavation, earth handling and compaction equipment.	Increased bearing capacity , reduced deformations.	Increased allowable bearing pressures, requires over-excavation for footings.	Low to moderate
	Vibro-replacement stone columns	Hole jetted into soft fine grain soils / backfilled w/ dense, compacted gravel	Soft clays and alluvial deposits	20 m	>1500 m^2	Gravel or crushed rock backfill	Vibroflot. crane or vibro-cat, water	Increased bearing capacity; reduced settlements	Faster than pre-compression. No dewatering; limited bearing capacity	Moderate to high, relative to depth penetration.

Table 2 (continued)

Stabilization of Soils for the Foundations of Structures

	Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth (feet)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Material	Special Advantages and Limitations	Relative Costs (1976)
Thermal	Heating	Drying at low temperatures; alteration of clays of intermediate temps (400 – 600 ° C): Fusion @ high temps (> 1000° C)	Fine grained soils; especially partiall y saturated silts and clays: loess	15 m	Small	Selected fuels	Fuel tanks, burners, blowers	Reduced water control, plasticity, water sensitivity; increased strength	Can obtain irreversible improvements in properties; introduces stabilization w/ hot gases. Experimental @ this writing (1976)	High
	Freezing	Freezes soft, wet ground to increase strength, reduce pliability	All soils	Several m	Small	Refrigerant	Refrigeration system	Increased strength, reduced pliability	Cannot be used with flowing ground water; temporary.	High

Table 2 (continued)

Stabilization of Soils for the Foundations of Structures

	Method	Principle	Most Suitable Soil Condition/ Type	Maximum Effective Treatment Depth (feet)	Economical Size of Treated Area	Special Materials Required	Special Equipment Required	Properties of Treated Material	Special Advantages and Limitations	Relative Costs (1976)
Miscellaneous	Remove and replace, with / without admixtures	Foundation soil excavated; improved by drying or admixtures	Inorganic soils	10 m	Small	Only if admixtures are needed	Excavation and compaction equipment; dehydrating system	Increased strength and stiffness; reduced compressibility	Uniform, controlled foundation soils when replaced; may require large area of de-watering.	High
	Moisture barriers	Excess water in foundation soils is prevented	Expansive soils	5 m	Small	Membranes, gravel, lime or asphalt	Excavating, trenching, and compaction equipment	Original natural or as compacted properties retained	Best used with small structures/ may not be 100% effective.	Low to moderate
	Pre-wetting	Soil is brought to final estimated water content prior to construction	Expansive soils	2-3 m	Small	Water	Water tanks	Decreased swelling potential	Low cost, best used for small light constructions; shrinking and swelling may sill occur	Low
	Structural Fills (with or without admixtures)	Fill distributes loads to underlying soils	Use over soft clays or organic soils, marsh lands	----	Small	Sand, gravel, fly/bottom ash, clam/oyster shell , incinerator ash	Compaction equipment	Soft subgrade protected by structural load-bearing fill	High strength, good load distribution to underlying soft soils.	Moderate to high.

Table 2 (continued)

Stabilization of Soils for the Foundations of Structures

Category of Structure	Structure	Permissible Settlement	Load Intensity/ Usual Bearing Pressure Required kPa (tsf)	Probability of Advantageous Use of Soil Improvement Techniques		
				Loose Cohesionless Soils	Soft Alluvial Deposits	Old, Inorganic Soils
Office/Apartment Frame or load bearing construction	High rise/ more than six stories	Small<25-50mm	High 287-96 (3-1)	High	Unlikely	Low
	Medium rise 3-6 stories	Small<25-50mm	Moderate 192 (2)	High	Low	Good
	Low rise 1-3 stories	Small<25-50mm	Low 96-192 (1-2)	High	Good	High
Industrial	Large span w/heavy machines, cranes;process and power plants	Small<25-50mm Differential Settlement Critical	Variable/ high local concentrations to >383 (4)	High	Unlikely	Low
	Framed warehouses & factories	Moderate	Low 96-192 (1-2)	High	Good	High
	Covered storage, storage rack systems, production areas	Low to moderate	Low <192 (2)	High	Good	High
Others	Water /waste water treatment plants	Moderate Differential settlement important	Low <14364 (150) <144 (1.5)	High, if needed at all	High	High
	Storage tanks	Moderate to high, Diff. maybe critical	High/up to 28728 (300)	High, if needed at all	High	High
	Open storage Areas	High	High/up to 28728 (300)	High, if needed at all	High	High
	Enbankments/ Abutments	Moderate to high	High/up to 28728 (300)	High, if needed at all	High	High

Table 3

Applicability of Foundation Soil Improvement for Different Structures and Soil Types (for Efficient Use of Shallow Foundations)

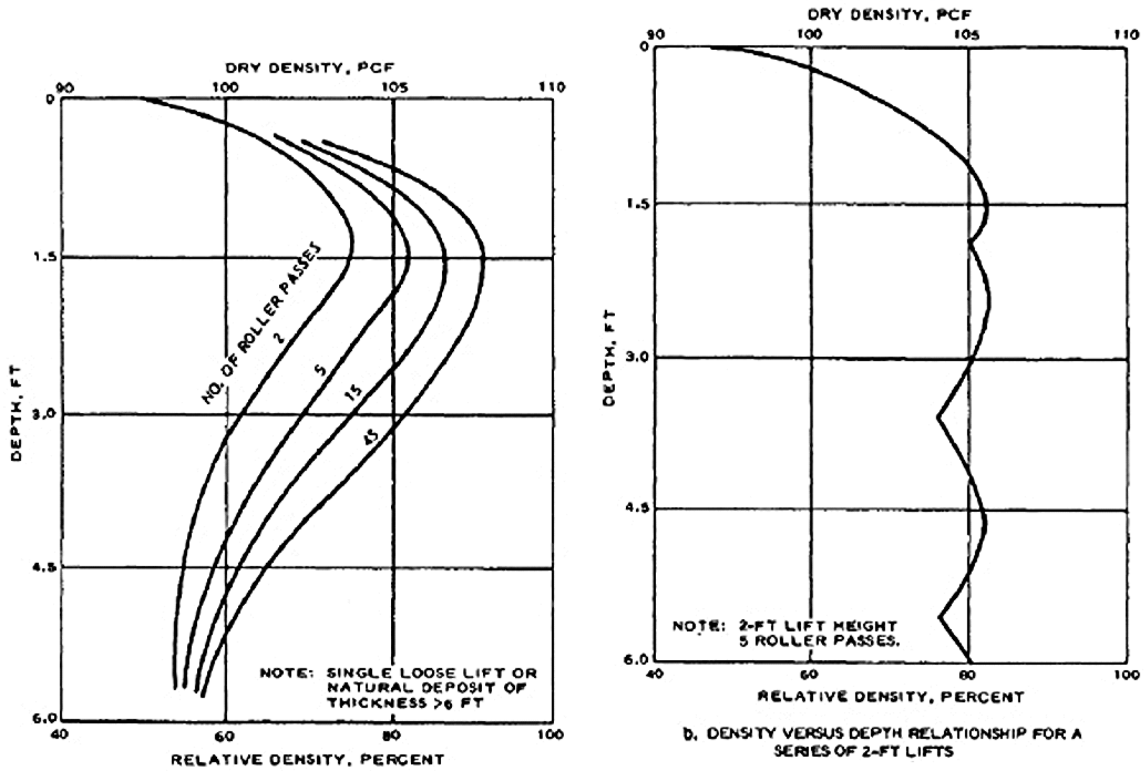

Figure 1

Sand Densification Using Vibratory Rollers

2.7.4 GROUTING AND INJECTION. Grouting is a high-cost soil stabilization method that can be used where there is sufficient confinement to permit required injection pressures. It is usually limited to zones of relatively small volume and to special problems. Some of the more important applications are control of groundwater during construction; void filling to prevent excessive settlement; strengthening adjacent foundation soils to protect against damage during excavation, pile driving, etc.; soil strengthening to reduce lateral support requirements; stabilization of loose sands against liquefaction; foundation underpinning; reduction of machine foundation vibrations; and filling solution voids in calcareous materials.

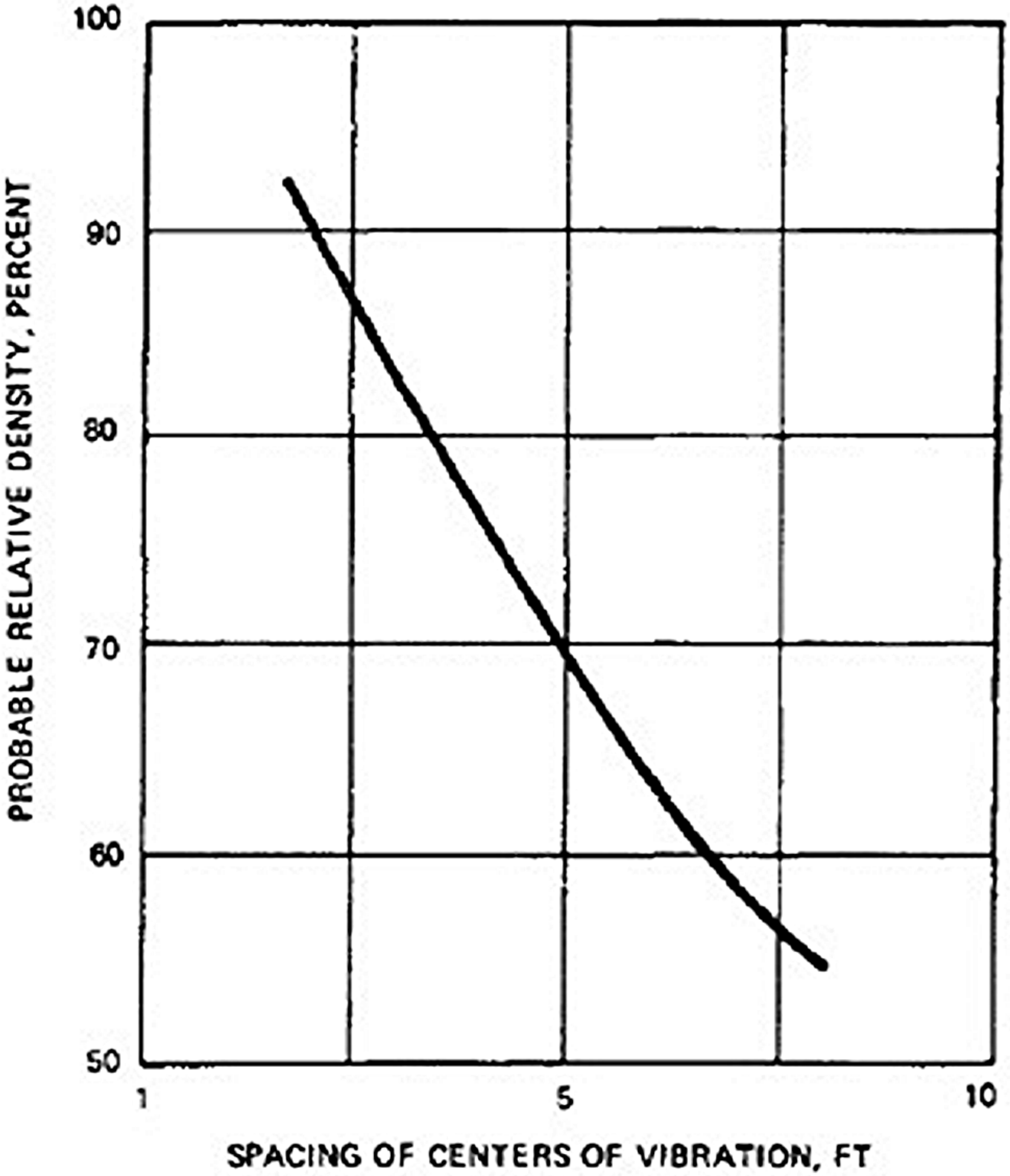

Figure 2

Relative Density as a Function of Vibrofloat Hole Spacings

2.7.4.1 GROUT TYPES AND GROUTABILITY. Grouts can be classified as particulate or chemical. Portland cement is the most widely used particulate grouting material. Grouts composed of cement and clay are also widely used and lime-slurry injection is finding increasing application. Because of the silt-size particles in these materials, they cannot be injected into the pores of soils finer than medium to coarse sand. For successful grouting of soils, use the following guide:

$$(D_{15})_{soil}/(D_{85})_{grout} > 25$$

Type 1 portland cement, Type III portland cement, and processed bentonite cannot be used to penetrate soils finer than 30, 40 and 60 mesh sieve sizes, respectively. Different types of grouts may be combined to both coarse- and fine-grained soils.

2.7.4.2 CEMENT AND SOIL-CEMENT GROUTING. See the American Society of Civil Engineers Grouting Publications for cement and soil-cement grouting.

2.7.4.3 CHEMICAL GROUTING. To penetrate the voids of finer soils, chemical grout must be used. The most common classes of chemical grouts in current use are silicates, resins, lignins, and acrylamides. The viscosity of the chemical-water solution is the major factor controlling groutability. The particle-size ranges over which each of these grout types is effective is shown in Figure 4.

2.7.5 PRECOMPRESSION.

2.7.5.1 PRELOADING. Earth fill or other material is placed over the site to be stabilized in amounts sufficient to produce a stress in the soft soil equal to that anticipated from the final structures. As the time required for consolidation of the soft soil may be long (months to years) and varies directly as the square of the layer thickness and inversely as the hydraulic conductivity, preloading alone is likely to be suitable only for stabilizing thin layers and with a long period of time available prior to final development of the site.

2.7.5.1.1 SURCHARGE FILLS. If the thickness of the fill placed for pre-loading is greater than that required to induce stresses corresponding to structure-induced stresses, the excess fill is termed a surcharge fill. Although the rate of consolidation is essentially independent of stress increase, the amount of consolidation varies approximately in proportion to the stress increase. Therefore, the preloading fill plus surcharge can cause a given amount of settlement in shorter time than can the preloading fill alone. Thus, through the use of surcharge fills, the time required for preloading can be reduced significantly. The required surcharge and loading period can be determined using conventional theories of consolidation. Both primary consolidation and most of the secondary compression settlements can be taken out in advance by surcharge fills. Secondary compression settlements may be the major part of the total settlement of highly organic deposits or old sanitary landfill sites. Because the degree of consolidation and applied stress vary with depth, it is necessary to determine if excess pore pressures will remain at any depth after surcharge removal. If so, further primary consolidation settlement under permanent loadings would occur. To avoid this occurrence, determine the duration of the surcharge loading required for points most distant from drainage boundaries. The rate and amount of preload may be controlled by the strength of the underlying soft soil. Use berms to maintain foundation stability and place fill in stages to permit the soil to gain strength from consolidation. Predictions of the rates of consolidation strength and strength gain should be checked during fill placement by means of piezometers, borings, laboratory tests, and in-situ strength tests.

2.7.5.2 VERTICAL DRAINS. The required preloading time for most soft clay deposits more than about 1.5 to 3 m (5 to 10 ft) thick will be large. Providing a shorter drainage path by installing vertical sand drains may reduce the consolidation time. Sand drains are typically 254 to 370 mm (10 to 15 in) in diameter and are installed at spacings of 1.5 to 4.5 m (5 to 15 ft). A sand blanket or a collector drain system is placed over the surface to facilitate drainage. Other types of drains available are special cardboard or combination plastic-cardboard drains. Provisions should be made to monitor pore pressures and settlements with time to determine when the desired degree of pre-compression has been obtained. Both displacement and non-displacement methods have been used for installing sand drains. Although driven displacement drains are less expensive than augured or "bored" non-displacement drains, they should not be used in sensitive deposits or in stratified soils that have higher hydraulic conductivity in the horizontal than in the vertical direction. Vertical drains are not needed in fibrous organic deposits because the hydraulic conductivity of these materials is high, but they may be required in underlying soft clays.

2.7.5.3 DYNAMIC CONSOLIDATION (HEAVY TAMPING). Densification by heavy tamping has also been reported as an effective means for improving silts and clays with preconstruction settlements obtained about 2 to 3 times the predicted construction settlement. The time required for treatment is less than for surcharge loading with sand drains. The method is essentially the same as that used for cohesionless soils except that more time is required. Several blows are applied at each location followed by a 1- to 4-week rest period; then the process is repeated. Several cycles may be required. In each cycle, the settlement is immediate followed by drainage of pore water. Drainage is facilitated by the radial fissures that form around impact points and by the use of horizontal and peripheral drains. Because of the necessity for a time lapse between successive cycles of heavy tamping when treating silts and clays, a minimum treatment area of 15,000 to 30,000 m^2 (18,000 to 35,000 sq yd) is necessary for economical use of this method. This method is presently considered experimental in saturated clays.

2.7.5.4 ELECTRO OSMOSIS. Soil stabilization by electro osmosis may be effective and economical under the following conditions: saturated silt or silty clay soil, normally consolidated soil, and low pore water electrolyte concentration. Gas generation and drying as well as fissuring at the electrodes can impair the efficiency of the method and limit the magnitude of consolidation pressures that develop. Treatment results in non-uniform changes in properties between electrodes because the induced consolidation depends on the voltage, and the voltage varies between anode and cathode. Thus, reversal of electrode polarity may be desirable to achieve a more uniform stress condition. Electro osmosis may also be used to accelerate the consolidation under a preload or surcharge fill. The method is relatively expensive.

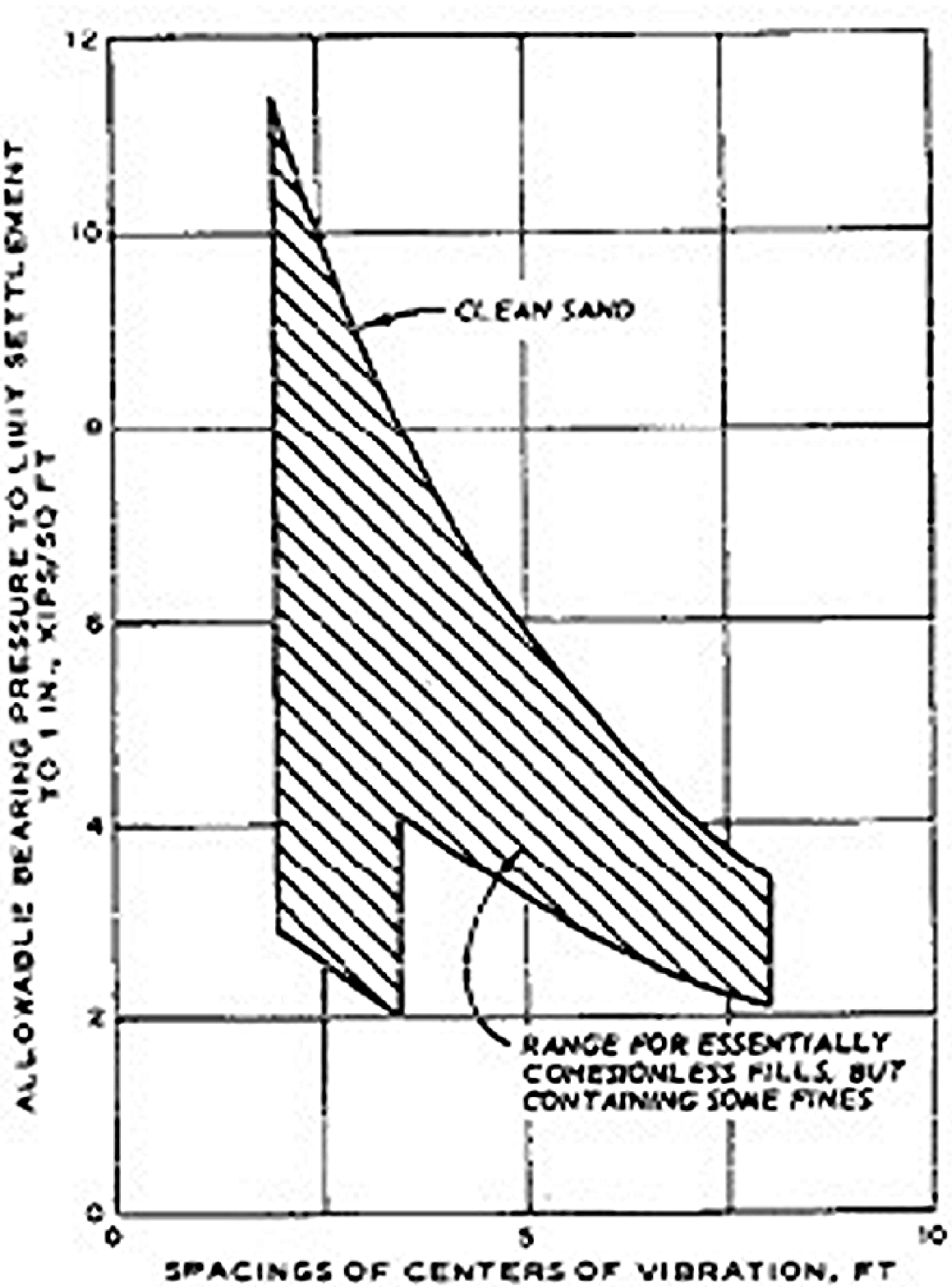

Figure 3

Allowable bearing pressure on cohesionless soil layers stabilized by vibroflotation

Square Footing Size in meters (feet)	Vibroflotation Points	Center to Center Spacing in meters (feet)	Pattern
1.2 (4.0)	1	---	---
1.4 – 1.7 (4.5 – 5.5)	2	1.8 (6.0)	Line
1.8 – 2.1 (6 - 7)	3	2.3 (7.5)	Triangle
2.3 – 2.9 (7.5 - 9.5)	4	1.8 (6.0)	Square
3.0 – 3.7 (10 – 12)	5	2.3 (7.5)	Square +1 @ center

Table 4

Vibroflotation Patterns for Isolated Footings for an Allowable Bearing Pressure

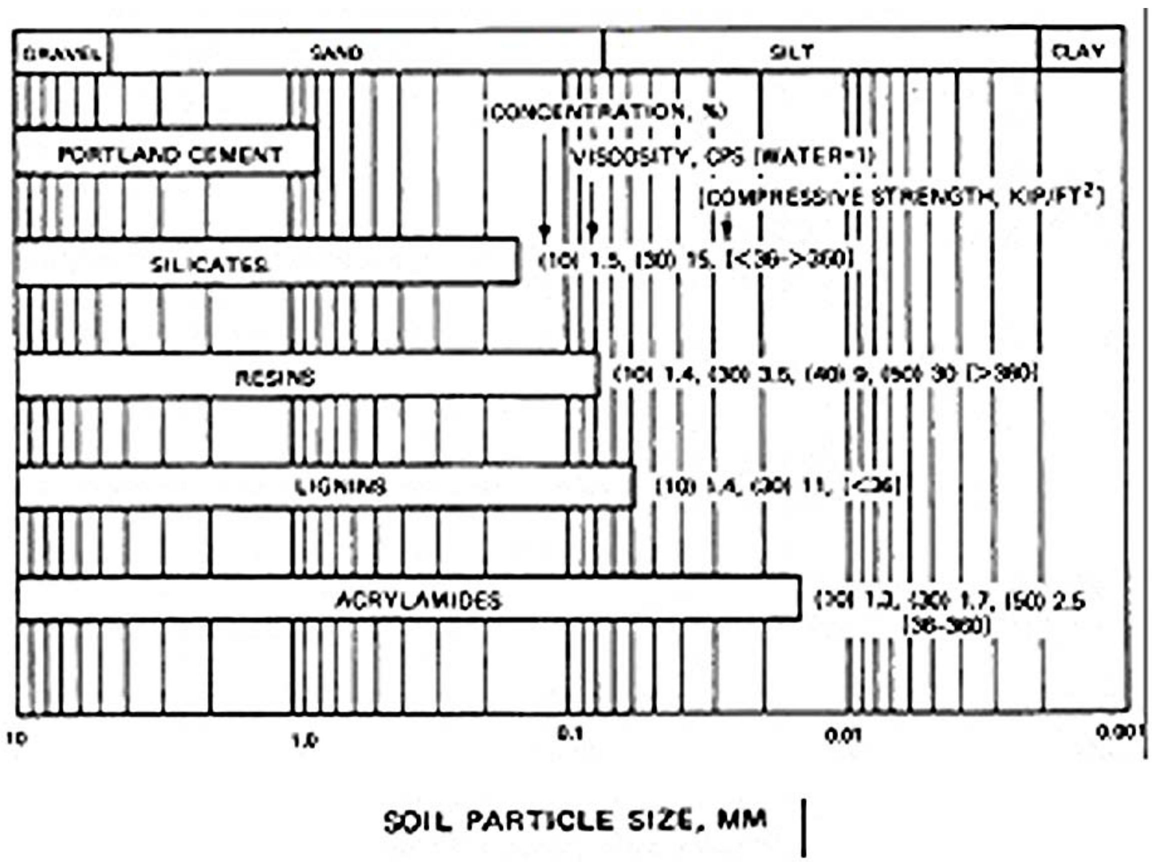

Figure 4

Soil Particle Sizes Suitable for Different Grout Types and Several Concentrations and Viscosities Shown

2.7.6 REINFORCEMENT. The supporting capacity of soft, compressible ground may be increased and settlement reduced through the use of compression reinforcement in the direction parallel to the applied stress or tensile reinforcement in planes normal to the direction of applied stress. Commonly used compression reinforcement elements include mix-in-place piles and walls. Strips and membranes are used for tensile reinforcement, with the latter sometimes used to form a moisture barrier as well.

2.7.6.1 MIX-IN-PLACE PILES AND WALLS. Several procedures are available (most of which are patented or proprietary) which enable construction of soil-cement or soil-lime in situ. A special hollow rod with rotating vanes is augered into the ground to the desired depth. Simultaneously, the stabilizing admixture is introduced. The result is a pile of up to 0.6 meters (2 feet) in diameter. Cement, in amounts of 5 to 10 percent of the dry soil weight, is best for use in sandy soils. Compressive strengths in excess of 9.6 mPa (200 kips) per sq ft can be obtained in these materials. Lime is effective in both expansive plastic clays and in saturated soft clay. Compressive strengths of about 0.96 – 1.92 kPa (20 to 40 kips) per square foot are to be expected in these materials. If overlapping piles are formed, a mix-in-place wall results.

2.7.6.2 VIBROREPLACEMENT STONE COLUMNS. A vibroflot is used to make a cylindrical, vertical hole under its own weight by jetting to the desired depth. Then, up to 1 m^2 (cubic yard) coarse granular backfill, usually gravel or crushed rock of 19 to 25 mm (¾ to 1 in) diameter is dumped in, and the vibroflot is used to compact the gravel vertically and radially into the surrounding soft soil. This process of backfilling and compaction by vibration is continued until the densified stone column reaches the surface.

2.7.6.3 STRIPS AND MEMBRANES. Low-cost, durable waterproof membranes, such as polyethylene, polypropylene asphalt and polyester fabric asphalt, have been applied as moisture barriers. At the same time, these materials have sufficient tensile strength that when used in envelope construction, such as surrounding a well-compacted, fine-grained soil, the composite structure has a greater resistance to applied loads than conventional construction with granular materials. The reason is that any deformation of the enveloped soil layer causes tension in the membrane, which in turn produces additional confinement on the soil and thus increases its resistance to further deformation. In the case of a granular soil where moisture infiltration is not likely to be detrimental to strength, horizontally bedded thin, flat metal or plastic strips can act as tensile reinforcing elements. Reinforced earth has been used mainly for earth retaining structures; however, the feasibility of using reinforced earth slabs to improve the bearing capacity of granular soils has been demonstrated. Model tests have shown that the ultimate bearing capacity can be increased by a factor of 2 to 4 for the same soil unreinforced. For these tests, the spacing between reinforcing layers was 0.3 times the footing width. Aggregate strip width was 42 percent of the length of strip footing.

2.7.6.4 THERMAL METHODS. Thermal methods of foundation soil stabilization, freezing or heating, are complex and their costs are high.

2.7.6.4.1 ARTIFICIAL GROUND FREEZING. Frozen soil is far stronger and less pervious than unfrozen ground. Hence, artificial ground freezing has had application for temporary underpinning and excavation stabilization. More recent applications have been made to back-freezing soil around pile foundations in permafrost and maintenance of frozen soil under heated buildings on permafrost. Design involves two classes of problems: 1) structural properties of the frozen ground to include the strength and the stress-strain-time behavior, and 2) thermal considerations to include heat flow, transfer of water to ice, and design of the refrigeration system.

2.7.6.4.2 HEATING. Heating fine-grained soils to moderate temperatures, e.g., 100°C and more, can cause drying and accompanying strength increase if subsequent rewetting is prevented. Heating to higher temperatures can result in significant permanent property improvements, including decreases in water sensitivity, swelling, and compressibility, as well as increases in strength. Burning of liquid or gas fuels in boreholes or injection of hot air into 15 to 23 mm (6 to 9 in) diameter boreholes can produce 1.22 to 2.13 m (4 to 7 ft) diameter strengthened zones after continuous treatment for about 10 days. Dry or partly saturated weak clayey soils and loess are well suited for this type of treatment which is presently regarded as experimental.

2.7.7 MISCELLANEOUS METHODS.

2.7.7.1 REMOVE AND REPLACE. Removal of poor soil and replacement with the same soil treated by compaction, with or without admixtures, or by a higher quality material, offer an excellent opportunity for producing high-strength, relatively incompressible, uniform foundation conditions. The cost of removal and replacement of thick deposits is high because of the need for excavation and materials handling, processing and recompaction. Occasionally, an expensive dewatering system also may be required. Excluding highly organic soils, pests and sanitary landfills, virtually any inorganic soil can be processed and treated so as to form an acceptable structural fill material.

2.7.7.2 LIME TREATMENT. This treatment of plastic fine-grained soils can produce high-strength, durable materials. Lime treatment levels of 3 to 8 percent by weight of dry soil are typical.

2.7.7.3 PORTLAND CEMENT. With treatment levels of 3 to 10 percent by dry weight, portland cement is particularly well suited for low-plasticity soils and sand soils.

2.7.7.4 STABILIZATION USING FILLS. At sites underlain by soft, compressible soils and where filling is required or possible to establish the final ground elevation, load-bearing structural fills can be used to distribute the stresses from light structures. Compacted sands and gravels are well suited for this application as are fly ash, bottom ash, slag and various lightweight aggregates, such as expended shale, clam and oyster shell and incinerator ash. Admixture stabilizers may be incorporated in these materials to increase their strength and stiffness. Clam and oyster shells represent a new development as a structural fill material over soft marsh deposits. The large deposits of clam and oyster or reef shells that are available in the Gulf States coastal areas can be mined and transported short distances economically. Clamshells are 19 to 38 mm (¾ to 1½ in) in diameter, whereas, oyster shells which are coarser and more elongated are 50 to 100 mm (2 to 4 in) in size. When dumped over soft ground, the shells interlock. If there are fines and water presence, some cementation develops owing to the high calcium carbonate (>90 percent) content. In the loose state, the shell unit weight is about 3 kPa (63 lbs per sq ft). After construction, it is about 4.5 kPa (95 lbs per sq ft). Shell embankments "float" over very soft ground; whereas, conventional fills would sink out of sight. An approximately 1.5 m (5 ft) thick layer is required to be placed in a single lift. The only compaction used is from the top of the lift, so that the upper several inches are more tightly knit and denser than the rest of the layer.