CHAPTER 6
COPING WITH SOIL MOVEMENTS

Section I. Minimizing and Tolerating Soil Movements

6-1. General. Development of society leads increasingly to construction on marginal (soft, expansive, collapsible) soil subject to potential volume changes. Sufficient soil exploration and tests are necessary to provide reliable soil parameters for evaluating reasonable estimates of total and differential settlement.

a. Exploratory Borings. Exploratory borings should be made within soil areas supporting the structure and sufficient tests performed to determine upper and lower limits of the soil strength, stiffness, and other required parameters. Depth of borings should be sufficient to include the significantly stressed zones of soil from overlying structures. These depths should be twice the minimum width of footings or mats with length to width ratios less than two, four times the minimum width of infinitely long footings or embankments, or to the depth of incompressible strata, whichever is least.

b. Mitigation for Excessive Deformation Potential. If analysis by methods in this manual indicates excessive settlement or heave of the supporting soil, then the soil should be improved and/or various design measures should be applied to reduce the potential volume changes and foundation movements to within tolerable limits.

c. Additional Reference. Refer to Chapter 16, TM 5-818-1, for further information on stabilization of foundation soil.

6-2. Soil Improvement. Most foundation problems occur from high void ratios, low strength materials and unfavorable water content in the soil; therefore, basic concepts of soil improvement include densification, cementation, reinforcement, soil modification or replacement, drainage, and other water content controls. A summary with description of soil improvement methods is shown in Table 6-1. The range of soil particle sizes applicable for these soil improvement methods is shown in Table 6-2. Methods that densify soil by dynamic forces such as vibro-compaction and dynamic compaction (consolidation) may lead to a temporary, short-term reduction in strength of the foundation soil.

a. Soft Soil. Soft soils have poor volume stability and low strength and may be composed of loose sands and silts, wet clays, organic soils, or combinations of these materials. Most of the methods listed in Table 6-1 and 6-2 are used to minimize settlement in soft soil. Applicability of these methods depends on economy; effectiveness of treatment in the existing soil; availability of equipment, materials, and skills; and the effect on the environment such as disposal of waste materials. Some of the more useful methods for improving soft soil are described in more detail below.

(1) Removal by excavation. Soft soil underlain by suitable bearing soil at shallow depths (less than 20 ft) may be economical to remove by excavation and replace with suitable borrow material or with the original soil after drying or other treatment. Compacted lean clays and sands (if necessary, with chemical admixtures such as lime, flyash and/or portland cement) is an adequate replacement material if the water table is below the excavation

Table 6-1

Soil Improvement Methods (Includes Data from Item 10)

Method	Principle	Most Suitable Soils and Types	Maximum Effective Treatment, Depth, ft	Advantages and Limitations
		Vibrocompaction		
Blasting	Shock waves cause liquefaction, displacement, remolding	Saturated, clean sands, partly saturated sands and silts after flooding	60	Rapid, low cost, treat small areas, no improvement near surface, dangerous,
Terraprobe	Densify by vertical vibration, liquefaction induced settlement under overburden	Saturated or dry clean sand (less effective in finer sand)	60 (ineffect- above 12-ft depth)	Rapid, simple, good under water, soft underlayers may damp vibrations, hard to penetrate overlayers
Vibratory rollers	Densify by vibration, liquefaction induced settlement under roller weight	Cohesionless soils	6 to 9	Best method for thin layers or lifts
Dynamic compaction (consolidation) or heavy tamping	Repeated high intensity impacts at the surface gives immediate settlement	Cohesionless soils best, other soils can be improved	45 to 60	Simple, rapid, must protect from personal injury and property damage from flying debris; groundwater must be > 6 ft below surface faster than preloading but less uniform
Vibroflotation	Densify by horizontal vibration and compaction of backfill material	Cohesionless soil with less than 20 percent fines	90	Economical and effective in saturated and partly saturated granular soils

Table 6-1. Continued

Method	Principle	Most Suitable Soils and Types	Maximum Effective Treatment, Depth, ft	Advantages and Limitations
Hydro-compaction	Densify by vibration or repeated impact on surface of prewetted soil	Collapsible soil	< 10	Most effective method to densify silty loose collapsible sands
		Compaction Piles		
Compaction Piles	Densify by displacement of pile volume and by vibration during driving	Loose sandy soils, partly saturated clayey soils, loess	60 (limited improvement above 3 to 6)	Useful in soils with fines, uniform compaction, easy to check results, slow
Sand Compaction Piles	Sand placed in driven pipe; pipe partially withdrawn and redriven using vibratory hammer	All	-	Compressed air may be used to keep hole open as casing partially withdrawn
		Precompression		
Preloading	Load applied sufficiently in advance of construction to precompress soil	Normally consolidated soft clays, silts, organic deposits, landfills	-	Easy, uniform, long time required (use sand drains or strip drains to reduce time)
Surcharge Fills	Fill exceeding that required to achieve a given settlement; shorter time; excess fill removed	Same as for preloading	-	Faster than preloading without surcharge (use sand or strip drains to reduce time
Electro-osmosis	DC current causes water flow from anode towards cathode where it is removed	Normally consolidated silts and clays	30 - 60	No fill loading required; use in confined areas; fast; nonuniform properties between electrodes; useless in highly pervious soil

Table 6-1. Continued

Method	Principle	Most Suitable Soils and Types	Maximum Effective Treatment, Depth, ft	Advantages and Limitations
		Reinforcement		
Mix-in-place Piles and Walls	Lime, cement or asphalt placed by rotating auger or in-place mixer	All soft or loose inorganic soils	> 60	Uses native soil; reduced lateral support required during excavation; difficult quality control
Strips and Membranes	Horizontal tensile strips or membranes buried in soil under footings	All	< 10	Increased allowable bearing capacity; reduced deformations
Vibro-replacement Stone	Hole jetted in soft, fine-grain soil and back-filled with densely compacted gravel	Very soft to firm soils (undrained strength 0.2 to 0.5 tsf)	60	Faster than pre-compression; avoids dewatering required for remove and replace; limited bearing capacity
Vibro-displacement Stone	Probe displaces soil laterally; backfill discharged through probe or placed in layers after probe removed	Soft to firm soils (undrained strength 0.3 to 0.6 tsf)	50	Best in low sensitivity soils with low ground-water
		Grouting and Injection		
Particulate Grouting	Penetration grout fills soil voids	Medium to Coarse sand and gravel	Unlimited	Low cost; grout high strength
Chemical Grouting	Solutions of 2 or more chemicals react in soil pores to form gel or soil precipitate	Medium silts and coarser	Unlimited	Low viscosity; controllable gel time; good water shutoff; high cost; hard to evaluate

Table 6-1. Continued

Method	Principle	Most Suitable Soils and Types	Maximum Effective Treatment, Depth, ft	Advantages and Limitations
Pressure Injected Lime and lime-flyash	Lime slurry and lime-flyash slurry injected to shallow depths under pressure	Expansive clays, silts and loose sands	Unlimited (usually 6 to 9)	Rapid and economical for foundations under light structures; flyash with lime may increase cementation and strength and reduce permeability
Displacement or compaction grout	Highly viscous grout acts as radial hydraulic jack when pumped under high pressure	Soft, fine grained soils; soils with large voids or cavities	40	Corrects differential settlement; fills large voids; requires careful control
Jet grouting	Cement grouts injected to replace and mix with soils eroded by high pressure water jet ("soilcrete column)	Alluvial, cohesive, sandy, gravelly soils, miscellaneous fill and others	Unlimited	Increases soil strength and decreases permeability; wide application
Electrokinetic Injection	Stabilizing chemicals moved into soil by electroosmosis	Saturated silts; silty clays	Unknown	Soil and structure not subject to high pressures; useless in pervious soil
		Miscellaneous		
Remove and Replace	Soil excavated, replaced with competent material or improved by drying or admixture and recompacted	Inorganic soil	< 30	Uniform; controlled when replaced; may require large area dewatering

Table 6-1. Concluded

Method	Principle	Most Suitable Soils and Types	Maximum Effective Treatment, Depth, ft	Advantages and Limitations
Moisture Barriers	Water access to foundation soil is minimized and more uniform	Expansive soil	15	Best for small structures and pavements; may not be 100 percent effective
Prewetting	Soil is brought to estimated final water content prior to construction	Expansive soil	6	Low cost; best for small, light structures; soil may still shrink and swell
Structural Fills	Structural fill distributes loads to underlying soft soils	Soft clays or organic soils; marsh deposits	-	High strength; good load distribution to underlying soft soils

line. Granular material such as sand, slag, and gravel should be used if the water table is above the bottom of the excavation. Additional mechanical compaction may be accomplished with vibratory or dynamic methods, Table 6-1.

(2) Precompression. Precompression densifies the foundation soil by placing a load or surcharge fill, usually a weight that exceeds the permanent structure load, on the site. The preload should eliminate most of the post-construction primary consolidation and some secondary compression and increase the soil strength.

(a) For embankments, additional fill beyond that required to construct the embankment is usually placed.

(b) For foundations other than earth structures, the preload must be removed prior to construction.

(c) Time required for preload may sometimes be appreciably reduced by sand or prefabricated vertical (PV) strip drains to accelerate consolidation of thick layers of low permeability. PV drains commonly consist of a filter fabric sleeve or jacket made of nonwoven polyester or polypropylene surrounding a plastic core. The drain is inserted into the soil using an installation mast containing a hollow mandrel or lance through which the drain is threaded. An anchor plate is attached to the end of the drain. Theoretical estimates of the rate of settlement are largely qualitative unless prior experience is available from similar sites because the analysis is sensitive to soil input

Table 6-2

Range of Particle Sizes For Various Soil Improvement Methods

<table>
<tr><th colspan="2">GRAVEL</th><th colspan="2">SAND</th><th colspan="2">SILT</th><th colspan="2">CLAY</th></tr>
<tr><td colspan="3">PARTICULATE GROUTING</td><td colspan="5"></td></tr>
<tr><td colspan="4">VIBRATORY ROLLERS</td><td colspan="4"></td></tr>
<tr><td colspan="5">VIBROFLOTATION</td><td colspan="3"></td></tr>
<tr><td colspan="5">COMPACTION PILES</td><td colspan="3"></td></tr>
<tr><td colspan="5">CHEMICAL GROUTING</td><td colspan="3"></td></tr>
<tr><td colspan="6">DYNAMIC COMPACTION</td><td colspan="2"></td></tr>
<tr><td colspan="8">SAND COMPACTION PILES, JET GROUTING</td></tr>
<tr><td colspan="2"></td><td colspan="2">TERRAPROBE</td><td colspan="4"></td></tr>
<tr><td colspan="2"></td><td colspan="4">BLASTING</td><td colspan="2"></td></tr>
<tr><td colspan="3"></td><td colspan="5">COMPACTION GROUT</td></tr>
<tr><td colspan="3"></td><td colspan="5">STONE COLUMNS</td></tr>
<tr><td colspan="4"></td><td colspan="4">PRELOADING, SURCHARGE FILLS</td></tr>
<tr><td colspan="4"></td><td colspan="4">LIME STABILIZATION</td></tr>
<tr><td colspan="4"></td><td colspan="4">ELECTROKINETIC INJECTION</td></tr>
<tr><td colspan="4"></td><td colspan="4">ELECTROOSMOSIS</td></tr>
</table>

parameters, particularly the coefficient of consolidation and existence of pervious bands of soil. Strip drains have largely replaced sand drains in practice.

(3) Stone or chemically stabilized soil columns. Columns made of stone or chemically stabilized soil increase the stiffness of the foundation and can substantially decrease settlement. Columns may fail by bulging if the adjacent soil gives inadequate support or fail by shear as a pile because of insufficient skin friction and end bearing resistance.

(a) Stone columns are made by vibroreplacement (wet) or vibrodisplacement (dry) methods, Table 6-1. Diameters range from 1.5 to 4 ft with spacings from 5 to 12 ft. A blanket of sand and gravel or a semirigid mat of reinforced earth is usually placed over stone column reinforced soil to improve load transfer to the columns by arching over the in situ soil. Stone columns are not recommended for soils with sensitivites greater than 5.

(b) Lime columns are made by mixing metered or known amounts of quicklime using drilling rigs to achieve concentrations of 5 to 10 percent lime by weight of dry soil. Structures are constructed on thin concrete slabs where settlement is assumed uniform over the entire area.

(c) Cement columns are made by adding 10 to 20 percent cement as a slurry. These columns are brittle, have low permeability, and have been used below sea level.

(4) Jet grouting. Jet grouting is the controlled injection of cement grouts to replace most any type of soil; this soil is eroded by water jets while grouting. The most common application has been underpinning of existing structures to reduce total and differential settlement and as cutoff walls for tunnels, open cuts, canals, and dams. Jet grouting may also be used to consolidate soft foundation soils for new structures, embankments, and retaining walls. Other applications include support of excavations for open cuts and shafts and slope stabilization.

(a) Jet grouting can either break up the soil and mix grout with the natural soil particles or break up the soil, partially remove the soil, and mix grout with the remaining soil particles.

(b) Jet grouting can substantially increase the strength and stiffness of soft clay soil to reduce settlement and substantially reduce the permeability of sandy soil.

(c) Jet grouting is generally used with rapid set cement and with fly ash. Fly ash when mixed with cement or lime produces a cementatious material with excellent structural properties. Other chemicals may be used instead of cement.

(d) A single jet nozzle can be used to both break down the soil structure and force mixing of grout with the natural soil. A water jet can also be sheathed in a stream of compressed air to erode the soil while a grout jet beneath the water jet replaces the broken or disturbed soil. Diameter and discharge pressure of the nozzles, withdrawal and rotation rates, type and quality of grout, and soil type influence volume and quality of the grouted mass. Withdrawal rates and nozzle pressures are the primary design factors. Withdrawal rates vary from 1 to 50 inches/minute and nozzle pressures often range from 3000 to 9000 psi depending on the type of soil.

(5) Dynamic compaction (Consolidation). Weights from 5 to 40 tons and more may be dropped from heights of 20 to 100 ft following a particular pattern for each site. The impact appears to cause partial liquefaction of granular deposits, thereby allowing the soil to settle into a more dense state.

(6) Removal by displacement. Sufficient cohesionless fill is placed to cause bearing failures in the underlying soft soil. The soft soil is displaced in the direction of least resistance, which is usually ahead of the embankment fill. The displaced soil causes a mudwave that should be excavated at the same rate that the embankment is placed to minimize trapping pockets of soft soil beneath the embankment.

(7) Lightweight fills. Sawdust, expanded foam plastic blocks, expanded shale or clay, oyster shell, and fly ash fills can partially replace excavated heavier soft material and reduce the net increase in pressure on underlying soft soil. The availability of lightweight fill in sufficient quantity at reasonable cost and suitable locations to dispose of the excavated soft soil limit application of this method.

(8) Structural (Self-supporting fills). Some naturally occurring materials such as dead oyster shell can form a barge-like structure from particle interlocking. Fills of loose shell have been used for highway embankments and foundations for flexible facilities such as warehouses on marsh and swamp deposits.

(9) Blasting. Cohesionless, saturated sands (less than 25 percent passing the 200 mesh) are most responsive to densification by the detonation of dynamite charges in loose deposits. Soft soils that can be liquefied or displaced by advancing fill can be removed by blasting for embankment construction. Soft soils may be displaced by blasting or toe shooting in front of the embankment. The extent of soil improvement by blasting is often uncertain.

(a) The underfill method, where backfill is placed on top of soft soil and explosives are placed under the embankment by lowering down casing into the soft deposits, is most effective when the embankment width is less than 60 ft.

(b) The ditching method, where fill is placed immediately into excavations made by blasting, is effective for depths of soft soil less than 15 ft.

(c) The relief method may be useful where ditches are blasted along each side of the embankment to provide lateral stress relief and force soft shallow soil to move laterally into the ditches.

b. Expansive Soil. Potentially expansive soils are usually desiccated and will absorb available moisture. These soils can be made to maintain volume changes within acceptable limits by controlling the soil water content and by reducing the potential of the soil to heave. Methods for improving the performance of foundations in expansive soil are illustrated in Table 6-3.

c. Collapsible Soil. Collapsible soils settle when wetted or vibrated; therefore, the usual approach toward optimizing performance of structures on collapsible soil is prewetting the construction site. Hydrocompaction (see Table 6-1) of the site prior to construction is commonly recommended. Chemical stabilization with lime, sodium silicate, or other chemicals is not always successful. Methods applicable to improving performance of structures on collapsible soil are illustrated in Table 6-4.

Table 6-3

Improving Performance in Expansive Soil

Method	Description
Removal by excavation and replacement with non-expansive fill	Removal of surface expansive soil to depths of from 4 to 8 ft and replacement with compacted nonexpansive fill usually eliminates most potential soil heave because the depth of moisture change is often limited to about 8 ft.
Placement of vertical moisture barriers	Vertical moisture barriers placed adjacent to pavements or around the perimeter of foundations down to the maximum depth of moisture changes is effective in maintaining uniform soil moisture within the barrier. Differential movements are minimized. Long-term soil wetting with uniform heave beneath impervious foundations may occur from lack of natural evapotranspiration
Lime stabilization	Lime injected or mixed into expansive soil can reduce potential for heave by reducing the mass permeability thereby reducing amount of water seeping into the soil, by cementation, and by exchange of sodium for calcium ions. Fissures should exist in situ to promote penetration of lime injected slurry. Lime may be detrimental in soils containing sulfates.
Potassium injection	Potassium solutions injected into expansive soil can cause a base exchange, increase the soil permeability and effectively reduce the potential for swell.
Prewetting	Free water is added by ponding to bring soil to the estimated final water content prior to construction. Vertical sand drains may promote wetting of subsurface soil.
Surcharge	Placing 1 or 2 ft or more of permanent compacted fill on the surface of a level site prior to construction increases the overburden pressure on the underlying soil reducing the negative (suction) pore water pressure; therefore, the potential for swell is less and tends to be more uniform. This fill also increases elevation of the site providing positive drainage of water away from the structure.

6-3. Foundation Techniques. Foundation design and construction methods can minimize soil volume changes and differential movement.

a. Floating Foundations. Foundation elements such as mats and footings can be placed in excavations of sufficient depth where the pressure applied by the structure to the underlying foundation soil approximately balances pressure applied by the excavated soil. Observed deformation will be elastic re-

Table 6-4

Improving Performance of Collapsible Soil

Depth of Soil Treatment, ft	Description
0 to 5	Wetting, mixing, and compaction
> 5	Overexcavation and recompaction with or without chemical additives such as lime or cement
	Hydrocompaction
	Vibroflotation
	Lime pressure injection
	Sodium silicate injection
	Prewetting by ponding; vertical sand drains promote wetting of subsurface soil

compression settlement. The exposed soil in the bottom of the excavation must be protected from disturbance and deterioration.

b. Ribbed Mats. Slab foundations supported by a grid of stiffening beams can transfer structural loads to soil of adequate stiffness and bearing capacity. The stiffness of ribbed mats also reduces differential movement in expansive soil. The depth of stiffening beams normally does not exceed 3 ft. Ribbed mats supported on compacted cohesive nonexpansive fills are commonly constructed in expansive soil areas.

c. Leveling Jacks. Structures may be supported by jacks on isolated footings in which the elevation can be periodically adjusted to reduce distress from excessive differential movement. Proper adjustment of leveling jacks requires periodic level surveys to determine the amount and direction of adjustment, whether up or down, and frequency of adjustment to minimize differential movement. Leveling jacks are usually inconvenient to owner/operators of the structure.

d. Deep Foundations. Structural loads can be transferred to deep, firm bearing strata by piles or drilled shafts to eliminate or minimize effects of shallow soil movements on structural performance. Uplift thrust from skin friction on the perimeter of deep foundation piles or drilled shafts in expansive soil or downdrag in consolidating or collapsing soil should be considered in the design. Refer to TM 5-809-7, Design of Deep Foundations, for further details.

e. Construction Aids for Excavations. Settlement or loss of ground adjacent to excavations may become excessive. Cause of loss of ground include lateral rebound of perimeter walls into the excavation, rebound at the bottom of the excavation, and dewatering. Damage may occur in adjacent structures including pavements and utilities if loss of ground exceeds 0.5 inch or lateral movement of perimeter walls into an excavation exceeds 2 inches. Level readings should be taken periodically to monitor elevation changes so that steps may be taken to avoid any damage. Construction aids include placement of bracing or retaining walls, placement of foundation loads as quickly as possible after the excavation is made, avoidance of ponding of water within excavations, and ground freezing. Load bearing soils at the bottom of the excavation must be protected from deterioration and water content changes following exposure to the environment. Ground freezing provides temporary support and groundwater control in difficult soils and it is adaptable to most size, shape, or depth of excavations. Ground freezing is accomplished by circulating a coolant, usually calcium chloride brine, through refrigeration pipes embedded in the soil. Refer to TM 5-818-5/AFM 88-5, Chapter 6, for details on dewatering and groundwater control.

6-4. Flexible Techniques. Structures may be made flexible to tolerate differential movement by placing construction joints in the superstructure or by using flexible construction materials. Steel or wood frames, metal siding, wood paneling, and asphalt floors can tolerate large differential settlements or angular distortions up to about 1/150.

Section II. Remedial Methods

6-5. General. Remedial work for damaged structures is often aggravated because it is difficult to determine the cause of the problem (e.g., location of source or loss of soil moisture with swelling or settling of expansive/collapsible soil may not be readily apparent). Investigation and repair are specialized procedures that usually require much expertise and experience. Cost of repair work can easily exceed the original cost of the foundation. Repair of structures in heaving soil is usually much more costly than in settling soil. Structures are less able to tolerate the tensile strains from heaving soil than the compressive strains in settling soil. The amount of damage that requires repair also depends on the attitudes of the owner and effected people to tolerate distortion and consequences if the distortion and damage are ignored. Only one remedial procedure should be attempted at a time after a course of action has been decided so its effect on the structure may be determined. Several common remedial methods are discussed below. Refer to TM 5-818-7, Foundations in Expansive Soils, for further details on remedial methods for foundations.

6-6. Underpinning with Piles. Underpinning may be accomplished by a variety of methods: drilled-in-place tangent piles, cast-in-place rigid concrete slurry walls, precast concrete retaining walls, root or pin piles, concrete underpinning pits, and jacked steel piles. Selection of the underpinning method depends on the nature of the subgrade soil and its expected behavior during underpinning. Refer to TM 5-809-7, Deep Foundations, for details on piles.

a. Avoid Ground Loss. Possibility of ground loss during installation may eliminate use of tangent piles, slurry walls, and precast concrete retaining walls.

b. Interference with Utilities. Underground utilities may eliminate use of piles or cast-in-place concrete shafts.

6-7. Grouting. Structures may be stabilized by injecting portland cement, fine soil, and chemicals into the problem soil. Grouting mixtures usually consist of fine soil, portland cement, and water; lime and water; sodium silicate; calcium chloride; polymers; and resins. Jet and compaction grouting, for example, reduce differential settlement of structures. Compaction grouting can raise a structure that has settled. The stiffness and strength of the soil may be increased by injecting a grout containing additives such as portland cement to improve the performance of the soil. Compaction grouting may use 12 to 15 percent by weight of portland cement mixed with soil and water to make a viscous, low slump grout that is to be pumped into bored holes at pressures up to 500 psi. Refer to TM 5-818-6, Grouting Methods and Equipment; EM 1110-2-3504, Chemical Grouting; and EM 1110-2-3506, Grouting Technology, for details on grouting.

6-8. Slabjacking. Slabjacking, the lifting or leveling of distorted foundations, is usually faster than other solutions for remedial work. Grouting materials include portland cement, hydrated lime, fly ash, asphalt bitumen, drilling mud, casting plaster, and limestone dust. Consistency of the grout varies from less commonly used thin fluids to more common heavy pourable or stiff mortar-like mixtures (with nearly zero slump). Cement contents vary from 3 to 33 percent with sand or soil materials all passing the No. 16 sieve. Leakage from joints and along the edges of slabs can present serious problems, which are commonly offset by increasing the consistency of the grout. Lifts of as much as 1 ft are common. Properly performed slabjacking will not usually cause new fractures in the foundation, but existing cracks tend to open. Experience is required to cause low points to rise while maintaining high points at a constant elevation.