of Public Works for the use of their manuals in the preparation of this chapter. William P. Hofmann, Deputy Chief Engineer for Technical Services (retired) of the New York State Department of Transportation, provided the information in the section on Cold Weather Construction. The comments of the reviewers and editors were also helpful in completing this chapter.

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ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
FHWA	Federal Highway Administration

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5

Drainage

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Water affects many aspects of earthwork construction. In the vicinity of the construction area, surface or subsurface water needs to be controlled by some type of drainage system. Controlling usually means removing, but there are some instances in which water is needed to facilitate construction, for example, to increase compaction efficiency (Chapters 3 and 4) or to maintain vegetative growth (Chapter 8).

Controlling water on the construction site is one of the contractor's major concerns, but it tends to be neglected because often the drainage work is not a pay item. However, good drainage helps the contractor produce a more acceptable project; therefore, the contractor's profit should be increased. A job that controls erosion and stays out of the mud is much easier to run and much more efficient. Drainage is important because

1. Soils that are too wet or too dry cannot be efficiently compacted to specified densities.
2. Most soils lose strength when they are wet, that is, above optimum moisture, and both the stability of cut and fill slopes and the operation of equipment at the construction site are adversely affected.
3. Erosion can damage adjacent property.

BASIC DRAINAGE PRINCIPLES

The basic principles of drainage are as follows:

1. Water runs downhill.
2. Gravity is cheaper than plumbing.
3. Erosion depends on water velocity.
4. Erosion problems are easier to prevent than to fix later.

The aspects of drainage that affect earthwork construction are discussed in this chapter. Included are control of erosion of side slopes, ditches, and the basins at the ends of culverts; sedimentation control measures, including detention ponds; and subsurface water and underdrains.

SURFACE WATER

It is important to remove surface water from the embankments as quickly as possible to prevent it from being absorbed by the near-surface materials. Surface waters should also be controlled to prevent erosion, and if erosion occurs in spite of attempts to prevent it, the eroded soil particles should be encouraged to settle out of the runoff. The plans and specifications will almost always include permanent surface water control features (primarily ditches) to protect the finished facility; however, additional surface drainage systems will also be needed during construction. These as well as all other drainage items should be put in place as soon as possible, as they will simplify subsequent construction.

The area surrounding the site should also be considered because it may be possible to check erosion by retarding the flow of water onto the site or to prevent any water from encroaching on the site. This may not be easy to do on roadway widening projects, however. Runoff from the existing pavement and changes to drainage systems often make the problem worse on existing pavement than on new construction. It is false economy to allow slopes or drainage paths to erode badly, even though the contractor may be required to pay later for repairs as well as stabilization (HRB 1952).

Erosion

The detrimental effects of erosion can be minimized by understanding the erosion process and taking prompt and correct remedial action. The amount of erosion that takes place depends on (a) the velocity of the water that flows over the surface, (b) the type of soil or material that the water flows over, and (c) the vegetative cover. The relationship between the velocity of water and erosion is very important. Doubling the velocity of water will increase its erosive energy by four times, the size of particle that can be carried by 64 times, and the mass of soil that can be transported by 32 times (Israelson, 1980a). Thus, if job site erosion is to be prevented, certain characteristics that affect velocity must be kept in mind:

1. Slope—the steeper the slope, the faster water will flow.

2. Roughness of the slope channel—the smoother the channel, the faster water will flow.
3. Depth of flow—the deeper the flow over a surface, the faster it will flow.
4. The shape of the flow channel—the smaller the channel surface area in contact with the water, the faster the flow.
5. Quantity of flow—the larger the quantity, the faster the flow.

These characteristics lead to the prime rule of erosion control: do not allow water to concentrate; keep it dispersed whenever and wherever possible.The erodibility of a slope also depends on the type of soil and vegetation cover. Loose noncohesive soils tend to be more prone to erosion than dense cohesive soils. Fine sands and silts are the most erodible. Vegetation tends to decrease soil erodibility.

The contract plans and specifications will detail any required erosion control measures. The basic philosophy of some of the more common erosion control measures is explained in the sections that follow.

Control of Erosion on Side Slopes

The most critical time for slope erosion is immediately after the start of excavation or embankment construction. The soil on the surface is loose and is exposed to rainfall, and vegetation has not yet taken hold. A typical raindrop travels about 19 mph, and when it hits the soil surface, it displaces unprotected soil particles and starts washing them downslope (FHWA 1976; Israelson 1980a). The following measures should be taken to prevent side slope erosion:

1. Protect the newly exposed slope from the high velocity impact of raindrops. This should be done as soon as possible; one short, intense rainfall can ruin a well-designed and constructed slope. The most common method of dissipating the energy on newly exposed soils is by mulching. The mulch absorbs the impact energy and breaks up the raindrops. Common types of mulch are hay or straw, wood chips, crushed stone, and geotextiles. Details on the quantities of mulch to use can be found elsewhere (Israelson 1980b; CCSWC 1985).
2. Do not permit excessive quantities of water from outside the construction area to flow down cut slopes. Top-of-slope ditches are an important preventive measure (see Chapter 4, section on Slope Ditches). They should be put in promptly, as the slope is most vulnerable immediately after construction. Top-of-slope ditches need to be handled carefully,

however, as they tend to be quite steep (ditch erosion is discussed in the next section.

3. Keep the side slopes as flat as possible. (Cuts in rock, loess, or other lightly cemented permeable soils are exceptions.)

4. Be sure that the water arrives on the slope in a sheet and keep it in a sheet as long as possible. This is done by constructing continuous flat or slightly rounded slopes. Eventually adjacent slopes will intersect and the water will have to be concentrated into a ditch or stream, preferably under controlled conditions.

5. Establish a dense growth of grass or other vegetation as soon as possible. Vegetation slows down the water and lowers the erodibility of the slope surface. Mulching (Item 1) protects the slope and the seed or seedlings until the vegetation takes hold. After the vegetation is established, it ordinarily will dissipate the energy of raindrops.

Control of Erosion in Ditches

The following precautions should be taken to control erosion in ditches:

1. Ditches should carry no more water than necessary. Adjacent land owners should solve their own drainage problems, if possible.
2. Ditches should carry water only as far as necessary.
3. Avoid changes in direction of flow in a ditch. Use pipes for high flows and sharp turns.
4. Do not allow water to fall into a ditch. It should enter the ditch with as little impact as possible. Check dams can be engineered to handle large flows, but drop inlets into pipes or erosion protection linings are more appropriate for small ditches.
5. Do not allow water to pond in a ditch. When this happens the ditch is not carrying out its intended drainage function.

Well-sodded ditches should be used whenever possible; however, sod needs sun and cannot be maintained in channels that approach continuous flow. Also, it may not be practical or cost effective to sod a ditch during construction.

The factors that affect the velocity of flow in ditches are the same as those mentioned previously: (a) slope, (b) ditch roughness, (c) depth of flow, (d) ditch shape, and (e) quantity of flow. Slope is difficult to control because it is dictated by the geometry of the site. Nevertheless, slopes between about 0.5 and a maximum of about 2 percent should be maintained wherever possible.

Roughness of the ditch helps to decrease velocity at low flows, but it is not as effective at high flows. The quantity and depth of flow and the ditch shape are all interrelated. The general rule is to have wide flat ditches and keep them as short as possible.

If after everything else has been considered, the water is still eroding the natural ditch lining, then an alternative lining is needed. One of the most effective linings for small ditches is a geotextile, either natural (jute) or synthetic. This design, if well constructed, will tolerate about the same water velocities as grass sod.

Stabilizing Eroded Ditches

Fast-flowing water in a ditch or stream is always turbulent, and this produces large traction forces that dislodge material from the stream bed and carry it downstream. A natural stream develops a filter system of successively smaller particles below the stream bed, which is relatively stable at normal flow velocities. Given time, ditches will also develop these same filter systems, but usually by the time a construction ditch stabilizes, large gullies or other problems will have occurred. By constructing a filter system using natural aggregate materials or aggregate materials and geotextiles, it is possible to stabilize an eroding ditch.

To be successful, filter systems must have the following characteristics:

1. The aggregate or stones in the top layer must be large enough to resist the water traction forces.
2. The particles in each successive lower layer are smaller than those in the layer above, but they are too large to pass through the voids in the layer above it.
3. Each layer must allow water to freely pass through it.

In many cases a two-layered system is all that is needed, although sometimes three aggregate layers are required. Geotextiles can be used in place of one or more of the finer filter aggregate layers (Christopher and Holtz 1985), but for permanent installations, the geotextile may need to be protected by a layer of gravel between it and large stones on the ditch bed. Riprap used to protect stream beds and slopes adjacent to water bodies require granular filters or geotextiles and should be constructed accordingly.

Culvert and Pipe Outlets

Because water leaving culvert and pipe outlets is concentrated and usually traveling at velocities that will erode the natural stream bed, these features are of particular concern. In most cases, construction of a filter system that includes riprap from the outlet to a point downstream where the stream velocity is harmless will solve the problem.

In severe cases, stilling basins together with filters are needed. Care must be taken to protect the natural material at the edges of stilling basins until water velocities become tolerable. Placing large rocks or riprap at the ends of pipes (or in other parts of a stream bed that is experiencing erosion problems) without providing a filter underneath is not the way to solve the problem. Eventually the stream will form its own stilling basin and filter, but usually this will not happen until after some detrimental erosion has occurred.

SEDIMENT CONTROL

Sediment is the soil material that settles out of a dilute mixture of soil and water. Sediment will separate from the water when the velocity is slowed to a level that will no longer carry or move the soil particles. Environmental Protection Agency regulations require that material that has been eroded on a construction site must be retained within the bounds of the construction area.

Sedimentation control is needed on a construction site because of the inability of the contractor's erosion control practices to prevent all erosion. Sedimentation of material from water is not necessarily easy, and it is usually false economy to allow erosion to take place and then try to recover the materials.

All sedimentation control facilities must perform three functions: (a) decrease the velocity of the water to a level that will allow the suspended material to settle, (b) retain the water for a sufficient time for settling to take place, and (c) release the water without causing erosion or flooding downstream.

Because sedimentation control measures must decrease the velocity of the water in a stream or ditch, the size and extent of the facilities required are directly related to the quantity and duration of flow. The simplest sedimentation control measures, straw bales and geotextile silt fences, can be used on smaller swales and ditches when the flow is intermittent. Larger continuous flowing ditches or streams require detention ponds and barrier structures, as discussed in the next section.

Straw bales and silt fences are not complicated structures, but to function successfully they must be properly constructed and maintained. These barriers are designed to allow the water to seep through the material. Water must not be allowed to flow around the edges or under silt barriers, or flow over the top in a concentrated high velocity flow. The channel downstream of the barrier should be constructed to carry the flow without allowing further erosion to take place. The ditch section just beyond the silt barrier may need erosion protection similar to that used at culvert outlets.

Any required periodic maintenance should be detailed in the contract specifications. For example, to ensure that the velocity is slowed and that there is sufficient storage in case of a storm, the backwater area must be cleaned if the deposited material comes halfway up the height of the barrier. Any damage or displacements in the barriers should be repaired immediately. Clogged barriers should be replaced.

Detention ponds should be treated as major features, and the plans and specifications for the barriers should be followed closely. The barrier is a dam and should be designed and constructed as such. Failures of these structures could cause major downstream damage. Areas of particular concern are

1. *Construction of the embankment.* Density and material requirements for different parts of the structure should strictly follow the plans and specifications.
2. *Location and construction of the emergency spillway.* This is essentially a large steep ditch and the necessity of including a good filter system cannot be overemphasized. Failures of spillways can cause rapid erosion and loss of the retention structure. A stilling basin or other method of dissipating the energy of fast flowing water is needed at the base of the spillway to reduce the velocity of the discharge to the receiving stream.
3. *Installation of pipe conduits that extend through the embankment and act as a spillway and pond drain.* Because a pipe through an embankment is a major discontinuity, seepage between the embankment and the pipe is a potential source of failure. It must be controlled by the careful compaction of select material around the pipe and by the installation of seepage collars at specified lengths along the pipe.

SUBSURFACE WATER

The emergence of subsurface water is of concern on the construction site because it affects the strength and load-carrying capacity of the soil; it is a factor in almost all failures of soil slopes and excavations. Because the original source of the subsurface water is rain that has fallen somewhere upslope of the site, careful observation of the area surrounding the site will usually indicate the source of the subsurface water problem.

Underdrains

Subsurface water is generally removed with underdrains such as trench or French drains. Although these drains are easy to design, they are difficult to construct without segregation of the granular filter or contamination of the filter and drain aggregate. As a result they are often not as effective as they should be.

Today, most underdrains are constructed using either geotextiles to replace the graded granular filter materials or with prefabricated geocomposite drains, which greatly simplify construction operations. To ensure that the geotextile or geocomposite will work as designed, however, several important points must be kept in mind when installing them. They should be protected from dirt and contamination, exposure to sunlight, and damage during shipping and storage. Installation and backfilling must be carefully done to avoid tearing or puncturing the geotextile. If the drain is a geocomposite, care must be taken to avoid damaging the core. Finally, the drainpipe and its outlets must be properly located. See *Geotextile Engineering Manual* (Christopher and Holtz 1985) for additional information about using geotextile filters and geocomposites in underdrains.

Common Subsurface Drainage Problems

Sometimes unanticipated subsurface water problems occur during construction or maintenance. For example, shallow slope failures can occur because of subsurface water seeping from a slope or moving parallel to and near its surface. Three possible solutions are

1. Install one or more subsurface drains to lower the groundwater surface. These drains may also help to prevent deeper slope failures. A drain at or near the ditch line will also tend to increase the strength of the roadway subgrade.
2. After undercutting, place a thick blanket of stone or rock on the slope. Although this will help to prevent shallow slope failures, it will not increase the strength of the roadway subgrade nor will it help prevent deeper slope failures.
3. Flatten the slope so that the wet slope is stable.

If the roadway is unstable because of free water at or near the surface, often it is possible to solve this problem by crowning the roadway and constructing deeper side ditches to remove the surface water and to lower the water table below the roadway. After crowning the roadway and constructing side ditches, subsurface drains can be installed to further lower the water table. It may not be necessary to install these drains on both sides of the roadway. This method may be too slow to be helpful on a construction job because it may take too long to actually lower the water table. However, over the long term, this installation may be necessary to ensure a more stable roadway foundation. In this case, request advice from the engineer.

Another solution would be to install a geotextile and aggregate surface on the crowned and ditched roadway. This will permit the water to drain from the subgrade while preventing the subgrade material from intruding into the coarse stone subbase layers. The aggregate layers must be permeable so that they will remain stable when wet. Note that these solutions assume that corrective action can be taken without changing the grade of the roadway. If this is impossible, see Chapter 4, section on Unsuitable Materials.

If an excavation for a structure foundation is unstable because the original groundwater table is above the bottom of the excavation, side ditches can be constructed around the periphery of the excavation to lower the water table. The ditches must drain to a sump where the water can be pumped from the excavation.

A geotextile-aggregate mat thick enough to provide a stable working surface can be installed. The peripheral ditches with the sump pump are also needed. The aggregate mat needs to be permeable to internally drain water to the peripheral ditches and to remain stable when wet.

Well points around the periphery of the base can be installed to lower the free water surface to produce a stable base. The required spacing, usually between 3 and 12 ft, depends on the type of soil and the desired depth of groundwater lowering (Cedergren 1989). Again, these solutions assume no change in the elevation of the bottom of the structure foundation.

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ABBREVIATIONS

CCSWC	Connecticut Council on Soil and Water Conservation
FHWA	Federal Highway Administration

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6

Embankment Foundations

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New roads are increasingly being located on poor foundation soils. Thus, comprehensive geotechnical embankment foundation design studies are required to identify and solve potential stability, settlement, and construction problems. The results of these studies are normally incorporated into the construction plans and specifications.

The success of a foundation design is generally judged by embankment performance, although rate and cost of construction may also be important factors. Performance is reflected in pavement rideability, which includes smooth transitions at structures, effects on buried utilities, and frequency of maintenance required during the design life of the roadway. These postconstruction factors are dependent on the amount and rate of settlements, assuming that foundation stability requirements are met satisfactorily during construction. The success of an embankment construction project is directly proportional to the design and construction effort, and it requires good predictions of the behavior of the foundation in response to the applied loads.

With proper specification and construction controls (Chapter 4), incidences of faulty embankment construction are rare. Poor embankment performance is usually a consequence of unexpected variations in subsurface or foundation conditions, inadequate design for site-specific soil conditions, or in cases where a proper foundation design was provided for in the contract documents, lack of strict adherence to the construction specifications.

Project design starts with a preliminary site evaluation. Next, exploratory borings and sampling are conducted, followed by a laboratory testing program, design analyses, and design report. Finally, recommendations for foundation treatment, if any, are incorporated into the contract plans and specifications.

This chapter contains background information on embankment foundation design as it affects construction operations and inspection procedures. Briefly discussed are the several phases of the embankment

*Retired.

foundation design process. Possible treatment alternatives, which may be required for particular problem foundations sites, are also mentioned. Specific problem foundation soils are discussed in Chapter 9.

Good general references to the design and construction of embankment foundations are books by Terzaghi and Peck (1967), Winterkorn and Fang (1975), Cheney and Chassie (1982), and U. S. Navy (1982), as well as other textbooks on foundation engineering. Information on methods of treating problem foundation soils can be found in works by Sinacori et al.(1952), Moore (1966), and Welsh (1987). Also recommended are *NCHRP Syntheses of Highway Practice 2, 8, 27, 33, 89, 107,* and *147*.

DESIGN

Preliminary Data Acquisition Activities

Every subsurface exploration program and subsequent design analysis should be preceded by a site inspection followed by a review of all available information pertinent to the project. The latter includes, for example, data from previous projects in the area, geological and pedological reports and maps, well logs, U. S.Geological Survey maps, aerial photographs, and any existing subsurface exploration data. From this information, such items as old slope failures and landslides, swamps and bogs, different soil types as revealed by landforms, buried stream channels, sinkholes, landfills and dumps, mining activities, and poorly drained areas may be located. All pertinent information should be available to the construction engineer, usually in the project soils report.

Exploration Programs

The boring and sampling requirements for a highway project depend on the size, complexity, and location of the project. Exploratory borings (auger, split spoon), undisturbed sampling for subsequent laboratory testing, or in situ tests may all be used in the boring program. For additional information on this phase of the design process, consult the AASHTO (1988) *Manual on Subsurface Investigations*.

Foundation Design Procedures

Granular soils such as sands and gravels generally provide stable embankment foundations. Settlements on these soils are usually small and occur as the embankment is built.

Soft compressible soils such as clays, organic silts, marls, and peats cause embankment stability and settlement problems. First, a model of the subsurface conditions (soil profile) is established, followed by determinations of the strength and settlement design parameters from interpretations of laboratory test results on undisturbed samples or possibly from in situ tests performed during the subsurface exploration program.

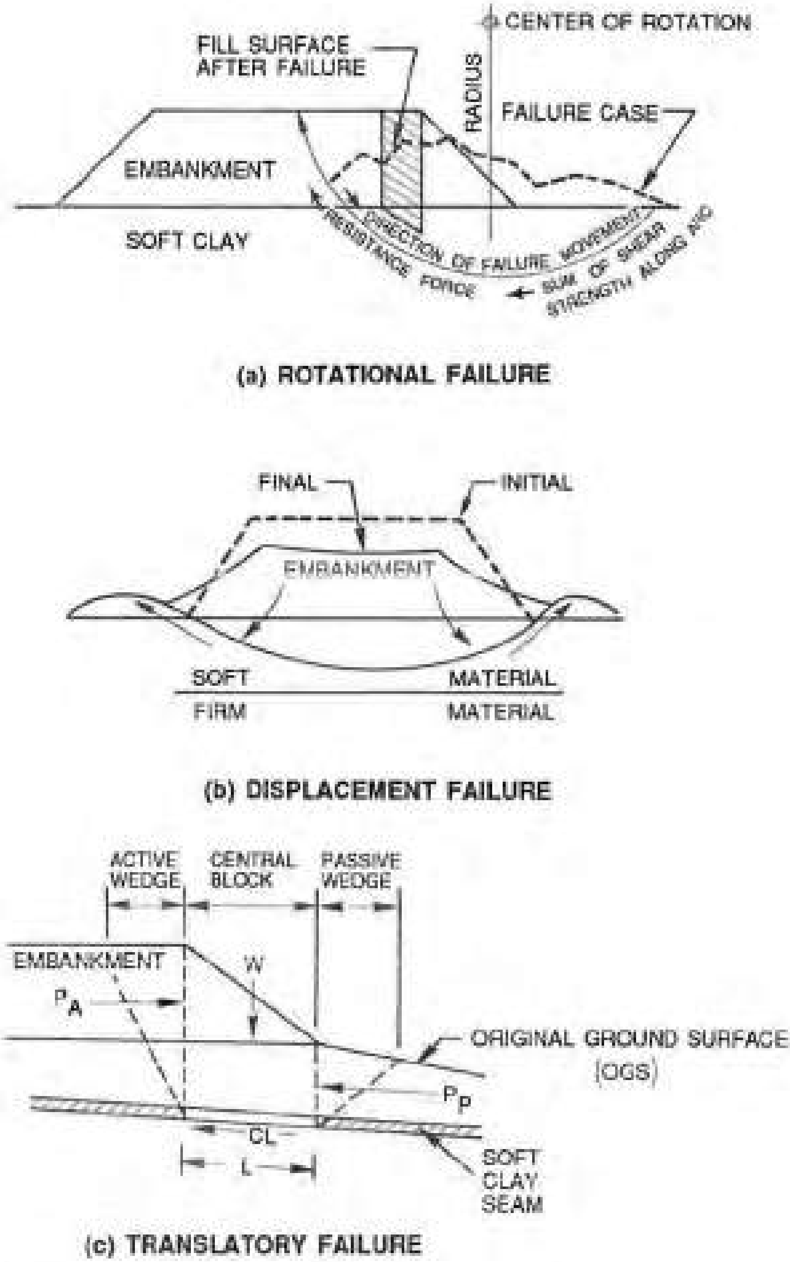
Stability Studies

Failures can occur in situations in which embankments are built on weak soils, such as soft clays, organic silts, and peats, without special foundation treatment. Foundation soils will provide adequate support if the additional stress from the embankment does not exceed the shear strength of any of the underlying strata. Overstressing the foundation soil may result in dramatic embankment failures, which generally occur in one of the ways shown in Figure 6-1. It is important for field engineers to be aware of these possibilities so that should unusual movements appear to be occurring or, for example, cracks start to appear in the embankment, the agency's geotechnical specialist should be contacted immediately. On critical projects or those in which the calculated factor of safety is marginal, the project soils report, or sometimes the project specifications, will state the acceptable limits of settlements or lateral movements of the embankment and foundation. In this case special geotechnical instrumentation (Chapter 10) is used to facilitate these performance observations.

As mentioned earlier, granular foundation soils generally produce small settlements, and because they take place rapidly, usually as the load is placed, they ordinarily pose no particular difficulty in embankment design or construction. On the other hand, foundation soils such as soft clays or organic soils, or both, are capable of large continuous settlements, depending on their geological and loading history and the magnitude of the embankment load. In organic materials especially, settlements may continue almost indefinitely after a project is built. Unusual settlement problems, if anticipated, will be mentioned in the project soils report.

METHODS OF FOUNDATION TREATMENT

If the designer determines that the calculated settlements are too large or that stability problems are likely to arise from construction of the em-



where

P_A = ACTIVE FORCE (Driving)   CL = RESISTING FORCE DUE TO COHESION OF CLAY

P_P = PASSIVE FORCE (Resisting)   W = WEIGHT OF CENTRAL BLOCK

FIGURE 6-1 Typical embankment failures (*courtesy New York State Department of Transportation.*

bankment, it may be possible to lower the grade or shift the alignment to avoid or minimize potential problems. Stability and settlement problems are often interrelated and time dependent. Finding the most appropriate procedure for ensuring stability and minimizing settlements requires an analysis of various foundation treatment techniques. The two most important factors to consider when selecting a treatment method are economics and construction time, while taking into consideration the sequence of operations and the duration of the contract.

Basically, problem foundation soils can be improved by

1. Reducing the load,
2. Replacing the problem materials with more competent materials,
3. Increasing the shear strength and reducing compressibility of the problem materials,
4. Transferring the loads to more competent layers, and
5. Reinforcing the embankment or its foundation, or both.

For treating problem embankment foundation soils, these general concepts are actually accomplished by the following specific methods: (a) berms or flatter slopes, (b) lightweight fill materials, (c) pile-supported roadways and embankments, (d) removal of soft or problem materials and replacement with suitable fill, (e) stabilization by consolidation of soft foundation materials, (f) chemical alteration/stabilization, (g) physical alteration/stabilization, including densification, and (h) reinforcement. These methods and their variations are listed in Table 6-1. All have been used singly or in combination in the United States, although some methods are much more popular than others, and some have only been used on an experimental basis or for structures other than highway embankments. Variations and combinations of the methods listed in Table 6-1 can be considered applicable, but not necessarily the most economical, for virtually any thickness or type of problem soil.

Berms and Flatter Slopes

Embankment instability in the case of a rotational failure (Figure 6-1a) can be improved by adding a counterweight or stabilizing berm to the lower portion of the embankment (Figure 6-2). Berms often necessitate additional rights-of-way. The berm is normally constructed at the same time as the embankment, not afterward, as has been discovered too late in a few embarrassing cases.

TABLE 6-1 FOUNDATION TREATMENT ALTERNATIVES (Holtz, 1989).

Method	Variations of Method	Generally Applicable to		Is Treatment Generally Time Dependent?		
		Stability Problems	Settlement Problems	Yes	No	Possibly
1. Berms; flatter slopes	—	X	—	—	X	—
2. Reduced stress method	Lightweight fill.	X	X	—	—	X
3. Pile-supported roadway	Elevated structure supported by piles driven into suitable bearing stratum.	X	X	—	X	—
	Swedish method of supporting embankment on piles driven into suitable bearing material. Piles have individual pile caps covering only a portion of base area of fill.	X	X	—	X	—
4. Removal of problem materials and replacement by suitable fill	Complete excavation of problem materials and replacement by suitable fill.	X	X	—	X	—
	Partial excavation (the upper part) of soft material and replacement by suitable fill. No treatment of soft material not removed.	X	X	—	—	X
	Displacement of soft material by embankment weight, assisted by controlled excavation.	X	X	—	X	—
	Displacement of soft material by blasting, augmented by controlled placement of fill.	X	X	—	X	—

5. Stabilization of soft materials by consolidation	Consolidation by surcharge only.	—	X	X	—	—
	Consolidation by surcharge combined with vertical drains to accelerate consolidation.	—	X	X	—	—
	Consolidation by surcharge combined with pressure relief wells or vertical drains along toe of fill.	—	X	X	—	—
6. Consolidation with paving delayed (stage construction)	Before paving, permit consolidation to occur under normal embankment loading without surcharge; accept postconstruction settlements.	—	X	X	—	—
7. Chemical Alteration and Stabilization	Lime and cement columns; grouting and injections; electro-osmosis; thermal; freezing; organic.	X	X	—	—	X
8. Physical alteration and stabilization; densification	Dynamic compaction (heavy tamping); blasting; vibrocompaction and vibroreplacement; sand compaction piles, stone columns; water.	X	X	—	X	—
9. Reinforcement	Geotextiles and geogrids; fascines; Wager short sheet piles; anchors; root piles.	X	—	—	X	—

NOTE: Some combinations of methods are feasible.

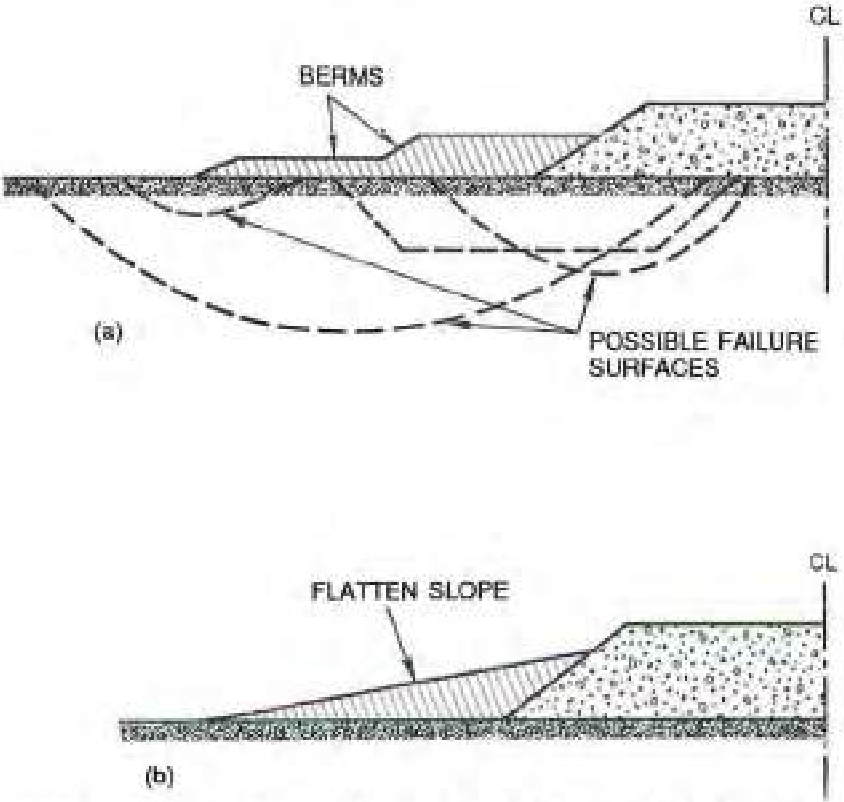


FIGURE 6-2 Embankments stabilized with (a) berms or (b) flatten slopes (*courtesy New York State Department of Transportation*).

Load Reduction

Where the roadway profile cannot be lowered, the use of lightweight embankment fill materials such as cellular concrete, expanded shale, slag, ash, cinders, sawdust and bark, shells, or expanded polystyrene may be considered to reduce the load on the foundation soils (Figure 6-3).

Special construction procedures for placing lightweight fill materials will be given in the special provisions of the project specifications (see Chapter 9, section on Lightweight Fill Materials).

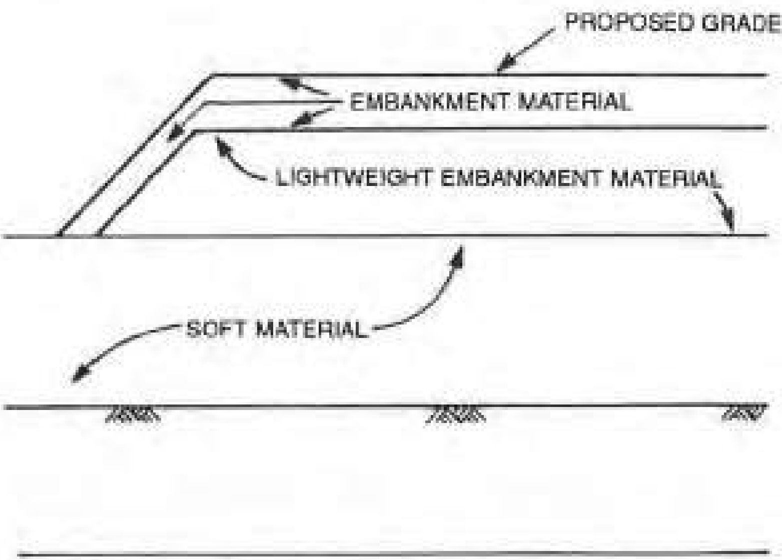


FIGURE 6-3 Use of lightweight embankment fill materials (*courtesy New York State Department of Transportation*).

Pile-Supported Roadways

Pile-supported roadways include elevated structures, such as bridges and viaducts, that are supported by pile foundations and earthen embankments that are supported by relief piles driven to firm bearing layers. The latter system is commonly used to support highway embankments in Scandinavia (Holtz 1989).

Excavation and Replacement

Where feasible, excavation of surface deposits, such as organic material or very soft clay, and replacement with select granular material is an effective means of solving foundation problems. As noted in Table 6-1, the excavation process may be either partial or complete. When the material to be removed is underwater, excavation and backfilling is usually carried out underwater to avoid collapse of the sides of the excavation.

Complete excavation (Figure 6-4) is appropriate where the depth to the bottom of the soft material is fairly shallow, that is, to 20± ft, making removal easy and economical. Partial excavation may be possible in areas where the very soft surface deposit is either quite deep or is underlain by a significantly stronger material. Sometimes the soft materials are displaced by the weight of the fill, as shown in Figure 6-5 (see Chapter 4,

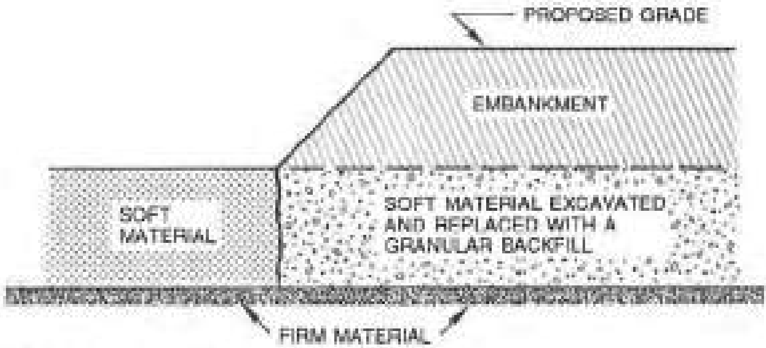


FIGURE 6-4 Complete excavation and replacement.

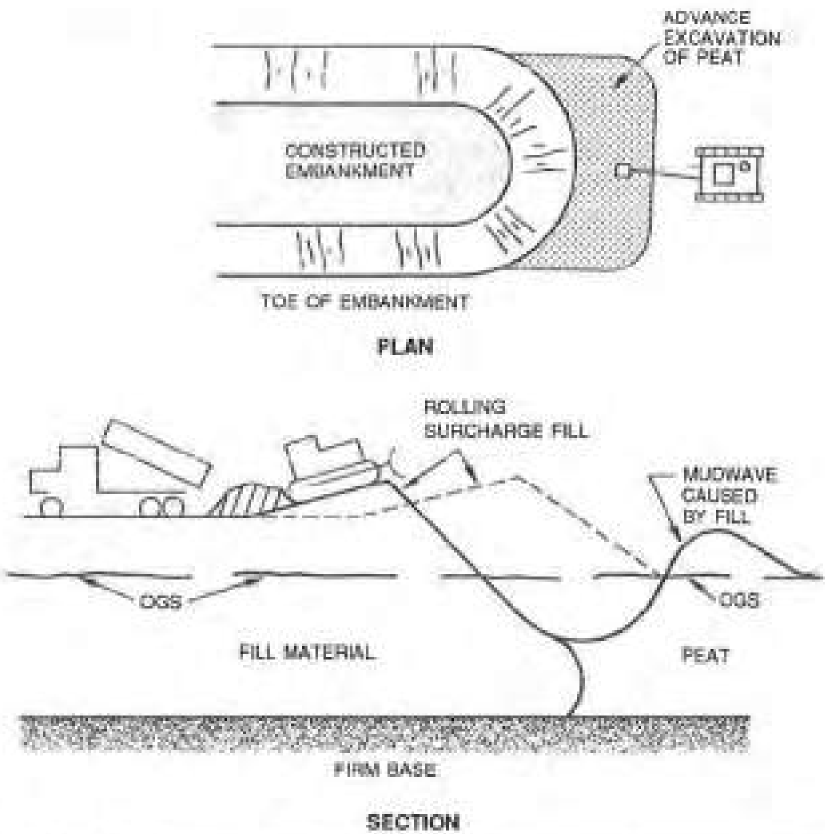


FIGURE 6-5 Gravity displacement method of fill using rolling surcharge and relief excavation at front (MacFarlane 1969; *reprinted with permission from University of Toronto Press*).

section on Unsuitable Materials). All these methods require very careful construction supervision and inspection. Close coordination with the geotechnical specialist is also necessary.

Stabilization by Consolidation

The basic concept of stabilization by consolidation is to force possible detrimental settlements that would otherwise occur after construction to occur during construction when they can be tolerated. This way, corrections can be made before opening the embankment to traffic. A temporary surcharge of additional fill material placed above grade combined with a waiting period causes more settlement in a given time period than would occur without a surcharge. With this procedure, the rate of embankment construction, including surcharge placement, is coordinated so that the surcharge is removed when field settlement and pore pressures equal the predicted values. The criteria given in the project soils report or in the special provisions are ordinarily based on the results of geotechnical instrumentation (Chapter 10) and surveys of line and grade. Although the additional cost of the surcharge fill is usually small, a surcharge may create potential stability problems in very soft foundations. Therefore, modifications in embankment design, such as slope flattening or berms, may also be required, as shown in Figure 6-6.

Also shown in Figure 6-6 are vertical sand drains or prefabricated "wick" drains, which are used to accelerate the consolidation settlements.

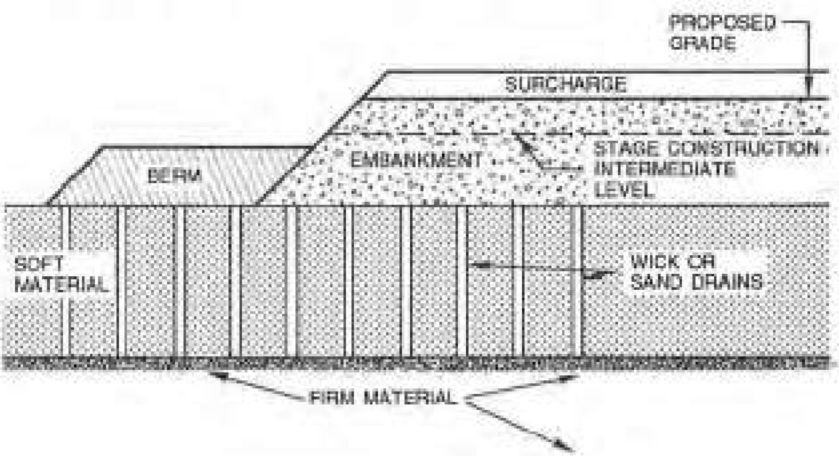


FIGURE 6-6 Stabilization by consolidation with a surcharge fill and wick or sand drains (*courtesy New York State Department of Transportation*).

Because the rate of pore water pressure dissipation increases as the square of the drainage distance decreases, vertical drains installed at typically 5- to 10-ft center-to-center spacings can dramatically reduce the time of consolidation. The corresponding soil strength increase that occurs with consolidation allows the embankment to be safely constructed, frequently in conjunction with stage construction of the fill. Again, these projects usually require monitoring with geotechnical instrumentation (Chapter 10).

Information on prefabricated vertical drains can be found in TRB (1986) Circular 309, and work by Rixner et al. (1986) and Holtz (1987).

Stage Construction with Delayed Paving

With programmed waiting periods between stages, the foundation soils can dissipate excess pore water pressure and settle without surcharge. Field instrumentation (Chapter 10) in the form of piezometers, settlement gauges, and optical survey stakes are required to monitor the foundation performance and regulate waiting periods. Criteria are ordinarily given in the project soils report.

Chemical and Physical Stabilization

Although most chemical and physical techniques have not been extensively utilized in the United States for highway embankments, they may be technically feasible and economical in some situations. Chemical stabilization techniques include lime and cement columns, grouting, electro-osmosis, and thermal (heating, freezing) techniques. Physical stabilization and densification techniques such as blasting, dynamic compaction, vibro-compaction and vibro-replacement, jet grouting, and stone columns have been utilized occasionally and quite successfully at some highway sites. Figure 6-7 shows a schematic diagram of a stone column installation. Details on design and installation of most chemical and physical stabilization techniques can be found in work by Welsh (1987) and Holtz (1989).

Reinforcement

Reinforcement involves the inclusion of some type of reinforcing elements at the interface between the embankment and the ground to increase the stability of the embankment. The most common types of embankment reinforcement are geotextiles and geogrids, although bamboo and brush fascines or mats, corduroy, short sheet piles, tie rods, and

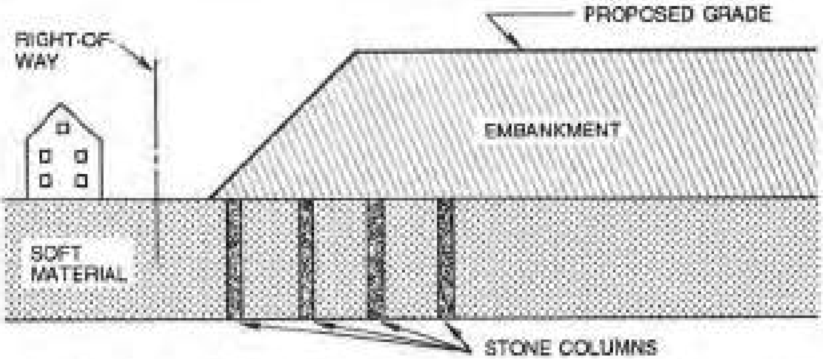


FIGURE 6-7 Stone columns used to stabilize highway embankment (*courtesy New York State Department of Transportation*).

the like have also been used. Common systems are shown in Figure 6-8. See *Geotextile Engineering Manual* (Christopher and Holtz 1985) and NCHRP Synthesis of Highway Practice 147 (Holtz 1989) for a discussion of the use, design, and construction of geotextiles to reinforce embankments on soft foundations.

Construction and Performance Monitoring

To ensure satisfactory construction and performance of the completed embankment, careful, competent inspection during construction is essential, especially for embankments in which some type of soil improvement and foundation treatment has been carried out. Visual observations and physical testing are obviously important components of construction inspection; perhaps not so obvious is that geotechnical instrumentation for taking measurements during construction is also an important aspect of construction monitoring. With a number of foundation treatments such as consolidation with vertical drainage, reinforcement, and chemical alteration, it may be desirable for foundation instrumentation and monitoring to continue for many years after construction is complete, especially if the particular treatment is considered experimental or if the stability of the site is marginal. Embankment instrumentation is discussed in Chapter 10 of this guide.

Inspection During Construction

The importance of well-trained, competent, and conscientious field and inspection personnel cannot be overemphasized. This is the only way to ensure that the essential features of the design are actually carried out in

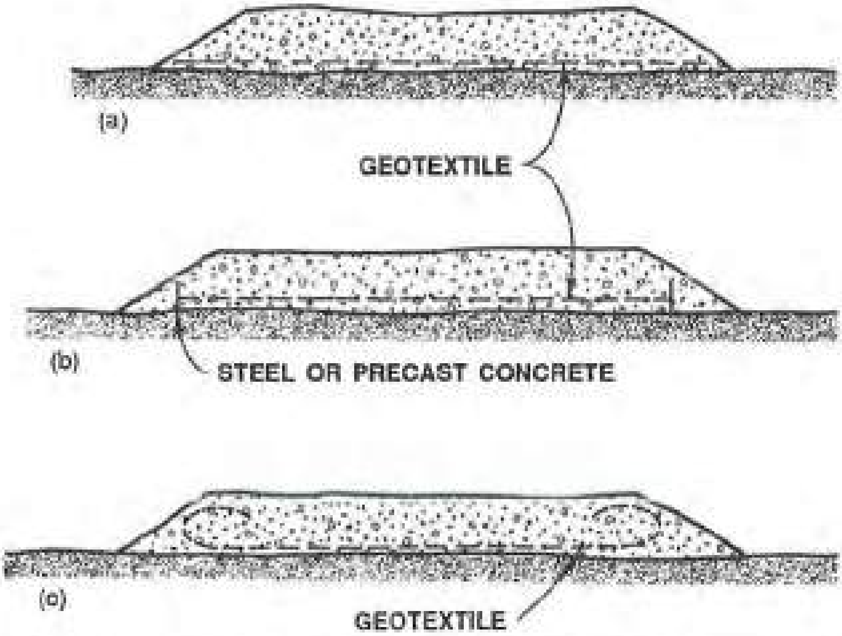


FIGURE 6-8 Concepts for using geotextiles to reinforce embankments on soft foundations (Christopher and Holtz 1985).

construction. With most, if not all, foundation improvement techniques, the success of the entire project is directly dependent on the success of the treatment, and competent inspection is the key element of the project.

To ensure that construction procedures for the treatment method are carried out properly, the designer should inform project engineers and field inspectors, by means of the project soils report and personal meetings prior to construction, about the important design concepts and key construction details of the treatment method. The on-site project engineer must be knowledgeable about the design assumptions to be able to make correct decisions about problems that will inevitably arise during construction. Uninformed construction decisions often result in cost overruns, contractor claims, or even failures.

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ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
FHWA	Federal Highway Administration

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7

Earthwork for Retaining Structures and Abutments

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Structural elements are often incorporated in earth embankments to retain or reinforce the soil mass. This chapter outlines the general design concepts and construction considerations for conventional earth-retaining structures and abutments as well as those with reinforced or mechanically stabilized backfills. Because such structures are often critical features of the highway system, details of design and construction that, if overlooked, may compromise their safety or reduce their life expectancy deserve careful attention.

CONVENTIONAL EARTH-RETAINING WALLS AND ABUTMENTS

Design Concepts

Conventional earth-retaining structures may be classified into two broad categories: rigid and flexible. Rigid retaining structures are commonly constructed of concrete or masonry. Rigid retaining structures used in highways include gravity, semi-gravity, cantilever, counterfort, and buttressed walls. All have occasionally been used for bridge abutments, some more commonly than others. Flexible retaining structures may be unbraced, as in the case of interlocking sheet piling, gabion walls, and crib walls. Alternatively, they may be braced or anchored, as in sheet pile walls, bulkheads, or tieback walls. Flexible walls are not commonly used for abutments. See *Foundation Engineering* (Peck et al. 1974) and *Design Manual 7.2* (U. S. Navy 1982) for information about the design of conventional retaining walls.

A properly designed conventional retaining structure must satisfy the following requirements:

1. The structural components of the wall or abutment must be capable of resisting the lateral earth pressures as well as any other loadings such as surcharges and hydraulic forces acting on it.
2. The wall or abutment must be safe against overturning and sliding at the base.
3. The foundation soil must have sufficient bearing capacity to avoid bearing failure due to both horizontal and vertical loads.
4. The wall and the soil mass it supports must be safe against an overall slip failure.
5. The structure must be able to tolerate the total and differential settlements caused by compression of the foundation soil.

All factors relating to the stability of a retaining structure are affected by the magnitude and distribution of the lateral earth pressures acting on the wall. In the design of rigid retaining walls with cohesionless backfills, it is standard practice to assume that the minimum or "active" earth pressure state exists because wall movements of less than 0.5 percent of the wall height are sufficient to mobilize the active earth pressures. On the other hand, movements less than this will result in greater earth pressures than assumed in design. Construction engineers need to remember this in case conditions occur during construction that effectively reduce or prevent wall movement. Examples of these conditions include the use of temporary bracing during backfilling and the discovery that the foundation of the wall is partially or entirely on bedrock instead of soil, as assumed in design. Abutments, on the other hand, are often designed assuming at-rest or greater earth pressures, especially if they are an integral part of the bridge.

The magnitude of the lateral earth pressures acting on the wall depends on the backfill, soil type, and placement density, as well as the compaction operations. Clean, free-draining granular soils should be used whenever possible. Backfills containing clay, silt, or organic matter are susceptible to swelling, shrinkage, creep, and frost action, all of which may cause excessively large earth pressures and detrimental settlements. For example, shrinkage cracks in clay may become filled with water and create undesirably large pressures against the wall. Particular care should be taken to prevent the use of swelling clays as backfill (see Chapter 9, section on Compaction Problems with Swelling Clays). Silt is also sensitive to moisture changes. Increase in moisture may cause a collapse of the soil structure and result in significant settlements. To reduce detrimental settlements behind abutments supported on piles, some states use free-draining select granular material as backfill.

Partial or total submergence of a backfill results in an undesirable increase in the active thrust acting on the wall. Seepage pressures are one of the most common causes of retaining wall failures. Reduction of water pressures can be enhanced by the use of free-draining backfill and by providing effective drainage of the backfill. Unexpected surcharge loadings, including traffic and temporary construction loads, can also be very detrimental to the wall. Although it is ordinarily desirable to achieve good compaction of the backfill, heavy compaction equipment operating near the wall can induce lateral stresses on the wall much greater than the active earth pressures assumed in the design.

Construction Considerations

Walls are normally constructed by first erecting the wall and then backfilling behind it.

Excavations

To provide room for wall construction, it is common to over-excavate the soil back of the wall. Whenever an open excavation is needed, a safe slope or temporary shoring is required for the excavation. The maximum safe inclination of the slope depends largely on the shear strength of the soil, but the Occupational Safety and Health Administration (OSHA) requires that all trenches exceeding 5 ft in depth be properly shored.

If a retaining structure is constructed near a stream or river, the excavation may be below the groundwater level and special precautions are needed to protect the construction. Temporary flooding may leave soft muck in the bottom of the excavation that must be stabilized or removed before backfilling.

Control of Water During Construction

Surface water can cause erosion and deterioration of a slope, or even induce a slope failure. It can also reduce the capability of the soil to support structures or construction equipment. As discussed in Chapter 5, section on Surface Water, surface runoff should be directed away from the site during construction. In addition, surface runoff from adjacent areas should be prevented from encroaching on the site. The simplest way to control surface water is to excavate a trench or construct a dike or curb around the perimeter of the site and dispose of the water by gravity or by pumping from sumps.

Retaining walls are sometimes constructed below the groundwater table, and dewatering may be required to provide a working platform (see Chapter 5, section on Subsurface Water). Although there are many methods available for this purpose (well points, horizontal drains, and the like), the simplest technique is to construct perimeter trenches and connect them to sumps. This method is most effective when the excavation is in cohesive material and the groundwater is not too high. The trench should be installed as far from the location of the wall base as practical to prevent disturbance due to groundwater seepage. In certain cases, impermeable barriers to reduce or eliminate the inflow of groundwater into the work site may be more effective than dewatering. Usually the selection of the method is left to the contractor.

Backfilling

Backfilling is generally the most important single aspect in the construction of walls. This is especially true when the space for compaction equipment is restricted. Inadequate compaction may cause excessive settlements or even failure of the structure. This is especially important when the abutment supports a spread footing foundation for a bridge (Cheney and Chassie 1982; Wahls 1983).

If possible, the backfill materials should be compacted at their optimum water content (Chapter 3). Backfill should be compacted in layers or lifts, which should slope away from the wall. The lift thickness depends on the compaction equipment and the backfill material, but typical lift thicknesses are 6 to 8 in. Thicker lifts may be used for coarser granular soils. When hand-held compactors are used, the loose lift thickness should be about 4 in. The recommendations of Chapter 4, particularly the sections on Compaction, Compaction in Confined Areas, and Structure Backfill, should be followed.

Constant supervision is necessary to obtain the proper lift thickness, especially in areas of limited working space. If the fill material is dumped in a pile and spread by hand, considerably thicker lifts than specified may result, leaving pockets of poorly compacted backfill behind the wall.

The specification for the gradation and density of the backfill should be adhered to strictly. Do not permit the contractor to substitute materials for the backfill without the prior approval of the engineer in charge. If clean granular backfill is specified, do not allow materials to be placed with clay or silt fines, organic materials, or any other material that does not meet the specifications.

The use of frozen materials in backfills is generally recognized as bad practice (see Chapter 4, section on Cold Weather Construction and Chapter 8, section on Frost Action in Embankment Design and Construction). Frozen backfill may look quite satisfactory when placed, but it can be extremely troublesome and totally unstable after it thaws. Care is needed during backfilling to prevent damage to any geotextile or geocomposite drains installed on the back of the wall or, in the case of anchored sheet pile walls, to tie rods. The soil in front of the toe and anchorage must also be adequately compacted.

Drainage

Conventional walls built above the groundwater table are normally designed with the assumption that no significant water pressures exist behind the wall. To ensure that this is the case, through-the-wall weep holes or a collector-drainage system, or both, are commonly provided and will be shown on the plans. Today a combination of granular drain materials and geotextiles, or a geocomposite drain, are commonly used (Christopher and Holtz 1985).

During installation, contamination of the drainage materials and system must be avoided. The drain outlet pipe, which connects to the drain, must also be carefully installed. Because proper drainage is very important to the long-term performance of the wall, all aspects of the drainage system construction should be carefully inspected.

To reduce percolation of surface water into the backfill, the site should be graded to direct runoff away from the back slope. Sometimes interceptor drains on the back slope are used (see Chapter 5, section on Surface Water). Periodic maintenance is also necessary to minimize runoff infiltration.

Scour

If a retaining wall is located adjacent to a stream or river, it is susceptible to scour during floods. Consequently, the erosion protection system is very important and must be constructed strictly according to the plans.

WALLS WITH REINFORCED BACKFILLS

Design Concepts

It is becoming increasingly common to use some type of tensile reinforcement in backfills behind retaining walls in order to reduce the earth pressures acting on the wall face. A variety of reinforcing materials such as steel strips, sheets of geotextiles or geogrids, welded wire mats, metal grids or bars, and various anchor systems have all been successfully used for this purpose. Although soils are relatively strong in compression and shear, they are very weak in tension. By incorporating a material of high tensile strength in the soil, the composite soil mass will exhibit greater strength and be able to tolerate larger movements without distress. The mechanisms of reinforcement for the different types of materials have been summarized by Mitchell and Villet (1987) in NCHRP Report 290. The reinforced retaining structure must satisfy both external and internal stability requirements. For external stability, all the requirements described in the section on Design Concepts for conventional retaining walls must be met. Internal stability must satisfy two criteria: (a) the tensile reinforcement must not break, and (b) there must be sufficient friction or bonding between the soil and reinforcement so that it does not pull out from the backfill. Many of the reinforcing systems commonly used today are proprietary, and designs and contract specifications are often prepared by the individual material suppliers or contractors.

The inclusion of tensile reinforcement in permanent highway structures requires that the reinforcement be sufficiently durable throughout its design life. Examples of problems include creep and chemical degradation of geosynthetics and the corrosion of metals.

Construction Considerations

Earthwork construction control for reinforced structures is essentially the same as that required for conventional retaining structures, but with a few additional details that require special attention. Several of the proprietary firms have published quality control procedures and manuals (for example, Reinforced Earth Co., 1987). The contractor should obtain a copy from the company or the design engineer and follow the recommendations as closely as possible. Field substitutions of backfill materials or changes in construction sequence, procedures, or details should *only* be permitted with the express consent of both the responsible geotechnical or preconstruction design engineer and the proprietary system material supplier.

Site Preparation

Before placement of the reinforcement, the ground should be graded to provide a smooth, fairly level surface. The surface should be clear of vegetation, large rocks, stumps, and the like; depressions should be filled; soft spots should be excavated and replaced with backfill material; and the site should be proof rolled (see Chapters 4 and 6).

With reinforcing systems utilizing precast concrete facing panels, a small strip footing is commonly employed as a foundation under the facing panels.

Handling of Reinforcement Materials

Specific material-handling instructions for proprietary reinforcement materials are generally provided by the individual material suppliers. Geosynthetics, especially geotextiles, should be protected from sunlight and extreme temperatures. Concrete facing panels should be handled carefully to prevent cracking and chipping. Damaged or improperly handled reinforcing materials should be rejected.

Placement of Reinforcement Material

After the reinforcement is in place, it should be examined carefully. Any damaged or torn materials should be removed or repaired as detailed in the specifications. In no case should construction equipment be allowed to operate directly on any reinforcement before fill is placed. In the case of geosynthetic reinforcement, it should be unrolled transverse to the alignment of the embankment or wall, and wrinkles and folds should be eliminated. Procedures for seams and overlaps detailed in the plans and specifications should be adhered to strictly.

Fill Placement and Compaction

Special attention should be given to ensuring good compaction of the backfill, especially near the face of the wall. Otherwise detrimental settlements behind the face may cause a downward drag on the reinforcement, which might induce excessive tensile stresses, particularly near the face where reinforcements are attached to concrete panels (see Chapter 4, sections on Compaction in Confined Areas and Structure Backfill).

At the end of each day's backfilling operation, the last lift of fill should be sloped away from the wall facing to direct any possible runoff away from the face.

Alignment of Facing Panels

Alignment of the structure is usually established by initial layout of the foundation wall section and strip footing, if required. In addition, some type of external bracing, formwork, or scaffolding, usually erected in front of the wall face, is often used to maintain the alignment of especially the first lift. For all reinforced structures, particularly for those that do not use precast concrete facing panels, care should be taken not to allow heavy construction equipment to operate too close to the face. Otherwise undesirable bulging of the face may result.

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ABBREVIATION

FHWA Federal Highway Administration

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8

Environmental Considerations

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This chapter discusses some of the environmental issues commonly encountered during construction operations. It is a brief overview and does not include all the possible environmental issues that may be encountered on a specific project. Fortunately, most environmental construction problems are anticipated during the design phase and are adequately addressed in the contract documents and specifications. However, specifying how a contractor shall operate to withstand the forces of nature and getting the contractor to actually comply with the contract and achieve the project objectives can be a very difficult and drawn-out process. For example, prevention of erosion during and shortly after construction is particularly difficult. Achieving satisfactory results requires diligence and cooperation by both the contractor and the construction engineering team.

This chapter discusses general and site-specific environmental considerations, soil erosion, the influence of construction on the local environment, hazardous and objectionable materials, long-term issues and considerations, and frost actions.

GENERAL ENVIRONMENTAL CONSIDERATIONS

It is important to recognize environmental problems and know how to solve them in a prompt and effective manner. Failure to properly identify and mitigate environmental problems often leads to construction delays and increased costs. Environmental problems rarely go away by themselves and usually get worse with time. A severe environmental problem, such as malodorous or highly toxic waste material, could stop construction, and in an extreme case, even force the project to be abandoned. In recent years, growing public concern about the environment has exerted considerable influence on some construction projects. This trend is likely to continue.

SITE-SPECIFIC CONSIDERATIONS

Each construction site has its own unique environment. Some of the items that must be taken into account before the start of construction include the immediate local surroundings (schools, parks, airports, industrial plants, and the like) and special local events (county fairs, races, music and art festivals, and so on). Another consideration is the potential effects of construction on the local environment: strong winds blowing soil and dust, heavy rains causing temporary flooding and silting of streams and drainage structures, and excessive traffic delays due to construction operations.

Once potential problems have been identified, solutions and procedures should be incorporated into the contract.

Recognize the specifics of the local climate. For example, in areas of significant snowfall, recognize that drifting snow can potentially clog temporary drainage channels. Vegetation should be planted during a period when there will be adequate moisture, heat, and light. The plans and specifications generally cover project landscaping requirements. If questions arise, consult the resident engineer.

SOIL EROSION

The most common environmental problems encountered in construction are erosion by wind and water. Normal embankment construction activities require destroying the natural vegetative cover and the natural balance of environmental forces near the ground surface. The best way to prevent local problems is to reestablish the natural vegetative cover and natural environmental balance as quickly as possible after construction. There are several methods that can be used, and combinations and variations to fit local site conditions are usually the most effective. A number of new products are available that can help reduce the effects of wind and water during construction (see Chapter 5, section on Surface Water). Although some of these products can be very effective in local areas, generally they are quite expensive. Construction erosion may often be more economically taken care of by controlling the contractor's operations so that environmental damage is avoided. Be careful not to order the contractor to use various erosion control measures unless the items are specifically mentioned in the contract. Consult the resident engineer if there are any questions.

Many states specify in the contract documents the size of the area that may be opened to construction at any one time before the permanent erosion control treatment is applied. The contractor should not be permitted to destroy the natural vegetative cover on extended lengths of the site unless erosion control and prevention measures can be installed at about the same time. The contract may require the contractor to submit an erosion control plan. State and federal soil conservation agencies can often provide valuable information and guidelines. As part of each contract, many states include standard plans for temporary erosion control features and/or devices.

Water Erosion

As noted in Chapters 4 and 5, one of the first requirements of construction is to prevent damage to local water bodies by not permitting the construction runoff water to mix with any local stream, lake, or other nearby water body. This can best be achieved by reducing soil erosion caused by surface runoff where possible and by preventing unavoidable soil erosion from leaving the construction site.

Normal rainfall will cause erosion of exposed soil, if not protected. During construction, it is nearly impossible to prevent rainfall from eroding the work area. Therefore, to protect the environment, all the runoff and all the eroded soil must be kept on the project site until the sediment can be removed from the runoff water. Hay bales, sedimentation basins, and silt fences have been used effectively to protect local streams and water bodies. Such installations are generally shown in the standard plans or elsewhere in the contract. Refer to Chapter 5, section on Surface Water for a detailed discussion of these installations.

If roadway construction is in lakes or open water, use of sheetpiling or properly designed silt curtains has been very effective in keeping construction runoff from contaminating the open water. Such measures are incorporated into the project by designers and ordinarily are not left to field forces to develop.

Methods for controlling soil erosion should not be used in ways that contribute to other problems. For instance, while the use of mulching is very effective in holding seed in place until it germinates, the type of mulch must be appropriate for the area; otherwise a heavy rainfall could easily transport the mulch into local drainage channels, causing flooding and other damage.

Wind Erosion

When strong winds blow across unprotected land, they move the soil. Long-term wind erosion can be prevented by planting ground cover and establishing vegetation. The short-term local effects of wind erosion must be handled on a temporary basis by the contractor. One of the major contributors to wind erosion is construction traffic, which may lift large quantities of silt-sized particles high enough so only light breezes are needed to transport them great distances. Damage to crops and other vegetation, local residences, and vehicles may result.

To prevent excessive construction dust in construction traffic areas, it is often necessary to use temporary pavements or chemical palliatives such as salt, calcium chloride, asphalt emulsion, tar, and numerous other chemicals. All dust palliatives are potential environmental contaminants. For example, salt is known to damage local vegetation, and it is undesirable for it to go directly into a water supply. Therefore, all proposed palliatives must be thoroughly evaluated before they may be used on construction projects. Most agencies usually have a list of acceptable dust palliatives for the contractor's use.

INFLUENCE OF CONSTRUCTION ON THE LOCAL ENVIRONMENT

Construction activities impose conditions on local environments that can be perceived by the public as ranging from slightly objectionable to completely intolerable. Controlling off-site trucking routes and limiting the hours of their use can often minimize inconvenience to the public caused by noisy truck traffic and soil spillage onto roadways. Close cooperation among the project engineer, local law enforcement officials, and contractor's personnel can usually prevent serious problems of this nature. Restrictions placed on the contractor's operations must, of course, conform to the contract.

HAZARDOUS AND OBJECTIONABLE MATERIALS

Although it is not uncommon to encounter waste materials from industrial operations in rural areas, they are much more likely to occur in urban excavations. Waste materials can vary from garbage dumps and paper mill wastes to mine and steel-making wastes (see Chapter 9, section on Waste Materials). Most of these wastes have concentrations of chemicals that can be harmful to the environment if not adequately handled. The excavation may even release gases that are harmful to humans, including the equipment operators and inspectors. Sometimes the gases have such noxious odors that they must be specially treated.

If there is any suspicion that the contractor has uncovered an area that might be environmentally obnoxious or hazardous, stop all operations and do not allow the contractor to transport the materials until a complete environmental assessment can be made. There are severe civil and criminal penalties if hazardous or contaminated materials are knowingly transported without proper permits, notification, and safeguards.

Occasionally the contractor may want to use waste products as part of the embankment construction (see Chapter 9, section on Waste Materials). Local industries are sometimes willing to pay contractors to haul away waste materials. Before accepting any of these materials on a project, have a complete evaluation made of the chemical constituents and of the stability of the materials when subjected to the local environment so that a long-term problem is not created. The contractor must also be alert to hazardous wastes coming from its own construction activities, for example, lead-based paint removed as part of the cleaning of bridges or asbestos from the demolition of old buildings. In these cases, applicable environmental laws must be strictly followed.

LONG-TERM ISSUES AND CONSIDERATIONS

Usually items that may have a long-term influence on the local environment are included as part of the contract documents. The engineer should be aware of the purposes of these long-term controls in the contract and make certain that the contractor's short-term activities do not negate the intent of any long-term environmental controls.

During construction, the engineer must be constantly aware of the need to prevent contaminants from reaching local water supplies. In order to grow vegetation on exposed soils, however, it is usually necessary to add fertilizers, lime, or other nutrients to the soil. These chemicals can cause concentrations that are very damaging to the local environment if they are improperly stored or misapplied. Certain contractor-produced wastes can cause permanent damage to the environment if not adequately controlled. The contractor's work yard needs to be constantly monitored for spills of fuel, oils, and chemicals, which should immediately be cleaned up. Crankcase oils, for example, should be collected and disposed of properly.

Unacceptable discharge from the project can produce permanent long-term damage to the environment if not adequately controlled. It may be necessary to separate runoff from the completed highway from local water supplies by salt berms, intercepted drainage, and other measures. However, when certain natural materials that are excavated and/or removed from their original location and used as construction materials are exposed to rainfall, harmful chemicals can be leached from them. These possibilities should be considered during the design phase and appropriately included in the plans and specifications. However, the engineer must be aware that any earthwork will be subjected to rainfall infiltration and possibly other materials, such as salts and oils, that might cause corrosion of structures under construction.

FROST ACTION IN EMBANKMENT DESIGN AND CONSTRUCTION

In areas where freezing temperatures occur, embankments and the facilities they support, such as pavements, rail lines, and so on, may be adversely affected by the freezing of the soil. This important factor has to be considered in the design of the project. The soils investigation should be done early in the location phase to properly prepare the specifications if problem materials exist. These problems should be noted in the contract documents so that the bidders are aware of unusual circumstances, requirements, disposal of unusable soils, and so forth.

Frost Effects

Frost heave is the upward expansion that occurs when certain soils freeze. Not only does the in situ moisture freeze, but more importantly, additional moisture flows to the freezing front. While the expansion of pore water upon turning to ice does contribute to heave, it is the additional water that moves to the freezing front that causes the dramatic heaving of road surfaces and railroad tracks (TRB 1974). Because heaving is seldom uniform over the area affected, road surfaces become very rough, resulting in cracked or damaged pavements. The distortion of road surfaces also leads to disruption of surface drainage.

Thaw settlement and instability occur with the advent of warmer temperatures in the spring. Thawing occurs from the surface downward, with the result that moisture is trapped between the surface and the still-frozen soil below. This results in greatly reduced bearing capacity. While most modern high-volume roads can withstand this condition, the typical pavement thickness on low volume or older roads is insufficient, and seasonal load restrictions may have to be imposed. At the end of the thaw season, the surface may not settle back to its original level, so there may be residual pavement roughness (TRB 1974; Armstrong and Csathy 1963). Permanent rutting often results in water ponding, leading to the danger of hydroplaning.

Damage to and disutility of buried facilities is another possible hazard. Culverts may be heaved either temporarily or permanently, resulting in sharp bumps in the road, disrupted surface drainage, and eventual complete destruction of the culvert (Fredrickson 1963). Stormwater drains and outfalls for subgrade or pavement underdrainage systems may be rendered ineffective as well.

Mechanism of Frost Heaving

Three factors are necessary for detrimental frost heaving to occur (TRB 1974; Linell et al. 1963): (a) freezing temperatures for a sufficient duration of time, (b) a water supply sufficient to support the growth of ice lenses, and (c) a frost-susceptible soil, that is, one with a texture favorable to the upward movement of water to the freezing front.

Design to Control Frost Heaving

If any one of the above three factors can be eliminated during design, frost heave and instability during the thaw period can be essentially eliminated.

A soil subgrade, subbase, or base course material is considered to be frost susceptible if it contains more than 3 percent by weight of particles smaller than 0.020 mm (Linell et al. 1963). For convenience and practicality, and depending on local soils and climate, many frostbelt states specify an equivalent limit, typically ranging from about 8 to 15 percent of the maximum allowable percent passing the No. 200 sieve. Therefore, if any frost-susceptible soil within the depth of frost penetration can be removed and replaced with non-frost-susceptible soil, heave can be largely prevented. Alternately, it may be more effective to simply cover the frost-susceptible soil with a sufficient thickness of select non-frost-susceptible soil. This has the effect of raising the gradeline above natural ground, which often has side benefits in drainage and in areas of heavy snowfall.

The availability of moisture depends primarily on the permeability and the height of capillary rise of the subgrade or embankment soils. Some agencies consider that if the water table is more than 10 ft below the surface, frost will present little problem. On the other hand, an effort is made to keep the gradeline at least 5 ft above the water table, depending on the specific soils at the site, and to use select granular material to construct the embankment (Erickson 1963). It will be noted that this results in an ambiguity where the gradeline is from 5 to 10 ft above the water table. Engineering judgment is required in this case.

Cuts are likely to be troublesome, especially when they are deep enough to approach the groundwater table. The cut will typically drain toward the cut-to-fill transition, and thus localized heaving problems can be created unless effective drainage is provided to keep the seepage out of the fill (TRB 1974; Armstrong and Csathy 1963).

It might seem that freezing temperatures would not be amenable to treatment, as they are inherent to the site. However, there has been considerable success in controlling frost heave by the use of foamed insulation boards placed on frost-susceptible subgrades. They are then covered by a foot or so of base course and pavement materials. Unfortunately, there have been cases where differential icing of the pavement surface occurred as a result of the interruption of the heat flow from the earth. As a result, many early installations of thermal insulation were removed (TRB 1974). At present there is a renewed interest in the use of insulation. Concerns for liability still remain, however.

Other Design Considerations

In general, frost penetration will be greater (although frost heave will be significantly less) for free-draining cohesionless soils, dry soils, and soils of greater dry density than for silts, clays, and wet soils. The project should be reviewed to determine the relative frost-susceptibility of the various soils that may become part of the embankment. Selective placement should be considered so as to place the least frost-susceptible soil nearest the top of the completed embankment (NCHRP 1974). If clean sands or gravels are conveniently available, they should be used to facilitate the drainage of the embankment.

Cold Weather Construction

Since basically all soils will heave when frozen, some more than others, uniformity of the soil in the embankment is an important objective of the contractor and construction inspectors. Having a uniform embankment will help eliminate differential heaving when freezing occurs. Methods to accomplish this are discussed in Chapter 4, sections on Embankments and Compaction.

Care should be taken during construction to see that design features intended to counteract frost action are not altered by construction operations. For example, clean cohesionless materials used at the top of the embankment may sometimes be difficult to traffic by earthmoving equipment, and there may be pressure to add a little cohesive material to correct the "problem." This, of course, would be counterproductive to the frost-prevention purpose of the materials.

In general, construction during winter or freezing temperatures is avoided by most highway agencies. As noted in Chapter 4, section on Cold Weather Construction, it is very difficult to compact frozen soil to the densities which are typically specified, with the result that when spring comes, there is excessive settlement, especially differential settlement, of the embankment.

Where the work involves rock fill or clean, free-draining sands or gravels, however, and the work can be planned to avoid using frozen soil, it is possible to obtain satisfactory results (Haas 1988; Haas et al. 1988). The key is to prevent the soil from freezing before it is compacted and to suspend operations if it becomes too cold to do so.

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9

Special Soil Deposits and Embankment Materials

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A number of soil deposits, both natural and man-made, can pose difficult problems for embankment foundations. These materials may be difficult, if not impossible, to sample and test by ordinary means, and thus their engineering behavior is not well documented or well understood. Consequently, normal practice, design rules, and experience may not lead to satisfactory embankment performance. A number of these special deposits are good candidates for some type of soil improvement and foundation stabilization, as discussed in Chapter 6, so that highway embankments can be constructed on them safely and with tolerable settlements. When used as fill directly in the embankment, these materials may cause unusual problems for the contractor and therefore for the field engineers and inspectors. Such materials may be stabilized and improved in special ways, some of which are mentioned in this chapter. Generally, such deposits and materials are handled by special provisions in the project specifications.

Deposits and materials discussed in this chapter include landfills, dumps, wastes from industrial and mining operations, lightweight fill materials, shales, swelling clays, and collapsible soils.

WASTE MATERIALS

Sanitary Landfills and Dumps

Roads in urban areas frequently must be located on sanitary landfills, garbage dumps, and similar areas. Construction is certainly possible on sanitary landfills, as shown by Moore and McGrath (1970) and Chang and Hannon (1976), but the results are often less than satisfactory unless some special foundation treatment is carried out. As noted by Holtz (1989), the types of problems encountered at such sites depend on the nature of the landfill materials and their age, both of which may be highly variable. Embankments on some well-operated landfills will normally consolidate rapidly, and thus only a simple surcharge is required to adequately densify them. In other instances, embankments on loosely dumped municipal garbage and building wastes will experience very large total and differential settlements, and this may mean a poor riding surface and high maintenance. Landfills that are 15 to 30 yr old may have already decomposed sufficiently to be good candidates for foundation treatment, although they may contain wastes that cause them to be considered hazardous by current Environmental Protection Agency (EPA) standards.

Feasible methods of foundation treatment (see Chapter 6) include the following:

- Proof rolling with very heavy rollers,
- Surcharge,
- Excavation and replacement as a compacted fill,
- Embankment piles,
- Grouting,
- Vibrocompaction, and
- Dynamic compaction.

Many waste dumps are not controlled landfills as described above, but are sites such as swamps, tidal flats, river and stream banks, lakes, and so on, where garbage, used appliances, wrecked cars, used tires, and the like have been often illegally discarded. In addition to the nature of the waste materials, the type and condition of the natural soils in the area must be considered in evaluating the site for possible foundation treatment.

Landfill sites pose other problems during construction. Decomposition of municipal wastes generates methane and carbon dioxide, and the introduction of fresh air into a dump site could cause a fire by spontaneous combustion or even from smoldering material buried in the landfill. Difficulties have been experienced with noxious gases, and in such cases it has been necessary for the field personnel to use breathing apparatus, apply deodorants to the site, and exercise special rodent and pest control measures after the area was opened.

Suspected toxic or hazardous waste dumps pose especially serious problems if they must be crossed by the highway. Special precautions must be taken to protect field crews, and it is prudent in these cases to call for specialized help.

Inorganic Industrial Wastes and Dredged Materials

Other wastes that are sometimes of concern to highway engineers include industrial by-products and wastes such as slags, bottom and fly ashes, and inorganic sludges. Dredged materials are sediments dredged from the bottoms of river channels, lakes, and harbors and deposited on land in diked containment areas. These waste materials are usually encountered in very localized areas, often near their source, although dredged materials and sludges may be transported some distance as slurries.

Loose deposits of predominantly granular materials such as slags and bottom ashes can be treated by methods appropriate for such materials (dynamic compaction, blasting, vibroreplacement). Provided proper environmental constraints are followed, they should make excellent embankment fills. Fly ashes are rarely foundation problems, and since they are mildly pozzolanic, they should be more than acceptable fill materials provided they are properly handled during transport, water addition and mixture, and compaction.

Sludge deposits and dredged materials, which may be silty or clayey or even somewhat organic, usually are a problem because of their high water content and compressibility. Holtz (1989) suggests acceptable foundation stabilization methods for these materials. Rarely do they make good fill materials.

Strip Mined Areas, Mine Wastes, Tailings, and Slurry Ponds

Both surface and underground mining operations usually leave rather unusual deposits and conditions that may cause locally difficult problems for embankment foundations. In addition, mineral processing operations also produce wastes in the form of tailings and slurries (slimes) that, if encountered, may be difficult to stabilize for construction.

Strip and underground mining operations often leave large areas of loosely dumped spoil materials. For embankment foundations, these deposits may be suitably treated (Holtz 1989), and in some cases may make excellent embankment fill.

Tailings from some mineral processing operations are another matter. They can be extremely difficult to stabilize for foundations, depending on their grain size and water content. Those factors, plus potentially hazardous conditions, for example, the presence of radioactivity, heavy metals, cyanide, or organics, make the use of tailings for highway fills very problematic. If such materials are suspected on your job, be sure that they meet all environmental requirements prior to approving their use as embankment fill.

LIGHTWEIGHT FILL MATERIALS

Both the stability and settlement of embankments on soft foundations can be improved by use of lightweight embankment fill (Moore 1966; Holtz 1989). Lightweight materials that have been used successfully in highway embankments include bark, sawdust, dried peat, fly ash, slag, cinders, cellular concrete, expanded clay or shale, expanded polystyrene, and oyster and clam shells. The advantages and disadvantages of the use of these materials are discussed by Holtz (1989).

Because the crushing strength of some lightweight materials is relatively low, care must be taken during construction to avoid damaging them, especially if conventional compaction equipment is used. Sometimes encapsulation is required for environmental reasons, and both synthetic liners (geomembranes) or compacted clay have been successfully used. In either case, great care must be taken during placement of the liner to avoid punctures, tears, and leaks. Strict adherence to the placement specifications is essential in these projects.

CONSTRUCTION OF EMBANKMENTS OF SHALE

The materials given the generic classification of "shale" are geologically widespread, and are frequently encountered in excavation and borrow situations. Two major problems have occurred when these materials have been used in highway embankments. Where the shales contain swelling clay minerals, the fills display the characteristic volume changes associated with swelling clays (see section on Compaction Problems with Swelling Clays). A somewhat more subtle problem situation occurs with the use of shales that are physically nondurable but are strong and rocklike when freshly excavated. Such materials have often been placed as rock fills, only to experience breakdown in service, producing excessive settlements and even slope failures.

This section concentrates on the technology required when building fills of hard but nondurable shales. These materials are commonly encountered throughout the midwestern United States, and thousands of examples of unsatisfactory performance have occurred where they were improperly placed.

Early classification of these materials is recommended, and the Franklin (1981) approach is appropriate. The primary test in this approach is the slake durability test, which combines two wet/dry cycles, with a rotational impact that dislodges slaked portions from the shale aggregates. The test is standardized as ASTM D 4644, Standard Test Method for Slake Durability of Shales and Similar Weak Rocks.

Once the second cycle slake durability index, $I_d\,(2)$, is defined, it serves as a general guide for relative durability and also determines the second test required to accomplish the Franklin classification. If the $I_d\,(2)$ is equal to or less than 80 percent, then a soil test such as the Atterberg limits and the plasticity index can be used to classify the material. On the other hand, if the $I_d\,(2)$ is greater than 80 percent, the point load strength index, adjusted for an aggregate dimension of 50.0 mm, must be used to complete the classification. All these procedures are briefly described in Oakland and Lovell (1983), and in greater detail in Oakland and Lovell (1982).

If the shale is nondurable and yet strong and hard, it is advisable to conduct a compaction-degradation test on it (Hale et al. 1981). A nondurable material must be intensely degraded during excavation, placement, and compaction, and it must be finally densified to a specification appropriate to a similar soil. This is difficult to accomplish with some shales, but the compaction-degradation test allows the problem to be anticipated.

The testing procedure, also described in Oakland and Lovell (1982), produces a numerical value, termed the index of crushing, which is the percentage reduction in mean aggregate size, produced in the laboratory compaction process. If this number is relatively high, for example, greater than about 40, the shale will be easily degraded in the field. If it has a lesser value, the shale will strongly resist efforts to break it down, and special wetting and heavy rolling procedures may be required. The procedures and compaction specifications for compacted shales are best developed in a full-scale field test pad, and the results of such tests should be made available to the project engineer. Special wetting and compaction procedures, if required, will be detailed in the special provisions of the project specifications.

Strom et al. (1978) and Strom (1980) have written good references on the design and construction of shale embankments.

COMPACTION PROBLEMS WITH SWELLING CLAYS

Compaction problems with swelling clays require special attention. Swelling soils, which are frequently clays but are sometimes shales, marls, or other soils, cause an estimated $10 billion in damage in the United States every year (Krohn and Slosson 1980). Half of this damage occurs to the nation's highways, with most of the remainder occurring to other transportation facilities such as airport runways, railroads, canals, pipelines, sidewalks, and so forth. Swelling materials occur in all but six states. The problem of swelling soils has been studied with considerable intensity through the years. One of the major efforts was a $700,000 research project funded by the Federal Highway Administration and conducted by the U. S. Army Corps of Engineers, Waterways Experiment Station, (Snethen et al. 1975; Snethen 1979 and 1980). Other major research has been done for the U. S. Air Force (McKeen 1980), and a variety of state agencies (for example, Watt and Steinberg 1972; Steinberg 1985). Many of these studies have been published by TRB (1981; 1985).

Once the contractor is aware of the potential of a swelling soils problem, standard Atterberg limits laboratory tests should confirm whether indeed there is a problem. From there on, the best advice is to avoid overcompacting the material. Density testing is a significant help in this regard. Keeping the material at a moisture level dictated by the density curves will assist in reducing the likelihood that the swelling material will turn the finished project into a roller coaster track in a few years. Properly compacting materials identified as having swelling potential and avoiding overcompaction are initial steps only. When embankments are constructed with swelling materials, the results tend to be satisfactory over an extended period of time, certainly much more so than when dealing with swelling clays in an excavation area.

Because the problem of expansive soils is an international one, it is reassuring to know that several solutions have been tried and found to be successful. Lime treatment has been used successfully both in the United States and abroad (TRB 1987). The important thing to remember is that enough lime should be used and that it should be placed to a depth that will control the potential movement. (Potential vertical rise tests will give an indication of what these depths might be.) Electro-osmotic chemical stabilization and pressure injection of chemicals, primarily lime, have been used, but with mixed results.

The key to the successful mitigation of the effects of swelling soils seems to be in minimizing moisture variation underneath the structure, be it a pavement, building, runway, track, or whatever, to prevent the destructive movements from taking place. Moisture barriers have been tried in several locations. Examples include pressure-injected lime barriers, deep vertical fabric barriers, and horizontal geomembranes. These tests have been reported by TRB (1981; 1985) as well as state transportation agencies (Steinberg 1985). Ponding has also been used in several instances to solve earthwork construction difficulties with swelling materials. Watt and Steinberg (1972) drilled holes 20 ft deep, backfilled them with a pervious material, and then ponded water in them for 30 days. This procedure produced sections that have not had to be replaced because of subgrade problems.

Studies are continuing on swelling soils, and to minimize the damage these soils cause transportation structures and facilities, the engineer should be aware of the results of this research.

COLLAPSING AND SUBSIDING SOILS

Collapsing soils undergo a very large decrease in volume if their water content increases significantly, even without an increase in surface load. Examples include loessial soils, weakly cemented sands and silts, and certain residual soils. All these soils have a loose, open, "honeycomb" structure, in which the larger bulky grains are held together by capillary films, montmorillonite or other clay minerals, or soluble salts such as halite, gypsum, or carbonates. Loess is, of course, wind-deposited; other collapsible soils are found on flood plains and in alluvial fans as the remains of slope wash and mud flows, colluvial slopes, and some residual soil deposits. Many, but not all, collapsible soil deposits are associated with dry or semi-arid climates, but some dredged material deposits and hydraulic fills can also be collapsible.

Treatment methods for collapsible soils depend on the depth of treatment required. For modest depths, compaction with rollers, wetting or inundation, and overexcavation and recompaction, sometimes with lime or cement stabilization, are used (Bara 1978). Dynamic compaction (Lukas 1986) may also be feasible. For thicker deposits, ponding or flooding are ordinarily very effective, as is dynamic compaction. However, explosives, displacement piles, and vibroreplacement-vibrocompaction methods could possibly be used as well. Design information for the deeper stabilization methods is given by Clemence and Finbarr (1981) and summarized by Holtz (1989). Any of these procedures required would be detailed in the special provisions of the project specifications.

LOOSE SATURATED SANDS IN EARTHQUAKE COUNTRY; FLOW SLIDES

It is possible for deposits of loose, saturated granular materials to lose all strength when subjected to shock or vibrations from, for example, blasting, pile driving, or earthquakes. The phenomenon is called liquefaction, and it results because there is a tendency for loose sands to decrease in volume when strained or shocked. This tendency causes a positive increase in pore water pressure which results in a decrease in effective stress within the soil mass. Once the pore pressure becomes equal to the total stress, the effective stress becomes zero, and the soil mass loses all its strength (Holtz and Kovacs 1981). Because this loss in shear strength is sudden, the effect on highway embankments and other structures supported by such deposits is disastrous.

Flow slides are a type of liquefaction that occurs almost spontaneously in loose deposits of fine sands often found on the banks of large rivers. When these deposits are strained, say by erosion at the river's edge, excess pore pressures can develop which can lead to liquefaction and collapse of the deposit.

Because of the potential for catastrophic collapse of the foundation of an embankment on liquefiable sands, it is important that these deposits be identified and treated before construction. Virtually all the methods described by Holtz (1989) for granular materials are appropriate for densifying or stabilizing such deposits. Particularly attractive are dynamic compaction, blasting, vibrocompaction and replacement methods, relief wells and drains, and excavation and replacement. These procedures are quite specialized and would be given in the special provisions of the project specifications.

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ABBREVIATIONS

ASCE	American Society of Civil Engineers
FHWA	Federal Highway Administration

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Instrumentation for Embankments

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On many highway embankment construction projects, geotechnical instrumentation is an essential tool for monitoring the performance of the foundation and the embankment. This is especially the case if some type of special foundation treatment is employed (Chapter 6) or special soil deposits (Chapter 9) are encountered. The instrumentation and monitoring program is primarily used to alert geotechnical and construction engineers to soil behavior or construction problems different from those anticipated in design. For instance, adverse soil behavior may call for a reduction in the rate of embankment construction. Alternatively, encountering soil behavior much better than that assumed in design may allow increased construction loading rates, steeper embankment slopes, and elimination or reduction of recommended special foundation treatments. Instrumentation is useful for determining the rate of strength gain and degree of consolidation of the foundation soils. It can also indicate conditions of impending failure.

This chapter is intended to provide construction personnel with an overview of geotechnical instrumentation and an appreciation of its importance to the overall success of the embankment construction. Depending on the project, department practice, and contractual arrangements, the instrumentation may be installed by the contractor or a specialty subcontractor. In this case, field personnel will be responsible for inspecting the installation of the instruments. In all projects, field personnel are responsible for monitoring the contractor's operations so that the instrumentation, which is expensive and important, is properly protected during construction. On many projects, construction engineers and technicians are required to periodically read the instruments and to report the values to the appropriate project supervisor or geotechnical engineer. This is a very important responsibility, and it must be done diligently and carefully.

OVERVIEW OF GEOTECHNICAL INSTRUMENTATION

Information on Instrumentation

The notes for the FHWA training course on geotechnical instrumentation (Dunnicliff and Sellers 1980) are probably the best overall reference on the subject for highway construction. Dunnicliff (1982) gives a useful summary of the training course notes. Hanna (1985), Dunnicliff (1988), and Wilson and Mikkelsen (1978) have written good general references on geotechnical instrumentation.

When Is Instrumentation Used?

Instrumentation is used under the following circumstances:

- When a foundation failure could be expensive, life threatening, or damaging to adjacent property;
- When the design dictates waiting periods or controlled rates of loading;
- When new methods of foundation treatment or unusual embankment materials are being used;
- When the embankment is expected to settle greater than 2 ft; or
- When information gained by instrumenting the first sections of a large project that is being designed and constructed sequentially can be used to improve the design of subsequent sections.

Instrumentation Selection and Location

Selection of the specific types and numbers of instruments and their locations is done by the geotechnical engineer who designed the embankment and/or its foundation. A number of considerations influence these design decisions, but these considerations are not routinely communicated to project engineers or field personnel. This is unfortunate because the more construction personnel know about the instruments and their purpose, the fewer problems there are likely to be with the installation and operation of the instruments, and the more reliable will be the measurements. Above all, good, frequent communication must be maintained between the geotechnical engineer and construction personnel. One way to ensure proper communication is for the geotechnical engineer to periodically visit the project site to discuss progress and review what to do at critical times during construction. The construction personnel should not hesitate to contact the geotechnical engineer if they have questions concerning any aspect of the instrumentation program.

Locations of the instruments will be indicated on the plans. In many instances instrumentation will be in the way of construction activities, or plans may call for instruments or readout devices to be placed in locations obviously hazardous to the instruments or equipment. The field engineer should consult with the soils engineer about relocating such items before they are installed. In most cases, soils engineers would rather have data from a less desirable location than no data at all, so changing the proposed location of instruments in the field is usually not a problem.

All instruments and readouts should be clearly marked or flagged when they are installed. Such marking cannot be overdone. The contractor's foremen, equipment operators, and laborers should be well aware of the location of the instrumentation and its importance to the project.

Instrument Types

Generally for embankment construction, measurements of pore pressures (using piezometers), vertical movements (using settlement platforms, Sondex tubes, and heave stakes), and horizontal movements (using inclinometers and survey stakes) are most commonly used. Other parameters such as earth pressure, soil strains, dynamic properties, and the like may occasionally be required.

There are numerous types of geotechnical instrumentation available, and each has its own advantages and limitations. Information on the specific instruments to be used on a project may be found in the references in the section on Information on Instrumentation or from a geotechnical engineer.

CONSTRUCTION MONITORING

It is often the responsibility of the construction engineer's staff to read the instruments. Soils engineers should make provisions for instructing and familiarizing construction personnel with the instrumentation and explain the purpose of the instrumentation program, how the information will be used, how to read the instruments, how often they need to be read, and what to do with the readings. Presentation and interpretation of the measurements are the geotechnical engineer's responsibility; rarely are field personnel involved in this aspect of instrumentation.

Rules of Data Acquisition

The following rules should be adhered to in the acquisition of data:

1. Read all the instruments at approximately the same time of day on each day they are scheduled to be read.
2. Try to take readings when construction is not in progress. Read all of the instruments in the morning before construction starts, and/or at the end of the day after it has stopped.
3. Obtain complete and accurate information about the construction operations at the time of the readings. Examples are fill height, changes in visible water surfaces (rivers, excavations, dewatering, and the like), and any nearby construction operations. Note the weather conditions at the time of the readings.
4. Pay special attention to readings that are different from previous readings. Do not omit or ignore any readings, no matter how inaccurate they may seem. Substantial differences may indicate a reading error, instrument or readout malfunction, or the need for rapid remedial action. Double-check and record the value, and inform the geotechnical engineer immediately.

Frequency of Readings

Establishing the frequency of readings is the geotechnical engineer's responsibility. It will depend on the project, how rapidly settlement is taking place, or whether stability is critical. In general, readings will range from several times a day to one to three times a week during embankment construction, and perhaps one to four times a month during waiting periods or after the embankment is complete. Geotechnical specialists may initially specify more frequent readings than are really necessary and then adjust the schedule after interpreting the first few sets of data. If consecutive readings show no changes, the time between readings may be extended. If there are large differences, the frequency of readings may be increased. It should be emphasized that if impending failure is indicated by the instruments, corrective action must be taken immediately, and instrumentation readings, data reduction, and interpretation done almost continually during such a time. Close coordination between field personnel and the geotechnical engineer is essential in such cases.

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