An Introduction to Earthwork for Foundations

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1. EARTHWORK: EXCAVATION AND PREPARATION FOR FOUNDATIONS

1.1 EXCAVATION.

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

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

1.1.2.1 GROUNDWATER*.* Probably the greatest source of problems in excavation operations is groundwater. If the seepage of groundwater into an excavation is adequately controlled, other problems will generally be minor and can be easily handled. Several points should be recognized that, if kept in mind, will help to reduce problems attributable to groundwater. In some instances, groundwater conditions can be more severe than indicated by the original field exploration investigation since field explorations provide information only for selected locations and may not provide a true picture of the overall conditions.

1.1.2.1.1 IF GROUNDWATER SEEPAGE BEGINS to exceed the capacity of the dewatering system, conditions should not be expected to improve unless the increased flow is known to be caused by a short-term condition such as heavy rain in the area. If seepage into the excavation becomes excessive, excavation operations should be halted until the necessary corrective measures are determined and affected. The design and evaluation of dewatering systems require considerable experience that the contractor or the owner often does not possess, and therefore the assistance of specialists in this field should be obtained.

1.1.2.1.2 GROUNDWATER WITHOUT SIGNIFICANT SEEPAGE flow can also be a problem since excess hydrostatic pressures can develop below relatively impervious strata and cause uplift and subsequent foundation or slope instability. Excess hydrostatic pressures can also occur behind sheet pile retaining walls as well as shoring and bracing in shaft and tunnel excavations. Visual observations should be made for indications of trouble, such as uncontrolled seepage flow, piping of material from the foundation or slope, development of soft wet areas, uplift of ground surface, or lateral movements.

1.1.2.1.3 ACCURATE DAILY RECORDS should be kept of the quantity of water removed by the dewatering system and of the piezometric levels in the foundation and beneath excavation slopes. Separate records should be kept of the flow pumped by any sump-pump system required to augment the regular dewatering system to note any increase of flow into the excavation. Flowmeters or other measuring devices should be installed on the discharge of these systems for measurement purposes. These records can be invaluable in evaluating “Changed Condition” claims submitted by the contractor.

The contractor should be required to have “standby” equipment in case the original equipment breaks down.

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

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

1.1.2.3.1 WHERE SHORING AND BRACING ARE NECESSARY to provide a stable excavation, and the plans and specifications do not provide details of these requirements, the contractor should be required to submit the plans in sufficient detail so that they can be easily followed and their adequacy checked. The first principle of excavation stabilization, using shoring and bracing, is that the placing of supports should proceed with excavation. The excavation cut should not be allowed to yield prior to placing of shoring and bracing since the lateral pressures to be supported would generally be considerably greater after yield of the unshored cut face than if no movement had occurred prior to placement of the shoring. All safety requirements for shoring and bracing should be strictly enforced.

1.1.2.3.2 THE INSPECTOR must be familiar with stockpiling requirements regarding the distance from the crest of the excavation at which stockpiles can be established and heavy equipment operated without endangering the stability of the excavation slopes. He must also know the maximum height of stockpile *or* weight of equipment that can be allowed at this distance.

1.1.2.3.3 EXCESSIVE EROSION of the excavation slopes must not be permitted. In areas subject to heavy rainfall, it may be necessary to protect excavation slopes with polyethylene sheeting, straw, silt fences, or by other means to prevent erosion. Excavation slopes for large projects that will be exposed for several seasons should be vegetated and maintained to prevent erosion.

1.1.2.4 STOCKPILING EXCAVATED MATERIAL. Generally, procedures for stockpiling are left to the discretion of the contractor. Prior to construction, the contractor must submit his plans for stockpiling to the contracting officer for approval. In certain cases, such as where there are different contractors for the excavation and the backfill phases, it may be necessary to include the details for stockpiling operations in the specifications. In either case, it is important that the stockpiling procedures be conducive to the most advantageous use of the excavated materials.

1.1.2.4.1 AS THE MATERIALS ARE EXCAVATED, they should be separated into classes of backfill and stockpiled accordingly. Thus the inspection personnel controlling the excavation should be qualified to classify the material and should be thoroughly familiar with backfill requirements. Also, as the materials are placed in stockpiles, water should be added or the materials should be aerated as required to approximate optimum water content for compaction. Field laboratory personnel can assist in determining the extent to which this is necessary. The requirements of shaping the stockpile to drain and sealing it against the entrance of undesirable water by rolling with spreading equipment or covering with polyethylene sheeting should be enforced. This step is particularly important for cohesive soils that exhibit poor draining characteristics and tend to remain wet once saturated by rain. Stockpiles must be located over an area that is large enough to permit processing where they will neither interfere with peripheral drainage around the excavation nor overload the slopes of the excavation.

1.1.2.4.2 IN CASES where significant energy and cost saving can be realized, special stockpiling requirements should be implemented. An example would be *a* large project consisting of a number of excavation and backfilling operations. The excavation material from the first excavation could be stockpiled for use as backfill in the last excavation. The material from the intermediate excavations could in turn be immediately used as backfill for the subsequent phases of the project and thereby eliminate double handing of excavated backfill for all but the first-phase excavation.

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

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

This record would be of value if subsequent claims of “Changed Conditions” are made by the contractor.

1.2 FOUNDATION PREPARATION.

1.2.1 GENERAL. In this discussion, preparation applies to foundations for backfill as well as those for structures to be placed in the excavation. Generally, if proper excavation procedures have been followed, very little additional preparation will be required prior to backfill placement.

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

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

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

1.2.2.3 BEFORE PLACEMENT OF ANY STRUCTURE FOUNDATION is begun, the plans should be rechecked to ensure that all required utilities and conduits under or adjacent to the foundation have been placed, so that excavating under or undermining the foundation to place utilities and conduits will not become necessary later.

1.2.2.4 OCCASIONALLY, it may be found upon completion of the excavation that if a structure was placed as shown on the plans, it would be supported on two materials with drastically different consolidation characteristics, such as rock and soil, rock and backfill, or undisturbed soil and backfill. This situation could occur because the predesign subsurface information was inadequate, because the structure was relocated or reoriented by a subsequent change in the plans, because of an oversight of the design engineer, or because of the excavation procedures followed by the contractor. Regardless of the reason, measures such as overexcavation and placement of subsequent backfill should be taken, where possible, and in coordination with the design office to provide a foundation of uniform material. Otherwise, the design office should evaluate the differences in foundation conditions for possible changes to the structural foundation elements.

1.2.2.5 PREPARING THE AREA TO RECEIVE THE BACKFILL consists of cleaning, leveling, and compacting the bottom of the excavation if the foundation is in soil. All debris and foreign material, such as trash, broken concrete and rock, boulders, and forming lumber, should be removed from the excavation. All holes, depressions, and trenches should be filled with the same material as that specified to be placed immediately above such a depression, unless otherwise designated, and compacted to the density specified for the particular material used. If the depression is large enough to accommodate heavy compacting equipment, the sides of the depression should have a positive slope and be flat enough for proper operation of compaction equipment. After the area is brought to a generally level condition by compacting in lifts in accordance with specifications, the entire area to receive backfill should be sacrificed to the depth specified, the water content adjusted if necessary, and the area compacted as specified. If the foundation is in rock, the area should be leveled as much as possible and all loose material removed.

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

2. BACKFILL OPERATIONS

2.1 PLACEMENT OF BACKFILL.

2.1.1 GENERAL. Backfill construction is the refilling of previously excavated space with properly compacted material. The areas may be quite large, in which case the backfilling operation will be similar to embankment construction. On the other hand, the areas may be quite limited, such as confined areas around or between and beneath concrete or steel structures and areas in trenches excavated for utility lines. Prior to construction of the backfill, the inspection personnel should become thoroughly familiar with the various classes of backfill to be used. They should be able to readily identify the materials on sight, know where the various types of material should be placed, and be familiar with the compaction characteristics of the soil types.

2.1.2 GOOD CONSTRUCTION PRACTICES, AND PROBLEMS*.* Problems with placement of backfill will vary from one construction project to another. The magnitude of the problems will depend on the type of materials available such as backfill, density requirements, and the configuration of the areas in which compaction is to be accomplished. Problems should be expected during the initial stages of backfill compaction unless the contractor is familiar with compaction characteristics of backfill materials. The inspector can be of great assistance to the contractor during this period by performing frequent water content and density checks. The information from these checks will show the contractor the effects of the compaction procedures being used and point out any changes that should be made.

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

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

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

2.1.2.2.2 INORGANIC CLAYS, inorganic silts, and very fine sands of low to medium plasticity are fairly easily compacted in open zones with sheepsfoot or rubber-tired rollers in the 15,000-pound and above wheel-load class. Some inorganic clays can be adequately compacted in confined zones using rammer or impact compactors with a static weight of at least 100 pounds provided close control of lift thickness and water content is maintained.

2.1.2.2.3 FINE-GRAINED, HIGHLY PLASTIC MATERIALS, though not good backfill materials, can best be compacted in open zones with sheepsfoot rollers. Sheepsfoot rollers leave the surface of the backfill in a rough condition, which provides an excellent bond between lifts. In confined areas the best results, which are not considered good, are obtained with rammer or impact compactors.

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

2.1.2.3.1 AS A GENERAL RULE, a loose-lift thickness that will result in a 6-inch lift when compacted can be allowed for most sheepsfoot and pneumatic-tired rollers. Cohesive soils placed in approximately l0-inch loose lifts will compact to approximately 6 inches, and cohesionless soils placed in approximately 8-inch base lifts will compact to 6 inches. Adequate compaction can be achieved in cohesionless materials of about 12- to 15-inch loose-lift thickness if heavy vibratory equipment is used. The addition of vibration to rolling equipment used for compacting cohesive soils generally has little effect on the lift thickness that can be compacted, although compaction to the desired density can sometimes be obtained by fewer coverages of the equipment.

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

2.1.2.4 DENSITY REQUIREMENTS. In open areas of backfill where structures will not be constructed, compaction can be less than that required in more critical zones. Compaction to 90 percent of CE 55 maximum dry density as obtained by MIL-STD-621 should be adequate in these areas. If structures are to be constructed on or within the backfill, compaction of cohesionless soils to within 95 to 100 percent of CE 55 maximum dry density and of cohesive soils to at least 95 percent of CE 55 should be required for the full depth of backfill beneath these structures. The specified degree of compaction should be commensurate with the tolerable amount of settlement, and the compaction equipment used should be commensurate with the allowable lateral pressure on the structure. Drainage blankets and filters having special gradation requirements should be compacted to within 95 to 100 percent of CE 55 maximum dry density. Table 5-1 gives a summary of the type of compaction equipment, number of coverages, and lift thickness for the specified degree of compaction of various soil types

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

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

2.1.2.5.2 UNDER NO CIRCUMSTANCES should frozen material, from stockpile or borrow pit, be placed in backfill that is to be compacted to a specified density.

2.1.2.5.3 PRIOR TO HALTING CONSTRUCTION during the winter, the peripheral surface drainage system should be checked and reworked where necessary to provide positive drainage of surface water away from the excavation.

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

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

2.1.2.5.6 DURING FREEZING WEATHER, records should be kept of the elevation of all critical structures to which there is the remotest possibility of damage or movement due to frost heave and subsequent thaw. It is important that frost-free bench marks be established to which movement of any structure can be referenced. Bench marks also should be established on the structures at strategic locations prior to freezing weather.

2.1.2.5.7 AT THE BEGINNING OF THE FOLLOWING construction season and after the temporary insulating coverings are removed, the backfill should be checked for frozen material and ice lenses, and the density of the compacted material should be checked carefully before backfilling operations are resumed. If any backfill has lost its specified density because of freezing, it should be removed.

2.1.2.6 ZONES HAVING PARTICULAR GRADATION REQUIREMENTS*.* Zones that have particular gradation requirements include those needed to conduct and control seepage, such as drainage blankets, filters, and zones susceptible to frost penetration.

Soil Group	Soil Types		Degree of Compaction	Fill and Backfill: Typical Equipment and Procedures for Compaction — Equipment	No. of Passes or Coverages	Comp. Lift Thick., in.	Placement Water Content	Field Control
Pervious (Free-Draining)	GW GP SW SP	Compacted	90 to 95% of CE 55 maximum density; 75 to 85% of relative density	Vibratory rollers and compactors	Indefinite	Indefinite	Saturate by flooding	Control tests at intervals to determine degree of compaction or relative density
				Rubber-tired roller[b]	2-5 coverages	12		
				Crawler-type tractor[c]	2-5 coverages	8		
				Power hand tamper[d]	Indefinite	6		
		Semicompacted	85 to 90% of CE 55 maximum density; 65 to 75% of relative density	Rubber-tired roller[b]	2-5 coverages	14	Saturate by flooding	Control tests as noted above, if needed
				Crawler-type tractor[c]	1-2 coverages	10		
				Power hand tamper[d]	Indefinite	8		
				Controlled routing of construction equipment	Indefinite	8-10		
Semipervious and Impervious	GM GC SM SC ML CL OL CH MH CH OH	Compacted	90 to 95% of CE 55 maximum density	Rubber-tired roller[b]	2-5 coverages	8	Optimum water content	Control tests at intervals to determine degree of compaction
				Sheepsfoot roller[e]	4-8 passes	6		
				Power hand tamper[d]	Indefinite	4		
		Semicompacted	85 to 90% of CE 55 maximum density	Rubber-tired roller[b]	2-4 coverages	10	(A) Optimum water content (B) By observation; wet side-maximum water content at which material can satisfactorily operate, dry side-minimum water content required to bond particles and which will not result in voids or honeycombed material	(A) Control tests as noted above, if needed (B) Field control exercised by visual inspection of action of compacting equipment
				Sheepsfoot roller[e]	4-8 passes	8		
				Crawler-type tractor[c]	3 coverages	6		
				Power hand tamper[d]	Indefinite	4		
				Controlled routing of construction equipment	Indefinite	6-8		

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

a From TM 5-818-1.
b Rubber-tired rollers having a wheel load between 19,000 and 35,000 lb and a tire pressure between 80 and 100 psi.
c Crawler-type tractors weighing not less than 20,000 lb and exerting a foot pressure not less than 6-1/2 psi.
d Power hand tampers weighing more than 100 lb; pneumatic or operated by gasoline engine.
e Sheepsfoot rollers having a foot pressure between 250 and 500 psi and tamping feet 7 to 10 in. in length with a face area between 7 and 16 sq in.

Table 3-1

Summary of compaction criteria

Drainage zones are often extremely important to the satisfactory construction and subsequent performance of the structure. To maintain the proper functioning of these zones, care must be taken to ensure that the material placed has the correct gradation and is compacted according to specifications.

2.1.3 SPECIAL PROBLEMS. In open zones, compaction of backfill will not generally present any particular problems if proper compaction procedures normally associated with the compaction of soils are exercised and the materials available for use, such as backfill, are not unusually difficult to compact. The majority of the problems associated with backfill will occur in confined zones where only small compaction equipment producing a low compaction effort can be used or where because of the confined nature of the backfill zone even small compaction equipment cannot be operated effectively.

2.1.3.1 CONSIDERABLE LATITUDE exists in the various types of small compaction equipment available. Unfortunately, very little reliable information is available on the capabilities of the various pieces of equipment. Depending upon the soil type and working room, it may be necessary to establish lift thickness and compaction effort based essentially on trial and error in the field. For this reason, close control must be maintained particularly during the initial stages of the backfill until adequate compaction procedures are established.

2.1.3.2 CIRCULAR, ELLIPTICAL AND ARCHED WALLED STRUCTURES are particularly difficult to adequately compact backfill beneath the underside of haunches because of limited working space. Generally, the smaller the structure, the more difficult it is to achieve required densities. Rock, where encountered, must be removed to a depth of at least 6 inches below the bottom of the structure and the overdepth backfilled with suitable material before foundation bedding for the structure is placed. Some alternate bedding and backfill placement methods are discussed below.

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

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

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

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

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

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

3. SPECIFICATION PROVISIONS

3.1 GENERAL

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

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

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

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

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

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

3.2.3.1 UNDER CERTAIN CONDITIONS, such as those that existed in the early stages of missile base construction where time was an important factor, it may be necessary or desirable to award contracts for the work in phases. As a result, one contractor may do the excavating and another place the backfill. It is probable that the excavation contractor will have little or no interest in stockpiling the excavated materials in a manner conducive to good backfilling procedures. When such a situation can be foreseen, the specifications should set forth stockpiling procedures. The justification for such requirements would be economy and optimum use of materials available from required excavation as backfill.

3.2.3.2 THE SPECIFICATIONS will contain provisions for removing, segregating, and stockpiling or disposing of material from the excavation and will refer to the plans for locations of the stockpiles. The subsoil conditions and engineering characteristics requirements may state that the specifications must be quite definite concerning segregation and stockpiling procedures so that the excavated materials can be used most advantageously in the backfill. The specification may require that water be added to the material or the material be aerated as it is stockpiled to the approximate optimum water content, that the stockpile be shaped to drain and be sealed from accumulation of excess water, and that the end dumping of material on the stockpile be prohibited to prevent segregation of material size or type along the length of the stockpile.

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

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

3.3.1 SPECIFICATIONS FOR STRUCTURES FOUNDED ON SOIL require the removal of all loose material and all unsuitable material, such as organic clay or silt, below the foundation grade. When doubt exists as to the suitability of the foundation materials, a soils engineer should inspect the area and his recommendations should be followed. When removal of rock material below the planned foundation level is required, the overexcavation will usually require filling with concrete. The specifications also require dewatering to the extent that no backfill or structural foundation is placed in the wet.

3.3.2 SPECIFICATIONS FOR PREPARATION OF THE SOIL FOUNDATION to receive backfill require removing all debris and foreign matter, making the area generally level, and scarifying, moistening, and compacting the foundation to a specified depth, generally 12 inches. Specific provisions may or may not be given with respect to leveling procedures.

3.4 BACKFILL OPERATIONS. The specifications define the type or types of material to be used for backfill construction and provide specific instructions as to where these materials will be used in the backfill, The percentage of CE 55 maximum dry density to be obtained, determined by a designated standard laboratory compaction procedure, will be specified for the various zones of backfill. The maximum loose-lift thickness for placement will also be specified. Because of the shape of the compaction curve, the degree of compaction specified can be achieved only within a certain range of water content for a particular compaction effort. Though not generally specified, the range of water contents is an important factor affecting compaction.

3.4.1 THE SPECIFICATIONS SOMETIMES STIPULATE the characteristics and general type of compaction equipment to be used for each of the various types of backfill. Sheepsfoot or rubber-tired rollers, rammer or impact compactors, or other suitable equipment are specified for fine-grained, plastic materials. Noncohesive, freedraining materials are specified to be compacted by saturating the material and operating crawler-type tractor, surface or internal vibrators, vibratory compactors, or other similar suitable equipment. The specifications generally will prohibit the use of rock or rock-soil mixtures as backfill in this type of construction. However, when the use of backfill containing rock is permitted, the maximum size of the rock is given in the specifications along with maximum lift thickness, loading, hauling, dumping, and spreading procedures, type of compaction equipment, and method of equipment operation. The specifications should protect areas where heavy equipment cannot operate. Rock-soil mixtures having greater than 8 to 10 percent binder should be prohibited in all areas. In the case of backfill containing rock, the density is not generally specified. Obtaining adequate density is usually achieved by specifying the compaction procedures. The specifications may require that these procedures be developed in field test sections.

3.4.2 SPECIFICATIONS MAY ALSO REQUIRE specific equipment and procedures to ensure adequate bedding for round-bottom structures such as tunnels, culverts, conduits, and tanks.

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

3.4.4 UNUSUALLY SEVERE SPECIFICATION REQUIREMENTS may be necessary for backfill operations in confined areas. The requirements may include strict backfill material type limitation, placement procedures, and compaction equipment.

3.4.5 IT IS SUGGESTED it should not be the policy of the owner to inform the contractor of ways to accomplish the necessary protection from freezing temperatures. However, to ensure that adequate protection is provided, it may be necessary to specify that the contractor submit detailed plans for review for such protection.

4. CONSTRUCTION CONTROL

4.1 GENERAL. The heterogeneous nature of soil makes it the most variable construction material with which engineers are required to work. Research in soil mechanics and experience gained recently in constructing large earth embankments have provided additional knowledge toward understanding and predicting the behavior of a soil as a construction material. However, only with careful control can engineers ensure that backfill construction will satisfactorily fulfill the intended functions. Both the contractor and the owner share dual responsibility in achieving a satisfactory product. The contractor is responsible for inspections and tests through his quality control system. The owner's responsibility is assuring that the contractor's quality control system is achieving the desired results through its quality acceptance system.

4.1.1 CONTRACTOR QUALITY CONTROL. The contractor is responsible for all of the activities that are necessary to ensure that the finished work complies with the plans and specifications to include quality control requirements, supervision, inspection, and testing. The construction contract special provisions explain the quality control system that the contractor must establish; the technical provisions specify the construction requirements with the tests, inspections, and submittals that the contractor must follow to produce acceptable work.

(1) Prior to construction, the contractor must submit for approval by the Contracting Officer his plan for controlling construction quality. The plan must contain all of the elements outlined in the special provisions and demonstrate a capability for controlling all of the construction operations specified in the technical provisions. The plan must include the personnel (whether contractor's personnel or outside private firm) and procedures the contractor intends to use for controlling quality, instructions and authority he is giving his personnel, and the report form he will use. The plan should be coordinated with his project construction schedule.

(2) During construction, the contractor is responsible for exercising day by day construction quality control in consonance with his accepted control plan. He must maintain current records of his quality control operations. Reports of his operations must be submitted at specified intervals and be in sufficient detail to identify each specific test.

(3) The prime contractor is responsible for the quality control of all work including any work by subcontractors.

4.1.2 OWNER ACCEPTANCE CONTROL. In contrast to the contractor's quality control, the owner is responsible for quality assurance, which includes: the checks, inspections, and tests of the products that comprise the construction; the processes used in the work; and the finished work for the purpose of determining whether the contractor's quality control is effective and he is meeting the requirements of the contract. These activities are to assure that defective work or materials are not incorporated in the construction.

4.1.3 COORDINATION BETWEEN OWNER AND CONTRACTOR*.* The contractor's quality control does not relieve the owner from his responsibility for safeguarding the Owner's interest. The quality assurance inspections and tests made by the Owner may be carried out at the same time and adjacent to the contractor's quality control operations. Quality control and quality assurance supplement one another and assist in avoidance of construction deficiencies or in early detection of such deficiencies when they can be easily corrected without requiring later costly tear out and rebuild. The remainder of this material discusses the owner quality assurance activities.

4.2 OWNER ACCEPTANCE CONTROL ORGANIZATION.

4.2.1 GENERAL. Difficulties in construction of a compacted backfill can be attributed at least in part to inexperience of the control personnel in this phase of construction work or lack of emphasis as to the importance of proper procedure and control. Since it is essential that policies with regard to control be established prior to the initiation of construction, thorough knowledge of the capabilities of the control organization and of the intent of the plans and specifications is required. Control is achieved by a review of construction plans and specifications, visual inspection of construction operations and procedures, and physical testing. A well-organized, experienced inspection force can mean the difference between a good job and a poor one. A good field inspection organization must be staffed and organized so that inspection personnel and laboratory technicians are on the job when and where they are needed. Thus the organization must have knowledge of the construction at all times. Prior to construction, the training, guidance, and support required to ensure that the inspection force is fully competent should be determined. If experience is lacking, training and supervision become more important and necessary.

(1) The training program for earthwork inspection personnel should consist of both classroom and field instruction. During the classroom sessions, the specifications should be studied, discussed, and interpreted as to the intent of the designer. The critical areas of compaction should be pointed out as well as the location of zoned and transitional areas. The inspection personnel should be instructed on the various zones of backfill, types of backfill, density requirements, and classification and compaction characteristics for each class of backfill. Inspection personnel should also be instructed as to approved sources of borrow for each type of backfill and borrow pit operations, such as loading procedures to provide uniform materials and pre-wetting to provide uniform moisture. The various types of backfill should be studied so inspection personnel can recognize and readily identify these materials. Jar samples may be

furnished for later reference and comparison; preferably these should be samples of the particular soils on which laboratory compaction tests were performed in design studies. Instructions should be given as to water content control, lift thickness, and most suitable compaction equipment for each type of backfill. Inspection personnel should be capable of recommending alternate procedures to achieve the desired results when the contractor's procedure is unsuccessful.

(2) Inspection personnel should be made aware of the importance of their work by explaining the engineering features of the design on which the construction requirements are based. Every opportunity should be taken to assemble the inspection force for discussion of construction problems and procedures so that all can gain knowledge from the experience of others. Inspection personnel should be kept informed of all decisions and agreements pertinent to their work that are made at higher levels of administration. They should be advised of the limits of their authority and contact with contractor personnel.

(3) Field training of inspection personnel should include observation of their control techniques and additional instruction on elements of fieldwork requiring correction. Inspection personnel should be instructed in the telltale signs that give visual indications whether sufficient compaction is being applied and proper water content is being maintained. They should develop the ability to determine from visual observations (based on correlations with tests on the project) that satisfactory compaction is being obtained so that considerable emphasis can be placed on such methods as a control procedure rather than relying on field tests alone. Inspection personnel should be capable of selecting locations at which field density and moisture determinations should be made. To meet this requirement they must be present almost continuously during compaction operations to observe and note areas where tests appear to be needed. Laboratory technicians should be made available to perform tests so that the inspection personnel will be free to observe the placement and compaction process on another

portion of the backfill. Inspection personnel should be able to use expedient quick-check field apparatus such as the Proctor and hand-cone penetrometers to make a rapid check of the field water content to supplement acceptance testing and to serve as a guide in determining areas that should be tested. Inspection personnel should also be well versed in normal testing procedures so they can properly supervise testing or explain the procedure in case they are questioned by contractor personnel.

(4) It is necessary and important that inspection personnel ascertain their authority and responsibility at an early stage in the construction. Their policy should be one of firmness coupled with practicality. The quality of the work should not be compromised; however, unreasonable requirements and restrictions should not be placed on the contractor in enforcing the specifications. If the inspection personnel know their job and are fair and cooperative in dealing with the contractor, they will gain his or her respect and cooperation and be able to efficiently carry out their responsibilities.

4.2.2 FIELD LABORATORY FACILITIES*.* The field laboratory is used for routine testing of construction materials (such as gradation, water content, compaction, and Atterberg limits tests) and for determining the adequacy of field compaction. The data obtained from tests performed by inspection personnel serve as a basis for determining and ensuring compliance with the specifications, for obtaining the maximum benefit from the materials being used, and for providing a complete record of the materials placed in every part of the project. The size and type of laboratory required are dependent on the magnitude of the job and the type of structures being built. Where excavation and backfill construction are extensive and widespread, the establishment of a centrally located field laboratory is generally beneficial. This laboratory in addition to having equipment for on-the-job control will provide a nucleus of experienced soils engineers or engineering technicians for general supervision and training of inspection personnel. Field control laboratories on the sites may be established as necessary during the excavation and backfill phases of the construction. They may be set up in an enclosed space allocated by the project officer or in mobile testing laboratories, such as pickup trucks with a camper and equipped with the necessary testing equipment for performance of field density tests, water content tests, and gradation tests. Another possibility is the use of large portable boxes in which equipment is stored. When special problems arise and the required testing equipment is not available at the site laboratory, the testing should be performed at the central laboratory.

4.3 EXCAVATION CONTROL TECHNIQUES. Control to obtain a satisfactory excavation is exercised by enforcement of approved plans, visual observations, a thorough knowledge of the contractor's plan of operation and construction schedule, the dimensions and engineering features of the structure(s) to be placed in the excavation, and vertical and horizontal control measurements to ensure that the proper line and grade requirements are met.

4.4 FOUNDATION PREPARATION CONTROL TECHNIQUES. The main control technique for ensuring proper foundation preparation is visual inspection. Prior to backfill placement, all uncompacted fill should be removed from those portions of the excavation to be backfilled. The items included are road fills, loose material that has fallen into overexcavated areas adjacent to foundations, and construction ramps other than those required for access to the excavation. Identification of such items will be easier if the inspection personnel have charted the items on the plans as they were created, since they are not always easily discernible by visual inspection. It is desirable to control earth backfill placed in foundation leveling operations by water content and density tests. Care should be exercised to ensure that all subdrains required in the foundation are protected by filters and transitional zones that are adequate to prevent infiltration of fines from the surrounding backfill that might otherwise clog the drains and undermine structures.

4.5 BACKFILL QUALITY ACCEPTANCE CONTROL. The necessary authority to assure that compacted backfill is in compliance with the specifications is given in the specifications. The control consists of inspecting and testing materials to be used, checking the amount and uniformity of soil water content, maintaining the proper thickness of the lifts being placed, and determining the dry unit weight being obtained by the compaction process. While control consists of all of these things, good inspection involves much more.

4.5.1 INSPECTION ACTIVITIES. One of the best inducements to proper placement and compaction of backfill is the presence of the inspection personnel when backfill is being placed. However, to be of value the inspector must know his job. He should be familiar with all aspects of backfill operation, such as selection and availability of materials, processing, hauling, compaction, and inspection procedures. Some of the most common deficiencies in inspection personnel activities are as follows:

(1) Failing to enforce specification requirements for preparation of the area for backfill. Often temporary fills, the working platform, debris, and other undesirable materials are left in the excavation causing weak areas and resulting in greater consolidation in the backfill.

(2) Failing to be cognizant of detailed site-adapted plans for stockpiling and placing backfill at specific locations. Without knowledge of these plans, inspection personnel are sometimes forced to make engineering decisions beyond their capabilities, such as on-site approval of new material or mixture of materials, and stockpile locations.

(3) Allowing processing of backfill material and adjustment of water content on the fill that should have been accomplished prior to placement. The results are the segregation of grain sizes and the nonuniform distribution of water content. All major processing,

including crushing, raking, mixing, and adjusting of water content, must be done in the stockpile or borrow areas.

(4) Allowing lift thickness that is inconsistent with equipment capabilities and thicker than that allowed by specifications. Field density determinations will not necessarily detect this inconsistency.

(5) Allowing construction of backfill slopes that are too steep to obtain the full effect of compaction equipment.

(6) Failing to require that the fill be built up uniformly in a well-defined pattern. Since the contractor's next move cannot be predicted, the inspection personnel cannot adequately plan their operations, and it is difficult to determine which areas of backfill have been tested and approved when the backfill is built up in an unorganized manner.

(7) Allowing segregation of coarse-grained, non-cohesive materials. This condition is caused by improper hauling, dumping, and spreading techniques.

(8) Allowing the use of compaction equipment not suited to material being compacted.

(9) Failing to perform sufficient field density testing in critical areas.

(10) Allowing material that is too wet or too dry to be compacted.

(11) Failing to require that intermediate backfill surfaces be shaped to drain during backfilling at other locations.

4.5.2 INSPECTION REQUIREMENTS. *To* properly control and inspect backfill operations, the inspection personnel must keep informed of the construction schedule at all times and be at the site where backfill is being placed. The inspection personnel must be thoroughly familiar with every aspect of the earthwork section of the specifications and know boundary locations for the various zones of material. They should be able to readily identify the various classes of backfill and know their compaction characteristics and requirements. Good inspection personnel will also know the compaction capabilities of various types of equipment and the materials that each type is best suited to compact.

(1) To maintain adequate control of compaction operations, a staff of earthwork inspectors and laboratory personnel commensurate with the importance of the work and size of the operation is essential. There should be at least one inspector at the fill when backfill is being placed. His sole duty should be inspection of earthwork. Although he should be familiar with the testing procedures and capable of directing testing operations and selecting locations for testing, he should not be required to perform the tests. Laboratory technicians should be available for this purpose.

(2) The specifications should require that necessary processing of backfill materials be performed in the stockpile or borrow pit. Processing includes raking or crushing to remove oversize material, mixing to provide uniformity, and watering or aerating to attain a water content approximating optimum for compaction. An earthwork inspector is required at the stockpile or borrow pit to enforce these provisions. In addition, this inspector has the duties of classifying the materials, determining their suitability, and directing the zone of backfill in which they are to be placed. He is charged with the responsibility of seeing that the contractor uses the materials available for backfill in the most advantageous manner. Generally, the stockpile or borrow pit inspector relies upon visual inspection and experience to exercise control over these operations. Occasionally, he may require that appropriate tests be performed to confirm his judgment.

(3) The duties of the backfill inspector consist of checking the material for suitability as it is placed on the fill and spread, ensuring that any oversize material, roots, or trash found in the material is removed, checking the thickness of the lift prior to compaction, checking for uniformity and amount of water content, observing compaction operations, and directing or monitoring testing of the compacted material for compliance with density and water content requirements.

(4) There are many techniques and rule-of-thumb procedures that the earthwork inspector can and must resort to for assistance in his work. A few of them are discussed below; others can be ascertained by inspectors meeting together to discuss problems and corrective action.

(a) The thickness of loose lifts can be checked easily by probing with a calibrated rod just prior to compaction. Compaction of lifts too thick for the equipment will not normally be detected by performing density tests on the lift, since adequate compaction may be indicated by a test made in the upper portion of the lift and the lower portion may still have too low a density. It is therefore a requisite that lift thickness be controlled on a loose and thickness basis prior to compaction

(b) Checks for proper bond between layers can be made by digging through a lift after compaction and using a shovel to check this bond. If the soil can be separated easily along the plane between lifts, sufficient bond is not being provided. Backfill materials should not be placed on dried or smooth surfaces, as bond will be difficult to obtain.

(c) Inspection personnel should be thoroughly aware of areas where compaction is critical. These areas are the confined spaces around and adjacent to structures that are not accessible to the rolling and spreading equipment. Although the volume of backfill is usually rather small in these areas, a much higher frequency of check testing for density is required as well as a careful check of the quality and water content of the materials to be placed.

4.5.3 COMPACTION CONTROL TESTS. Compaction tests will have been performed on representative specimens obtained from exploratory sampling prior to construction. The selection of suitable backfill material are in fact generally made based on these and other tests. At least during the early phases of the backfill operation, density requirements are based on these and in some cases additional preconstruction compaction tests. Conditions may develop that require compaction tests during backfill operations to establish new density requirements. Generally, these changes are the results of backfill material deviations. The need for additional control tests may be ascertained from visual observation and changes in compaction characteristics during field compaction. For most backfill materials, quality acceptance compaction control tests must be performed according to the procedure in ASTM D 1557, or the two-point test procedure (App B) for some cohesionless soils where higher maximum dry densities can be obtained using the vibratory (relative density) compaction.

4.5.4 FIELD MOISTURE-DENSITY CONTROL TECHNIQUES*.* Moisture-density control is the most important phase of backfill operations. The success of ensuring required backfill density often determines the functional service of the embedded structure. Good control involves many techniques. An experienced inspector will not rely on any one technique, but from experience will base his control on a combination of techniques. Moisture-density control techniques may be grouped into three categories: rule-of-thumb techniques, and indirect and direct moisture density measurements.

(1) *Rule-of-thumb methods.* Rule-of-thumb techniques are derived from experience and are based on visual observations and feel of the material. A rule-of-thumb for judging if the water content of a fine-grained, plastic material is near the optimum water content consists of rolling the material between the hands until it forms a thread approximately

1/8 inch in diameter. If the material at this stage tends to crack or crumble, it is in the proper water content range for compaction. It will be recognized that this method is similar to the method of determining the plastic limit of a soil. The methods are similar because the optimum water content for compaction of a cohesive soil roughly approximates the plastic limit of the soil.

(a) Another good indication of whether the proper water content has been obtained can be determined by observing the compacting equipment. When a sheepsfoot roller is being used and the soil sticks to the roller to any great extent, the material is being rolled too wet for the equipment being used; at optimum water content it may be expected that a few clods will be picked up by the roller but a general sticking will not occur. If the compacted fill does not definitely spring (noticeable to visual observation) under hauling and compaction equipment, it is probable that several lifts of fill have been placed too dry. The roller should roll evenly over the surface of the backfill if water content is uniform throughout the lift and should not ride higher on some portions of the backfill than on others. If on the first pass of a rubber-tired roller the tires sink to a depth equal to or greater than one-half the tire width, if after several passes the soil is rutting excessively, or if at any time during rolling the weaving or undulating (as opposed to normal “springing” of the surface) of the material is taking place ahead of the roller, either the tire pressure is too high or the water content of the material is too high. On the other hand, if the roller tracks only very slightly or not at all and leaves the surface hard and stiff after several passes, the soil is probably too dry. For most soils having proper water contents, the roller will track evenly on the first pass and the wheels will embed 3 to 4 inches. Some penetration should be made into soil at its proper water content, though the penetration will decrease as the number of passes increases. After several passes of a sheepsfoot roller, the roller should start walking out if adequate and efficient compaction is being obtained. Walking out means the roller begins bearing on the soil through its feet only; the drum is riding a few inches above the soil surface. If the roller walks out after only a few passes, the soil is probably too dry; if it does not walk out but

continues churning up the material after the desired number of passes, the soil is too wet or the foot contact pressure is too high.

(b) A trained inspector will spend some time in the field laboratory, performing several compaction tests on each type of backfill material to become familiar with the differences in looks, feel, and behavior and learning to recognize when they are too dry or too wet, as well as when they are at optimum water content.

(2) *Indirect methods.* Indirect methods of determining the density and water content involve measurement of the characteristic of the material that has been previously correlated to the maximum density and optimum water content. These methods of measuring in-place density and water content can usually effect a more detailed control of a job than can be accomplished by direct methods alone because they can provide quicker determinations. However, no indirect method should ever be used without first checking and calibrating it with results obtained from direct methods, and periodic checks by direct methods should be made during construction. Indirect methods include the use of the nuclear moisture-density meter, the Proctor penetrometer (often referred to as the “Proctor needle"), the hand cone penetrometer, and in the hands of an experienced inspector even a shovel.

(a) The nuclear moisture-density method conducted in accordance with ASTM D 2922 (for density determination) and ASTM D 3017 (for water content determination) is the only indirect control method recommended for quality acceptance control. The method provides a relatively rapid means for determining both moisture content and density. Of the three methods presented in ASTM D 2922, Method B - Direct Transmission is the best suited for a compacted lift thickness exceeding approximately 4 inches.

(b) Penetrometers, such as the Proctor and hand cone penetrometers, are useful under certain conditions for approximating density. However, both methods require careful calibration using soils of known density and water content and considerable operating experience. Even then, the results may be questionable because nonuniform water content (in fine-grained material) or a small piece of gravel can affect the penetration resistance. Penetrometers, therefore, are not recommended for general use in compaction control; however, they can be a very useful tool in supplementing the inspector's visual observations and providing a general guide for detecting areas of doubtful compaction. The procedure using the Proctor penetrometer for determining the relation between wet density, penetration resistance, and water content is described in ASTM D 1558.

(c) Many inspectors in the past have had good success in estimating density by simply observing the resistance of the compacted soil to penetration by a spade. This method requires considerable experience and is useful only in detecting areas that might require further density tests.

(3) Direct Methods. Direct field density determination consists of volume and weight measurements to determine the wet density of in-place backfill and water content measurements to determine in-place water contents and dry densities. The three methods used for the Corps quality acceptance density determination are:

(a) the sand-cone method according to ASTM D 1556;

(b) the rubber-balloon method according to ASTM D 2167; and for soft, fine-grained cohesive soils, the drive-cylinder method according to ASTM D 2937. In addition to the approved methods, a method sometimes employed to measure densities of coarse-grained cohesionless material consists of the large-scale, water-displacement method. The sand cone method is considered to be the most reliable method and is recommended as the proof or calibration test for calibrating other methods such as the nuclear density method.

4.5.5 WATER CONTENT BY MICROWAVE OVEN. The biggest problem associated with both field compaction tests and in-place density and water content control tests is the length of time required to determine water content. Conventional ovendrying methods require from 15 to 16 hours for most fine-grained cohesive soils. In some cases, such as confined zones, the contractor may have placed and compacted several layers of backfill over the layer for which density tests were made before quality acceptance test data are available. Even though the contractor places successive layers at his own risk, a rapid turn around between testing and test results could prevent costly-tear out and recompact procedures. Drying specimens in microwave ovens offers a practical means for rapid determination of water content for most backfill materials if properly conducted. Times required for drying in a microwave oven are primarily governed by the mass of water present in the specimen and the power-load output of the oven. Therefore, drying time must be calibrated with respect to water content and oven output. Also, it may not be possible to successfully dry certain soils containing gypsum or highly metallic soils such as iron ore, aluminum rich soils, and bauxite.

4.6 FREQUENCY AND LOCATION OF QUALITY ACCEPTANCE DENSITY TESTS. Acceptance control testing should be more frequent at the start of backfill placement. After compaction effort requirements have been firmly established and inspection personnel have become familiar with materials behavior and acceptable compaction procedures, the amount of testing can be reduced. Many factors influence the frequency and location of tests. The frequency will be dependent on the type of material, adequacy of the compaction procedures, and how critical the backfill being compacted is in relation to the performance of the structure.

(1) A systematic testing program should be established at the beginning of the job. Acceptance control tests laid out in a predetermined manner are usually designated as routine control tests and are performed either at designated locations or at random representative locations, no matter how smoothly the compaction operations are being

carried out. A routine acceptance control test should be conducted for at least every 200 cubic yards of compacted backfill material in critical areas where settlement of backfill may lead to structural distress and for at least every 500 cubic yards in open areas not adjacent to structures.

(2) In addition to routine acceptance control tests, tests should be made in the following areas: where the inspector has reason to doubt the adequacy of the compaction; where the contractor is concentrating fill operations over relatively small areas; where small compaction equipment is being used such as in confined areas; and where field instrumentation is installed, mainly around riser pipes.

4.7 ERRORS IN FIELD DENSITY MEASUREMENTS*.* Density and water content measurements determined by any of the methods discussed above are subject to three possible sources of errors. The three categories of possible error sources are human errors, errors associated with equipment and method, and errors attributed to material property behavior.

(1) Human error includes such factors as improper equipment readings and following improper test procedures. Human errors are not quantitative. However, errors of this type may be minimized by utilizing competent testing personnel familiar with testing procedures.

(2) There are two types of possible errors related to test equipment. One type of error relates to the sensitivity of the equipment with respect to its capability to accurately measure the true density or water content. Sensitivity errors are quantitative only in the sense that limiting ranges of possible error can be established. An example of sensitivity error would be the nuclear density device that is capable of determining densities only to within 3 to 5 pounds per cubic foot of true density. The second type of error relates to

constant deviations between measured and true density. Constant deviation errors can be corrected by calibrating test equipment against known densities.

(3) Material property errors are primarily limited to density determinations using either the sand-cone or the rubber-balloon method in sands. When a soil is physically sampled during the process of conducting an in-place density measurement using these two methods, a shearing action of the soil is unavoidable. Cohesionless soils are sensitive to volume change during shear, dense sands tend to expand and increase in volume, and loose sands tend to contract and decrease in volume. Errors of this nature cannot be quantified or detected in the field. However, such errors can be as high as 6 percent for sand using the rubber-balloon method for volume measurements.

4.8 ACCEPTANCE OR REJECTION. The inspection personnel have the responsibility to accept or reject the backfill or any part thereof based on the quality acceptance control tests. On the surface, this task seems straightforward. If a segment of the backfill tested at several locations for acceptance passes or fails to pass minimum requirements by a wide margin, then it is generally safe to assume that the backfill within that segment either has or has not been adequately compacted and the acceptance or rejection of that segment can be made based on the test results. On the other hand, if the tests indicated insufficient compaction, the size of the affected area may be questionable; it is possible that the test(s) represents only a small area and the lift being tested may be sufficiently compacted elsewhere. In view of the possible errors associated with control tests, tests that indicate marginal passage or failure should be treated with caution. The borderline case requires a close look at several factors: how the result compares with all previous results on the job, how much compaction effort was used and did it differ from previous efforts, how does this particular material compare with previously compacted materials, the importance of the lift location in relation to the entire structure, and the importance of obtaining the correct density or water content from the designer’s standpoint. When all factors have been considered, a decision is made as to which corrective measures are required. What makes such decisions so difficult is that they must be made immediately; time will not permit the problem to be pondered. Discussion with design engineers prior to beginning compaction operations may help in the evaluation of many of these factors.

(1) On jobs requiring large volumes of backfill, it may be advantageous to base the decision to accept or reject on statistical methods. Statistical methods require separate analysis for each backfill material type and compaction effort, complete random selection of test locations, and a large number of control tests as compared with the conventional decision method. In addition, statistical methods include water content control, which is not normally included in the specifications.

(2) The theory and details concerning the application of statistical methods for compaction control are well developed. Figure 4-1 shows a sequential inspection plan example of how the end results of a statistical analysis might be used for the purpose of acceptance or rejection. In this example, it was established by statistical analysis that adequate densities could probably be obtained with reasonable confidence by a given compaction effort for desired water contents ranging from 3 percentage points below to 1 percentage point above optimum. It was also established that a density corresponding to 95 percent of CE 55 maximum dry density was the minimum acceptable density based on required engineering performance of the backfill. The sequential inspection plan consists of examining, in sequence, single tests that are obtained at random from a segment of the backfill being considered for acceptance or rejection and, for each test, making one of three possible decisions: the segment is acceptable; the segment is unacceptable; and the evidence is not sufficient for either decision without too great a risk of error as indicated by the retest block in Figure 4-1. The reject areas in Figure 4-1 indicate conditions that cannot be corrected by additional rolling. The material must be replaced in thinner lifts and be within the desired water content range before adequate compaction can be achieved with the compaction equipment being used. If the retest

decision is reached, an additional test is made at a second random location, and the same three decisions are reconsidered in light of this additional information. If the second test falls below the accepted blocks, the segment of backfill representative of that test should be rejected; or if compaction procedures that have produced acceptable tests in the past have not been altered, then the compaction characteristics of that part of the backfill should be reevaluated.

(3) The primary advantage of statistical methods is that they offer a means of systematically evaluating acceptance or rejection decisions rather than leaving such decisions entirely to the judgment of the inspection personnel. However, if experienced and well trained inspection personnel are available, this approach may not be necessary.

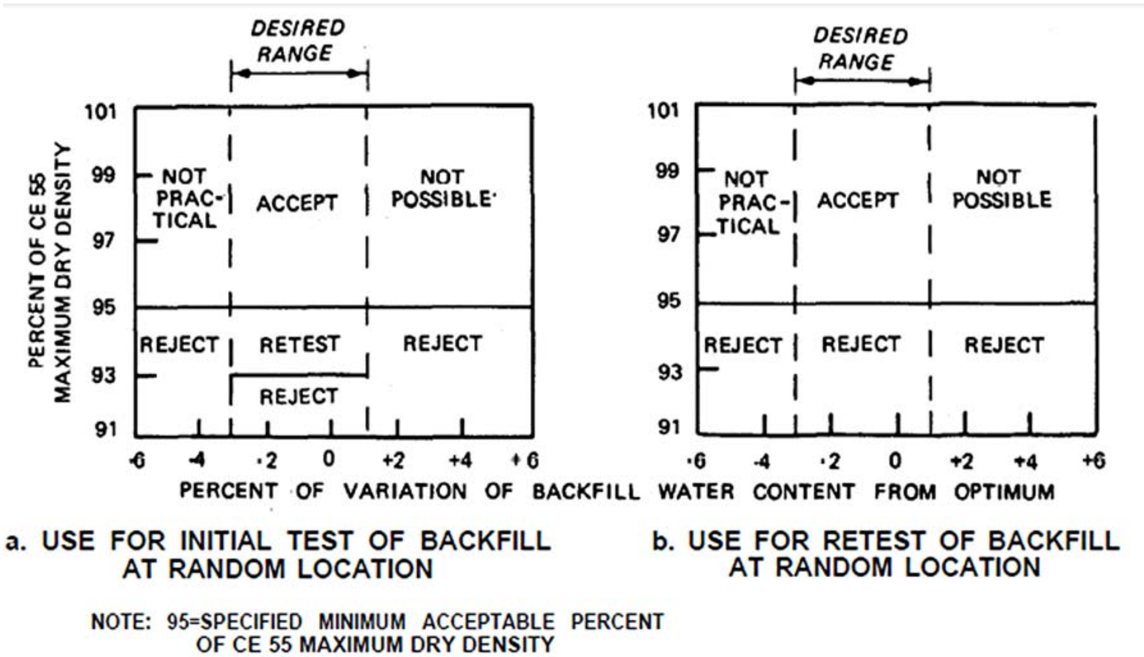

Figure 4-1

Acceptance/rejection scheme for a backfill area

4.9 CONSTRUCTION REPORTS. A record should be maintained of construction operations. It is valuable in the event repairs or modifications of the structure are required at a later time. A record is necessary in the event claims are made either by the contractor or the Contracting Officer that the work required or performed was not in accordance with the contract. Recorded data are also beneficial in improving knowledge and practices for future work. The basic documents of the construction record are the plans and specifications, modifications adopted that were considered to come within the terms of the contract, amendments to the contract such as extra work orders or orders for change, results of tests, and measurements of work performed. The amount of reporting required varies according to the importance and magnitude of the earthwork construction phase of the project and the degree of available engineering supervision. The forms to be used should be carefully planned in advance, and the inspection personnel should be apprised of the importance of their reports and the need for thorough reporting. Records should be made on every test performed in the laboratory and in the field. All information necessary to clearly define the locations at which field tests are made should be presented. In the daily reports, inspection personnel should include information concerning progress, adequacy of the work performed, and retesting of areas requiring additional work to meet specifications. These daily reports could be of vital importance in subsequent actions. It is a good practice for the inspection personnel to keep a daily diary in which the work area, work accomplished, test results, weather conditions, pertinent conversations with the contractor, and instructions received and given are recorded.

