Chapter 5
Earth-Fill and Rock-Fill Construction

Section I
Fill Processing and Compaction Equipment

5-1. Heavy Compaction Equipment

The three principal types of heavy equipment used to compact embankment fill are the tamping roller (sheepsfoot), the rubber-tired roller, and the vibratory steel-wheel roller. Corps of Engineers specifications, uses, advantages, and disadvantages of each roller are summarized in Figures 5-1, 5-2, and 5-3. Other general-purpose equipment sometimes used to compact fill are the fill hauling and spreading equipment itself, which is routed over fill to be semicompacted (paragraph 5-25), and crawler tractors, which sometimes can produce adequate compaction of pervious cohesionless materials.

5-2. Hand-Operated Compaction Equipment

For compaction in restricted areas such as those immediately adjacent to concrete walls, around conduits, or in depressions in rock surfaces, hand-operated power tampers or vibrated plate compactors are used. Power tampers should weigh at least 100 lb, and vibrated plate compactors are effective only in clean cohesionless backfill.

5-3. Spreading and Processing Equipment

Spreading and processing equipment commonly used on embankment fills is as follows.

a. Crawler and rubber-tired tractors and bulldozers. This equipment is used to tow compactors, plows, harrows, etc., with bulldozer blades to move and spread material and to remove oversize stones from embankment fill.

b. Motor graders (road patrols). Graders are used to spread and mix material, dress up boundaries between different zones (such as core, transition and filter), work out oversize stones, and scarify surfaces of previously compacted lifts.

c. Disks. Disks are typically towed by rubber-tired or crawler tractors (Figure 5-4) and used to scarify surfaces of previously compacted lifts or to aerate and blend water into uncompacted lifts before compaction.

Section II
Test Fills

5-4. Rock Test Fills

a. In the design of rock-fill dams, the construction of test embankments can often be of considerable value, and in some cases it is absolutely necessary. Design engineers should manage the test fill program, although construction personnel may administer the contract under which testing is performed. Test fills aid the designer by defining the effects of variables which would otherwise remain unknown. A properly executed test fill program should determine the most effective type of compaction equipment, the lift thickness, and the number of passes; maximum rock sizes; amount of degradation or segregation occurring during rolling; and physical properties of the in-place fill, such as density and grain-size distribution. The knowledge developed and the consequent improvement of design can significantly influence the cost of the structure. Hammer and Torrey (1973) provide guidance on the design and construction of test fills.

b. Test fills are often operated in conjunction with test quarries. This practice not only provides information about rock behavior during quarrying procedures, but also ensures that material used in the test fill is representative of material that will be produced by the proposed excavation. As in test quarries, test fill programs are often administered by both construction and design personnel, and it is advisable, when possible, to assign construction personnel involved in the test fill program to actual dam construction.

c. Construction of a test fill should be very strict, otherwise data obtained may be of questionable value. Plans and specifications for the test fill are prepared by the design engineer to evaluate construction procedures and material behavior so that results of the test fill can be used in design and construction of the prototype; therefore, changes or additions should not be made without approval of the design engineer.

d. Records and data required should be established by the design office; records should be kept up to date, and data plotted daily, as changes in the test program may be necessary to obtain desired information. It is important to record any and all observations made by field personnel, no matter how insignificant they may seem at the time. Photographs and notes or visual observations are extremely important, as they often provide answers to perplexing questions that would otherwise go unanswered.

TAMPING ROLLER (SHEEPSFOOT)

Specifications:

Towed:

Double-drum unit:	Water or sand and water ballasted. Towed by crawler or rubber-tired tractor at not more than 5 mph.
Drum:	Diameter, 60 in. (minimum); length, 60 in. (minimum).
Weight:	Weighted: at least 4,000 lb/ft of drum length. Empty: not more than 2,500 lb/ft of drum length.
Feet:	Uniformly spaced. Approximately three feet per each 2 sq ft of drum surface. Foot length: 9 to 11 in. Face area: 7 to 10 sq in.
Cleaning fingers:	Provided to prevent accumulation of material between feet.
Self-propelled:	May be used in lieu of towed roller if it causes no shearing of or laminations in fill. Specifications same as above except that (a) empty weight greater than 2,000 lb/ft of drum length may be used with face areas of feet not greater than 14 sq in. to approximate nominal foot pressure of towed roller, (b) inflation pressures of rubber-tired front wheels not greater than 40 psi. Speed not greater than 5 mph.
Use:	To compact fine-grained soils or coarse-grained soils with appreciable plastic fines.
Advantages:	Kneading, churning, and tamping action mixes soil and water better than other compaction equipment (this does not preclude proper processing of material prior to compaction, however); produces good bond between lifts; and breaks down weak rock or cemented soils.
Disadvantages:	Leaves surface rough and loose, and therefore susceptible to wetting by rains or surface waters. Compacts to shallower depth than other equipment. Effectiveness diminished in compacting soils containing cobbles or large rock fragments. Self-propelled rollers sometimes cause shearing of or laminations in fill.

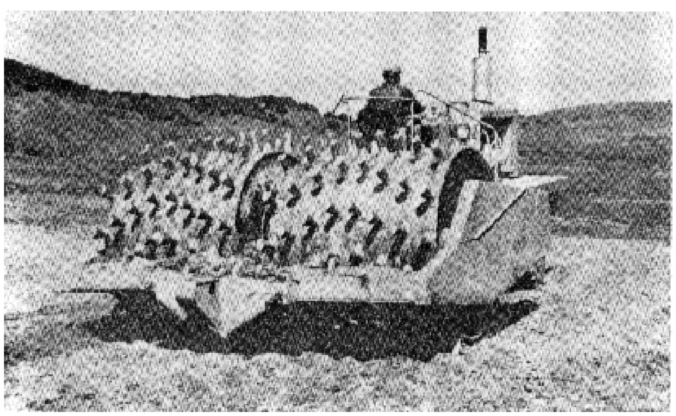

Figure 5-1. Tamping roller (sheepsfoot)

RUBBER-TIRED ROLLER

Specifications:

Unit with pneumatic-tired wheels towed at speeds not exceeding 5 mph.

Wheels: Minimum of 4 wheels abreast, each carrying equal load in traversing uneven surfaces.

Wheel spacing: Distance between nearest edges of adjacent tires not to exceed one-half of tire width under 25,000-lb wheel load. Tire pressure 80 to 100 psi.

Weight: Ballast loading to provide wheel loads from 18,000 to 25,000 lb.

Use: To compact cohesive (and sometimes cohesionless) soils.

Advantages: Compacts to greater depths than sheepsfoot roller. Produces relatively smooth compacted surface which is rain-resistant. Effective in compacting in closer quarters than sheepsfoot (i.e., against rock abutments and concrete structures). More effective than sheepsfoot in compacting cohesive soils containing large particle sizes. Wet areas of fill can be determined by observation of roller rutting.

Disadvantages: Compacted surfaces must be scarified before placing next lift. Not as effective as sheepsfoot roller in breaking down soft rock or in mixing fill material.

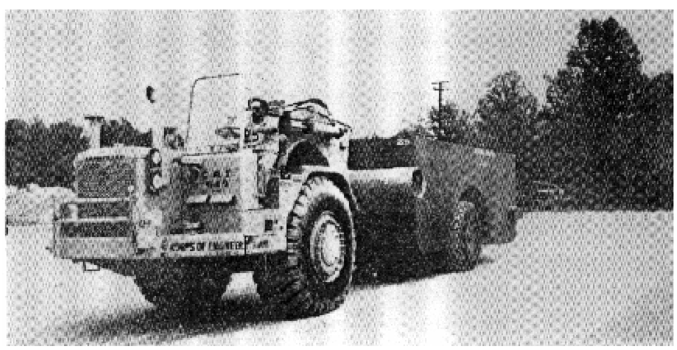

Figure 5-2. Rubber-tired roller

VIBRATORY STEEL-WHEEL ROLLER

Specifications:

Single drum unit. Towed by crawler tractor with minimum drawbar horsepower of 50 at speed not to exceed 1.5 mph (when compacting rock fill or sands and gravels), or self-propelled at speed not to exceed 1.5 mph (when compacting sands and gravels only).

Weight: Minimum total weight, 20,000 lb; 90 percent transmitted to ground by smooth drum with roller in level position attached to towing vehicle. Unsprung weight of drum shaft and internal mechanism not less than 12,000 lb. (Note: while guide specification CW 02212 specifies a roller with a minimum static weight of 20,000 lb, lighter rollers (7,000 to 10,000 lb) have been effectively used to compact pervious sand and/or gravel, and to compact soft rock that would be broken down too much by heavier rollers.)

Vibration: Frequency: between 1,100 and 1,500 vpm. Dynamic force: not less than 40,000 lb at 1,400 vpm.

Use: To compact cohesionless materials.

Advantages: Greater densities can be obtained in cohesionless soils than with tamping or rubber-tired equipment. Fill may be flooded with water to improve compaction.

Disadvantages: May cause degradation of soil or rock-fill particles and create layers of fines.

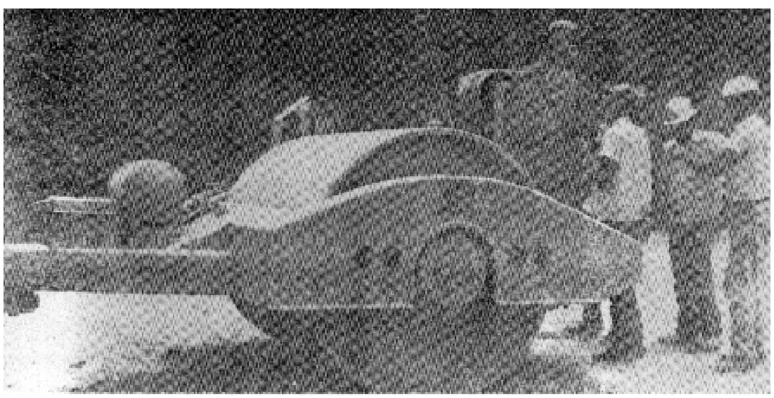

Figure 5-3. Vibratory steel-wheel roller

Figure 5-4. 36-in.-diam disk towed by D-8 tractor at DeGray Dam, Arkansas

e. Gradation tests should be performed on rock before and after compaction. A comparison of the before and after gradation curves will indicate the probable amount of particle breakage to be expected during handling and compaction. Lift thicknesses must be measured. In-place density of the compacted material after rolling must be determined directly by large-scale conventional methods or indirectly by observing settlement of the fill. The latter method is generally used because conventional density tests in rock fills are difficult and settlement measurements provide a better relative measurement of density. If densification of a layer is determined from settlement readings, caution must be exercised to ensure that settlement is in fact that of the layer in question and does not include settlement of the foundation or underlying layers. Settlement in the foundation and within lifts can be determined from settlement plates. A number of conventional density tests should be made to supplement settlement data in any case.

f. Test trenches should be excavated through the completed test fill to allow visual observation of compacted lift thicknesses, distribution of fines, and distribution of density. Test fill operations, including inspection of test trenches, should be thoroughly documented with measurements, photographs, and written results of visual observations. A test trench cut through a portion of the test fill for New Melones Dam, California, is shown in Figure 5-5.

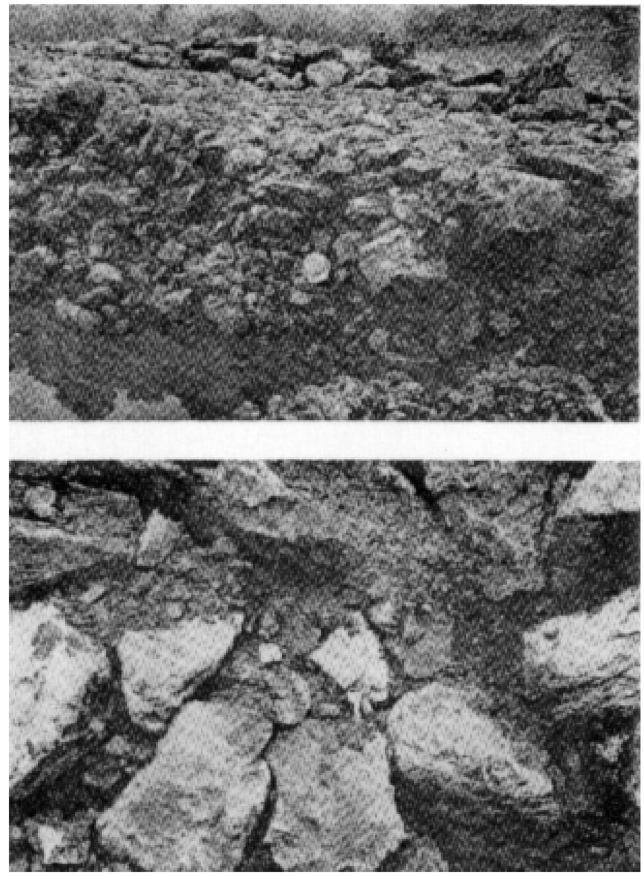

Figure 5-5. Test trench through portion of rock test fill at New Melones Dam, California. General view of trench (top); closeup view of trench wall (bottom)

5-5. Earth Test Fills

Test fills for earth embankments are often necessary to establish proper loose lift thicknesses and the number of passes required to compact soils for which there is no previous compaction experience. Test fills may be needed to determine the best procedure and equipment for adding and mixing in water to obtain the desired water content uniformity throughout the lift. Test fills are also constructed (at the contractor's expense) when the contractor wants to use equipment other than that permitted by the specifications, as the contractor must prove that desired results can be obtained with the proposed equipment. Test fills are also used to determine if desired densities can be economically obtained in the field, (for example, at Canyon Dam, Texas, Figure 5-6). A test fill is often a part of the embankment, and if satisfactory results are achieved, the compacted fill can be utilized as part of the embankment fill.

Section III
Impervious and Semipervious Fill

5-6. Definitions

Impervious materials include clays of high and low plasticity (CH and CL), clayey sand or gravel (SC and GC), and

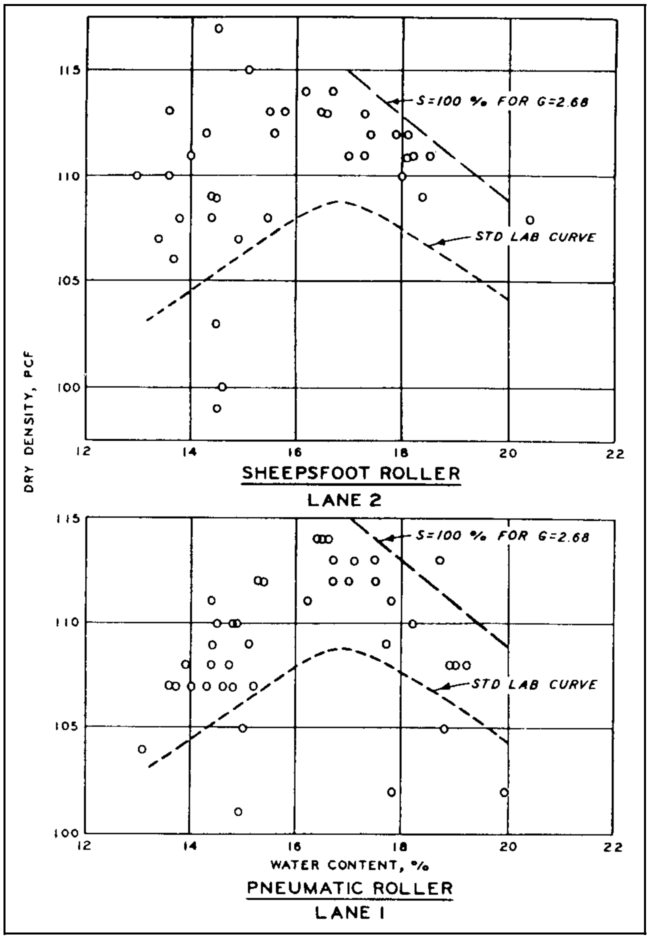

Figure 5-6. Test fill data from Canyon Dam, Texas

clayey silt (CL-ML). Semipervious materials include silts (ML) and silty sands and gravel (SM and GM). Note that sands with borderline gradations classifying as SM-SP, that is, sands having as high as 12 percent passing the No. 200 sieve (5 percent is the usual upper limit for a material to be classified as pervious), may have the characteristics of semipervious material even though such materials may be allowed by the specifications in embankment zones designated "pervious fill." Generally, compaction curves indicating adequately defined optimum water contents and maximum dry densities can be developed using the standard compaction tests on impervious and most semipervious materials.

5-7. Compaction Fundamentals

a. Soils containing fines can be compacted to a specific maximum dry density with a given amount of energy; however, maximum density can be achieved only at a unique water content called the optimum water content. Maximum dry density and optimum water content are determined in the laboratory by compacting five or more specimens of a soil at different water contents using a test procedure which utilizes a standard amount of energy called "standard compactive effort." A detailed description of the laboratory compaction procedure to establish maximum dry density and optimum water content is contained in EM 1110-2-1906.

b. In the field as in the laboratory, the two variables that control fill density are placement water content and field compactive effort applied by the passage of a piece of equipment a certain number of times over a lift of a specific thickness. When the water content of a soil being compacted with a certain compactive effort deviates from the optimum water content for that effort, a dry density less than maximum will result; the greater the water content deviation from optimum, the lower the resulting density will be. For soil with a water content on the dry side of optimum or at optimum, an increase in compactive effort will generally increase the density. For soil with water content considerably greater than optimum, an increase in compactive effort will tend to shear the soil but not further compact it.

c. Compactive effort can be increased by increasing contact pressure of the roller on the soil, increasing the number of passes, or decreasing the lift thickness. Combinations of these procedures to increase and control compaction on a job will depend on difficulty of compaction, degree of compaction required, and economic factors.

5-8. Compaction Specifications

a. Requirements of the more important compaction features (such as water content limits, layer thickness, compaction equipment, and number of passes) will be contained in the specifications and must be checked closely by the inspection force to ensure compliance.

b. Specifications will generally state the type and size of compaction equipment to be used and require that the contractor furnish the Government manufacturer's data and specifications on the equipment. Those data should be checked against job specification requirements along with a visual inspection to ensure that the equipment is in condition to produce the required compaction. If a sheepsfoot or tamping roller is to be used, some of the items to be checked include: drum diameter and length; empty weight and ballasted weight; arrangement of feet and length and face area of feet; and yoking arrangement. For a rubber-tired roller, tire inflation pressure, spacing of tires, and empty and ballasted wheel loads should be checked. For a vibratory roller, static weight, imparted dynamic force, operating frequency of vibration, and drum diameter and length should be checked.

c. Uncompacted or loose lift thickness will be specified. Lift thickness specified will be based on type of material and compacting equipment used. Impervious or semi-pervious materials are commonly placed in 6-to-8-in. loose lift thicknesses and compacted with six to eight passes of a sheepsfoot roller or in 9-to-12-in. loose lift thicknesses and compacted with four coverages or a 50-ton rubber-tired roller. When using a rubber-tired roller or any roller that leaves a smooth surface after compaction, scarification of the compacted lift prior to placing the next lift is specified to ensure a good bond between the lifts. In confined areas where hand-operated power tampers must be used, fill is commonly place in 4-in. loose lifts and compacted to densities achieved with sheepsfoot or pneumatic-tired equipment under the above-mentioned conditions.

d. In-place water content and density must be related to optimum water content and to maximum dry density to judge whether a compacted soil is suitable or unsuitable. Minimum acceptable field density is normally established in design as a percent (usually 95 or above) of maximum dry density[1], and an allowable range of placement water contents is given in the specifications relative to optimum water content of the soil being compacted. Each soil type has a different maximum dry density and optimum water content for a given compactive effort, and it is necessary that in-place field densities and water contents be compared with laboratory-determined optimum water contents and maximum densities of the same soil. Because mixing different soil strata in borrow areas can result in materials with unexpected compaction characteristics, if a material being compacted in the field cannot be related to available laboratory compaction data, a laboratory compaction test should be performed on that material. Check companion tests should be performed by field personnel before fill placement to ensure consistency with target values for a given soil.

e. Assumptions are made in design regarding shear strength, permeability, and deformation characteristics of the embankment fill. These properties vary with density and water content of the compacted soil. Therefore, soil must be placed as specified; otherwise, design assumptions are not met and problems may occur in the completed structure. Thus, desired density and placement water content range are not arbitrarily established but are specified for very definite reasons, and both requirements must be satisfied. If the water content is outside its specified range, even though the desired density is obtained, the soil must be reworked and recompacted. If the minimum density is not obtained even though the water content is within the specified limits, additional roller passes at Government expense will be required. Procedures for performing tests to determine field densities and water contents are contained in paragraph 5-10, and application of these tests to compaction control is included in Appendix B.

[1] When the compaction procedures are set forth in the specifications, the percentage of maximum dry density is not specified, but the desired value is given to field inspection forces by the design office.

5-9. Simple Control Procedures

a. Simple controls using both visual observations and rough measurements are the primary means by which construction control is carried out. However, they must not be used as the only means of control, but must be supplemented by an extensive program of control testing. For any estimate to be meaningful and accurate, the observer must have his eye and hand calibrated to all conditions expected. It is desirable to construct a small test section prior to the beginning of major fill placement so inspectors and the contractor can become familiar with the behavior and compaction characteristics of the fill material and with the performance of the compacting equipment. Noncritical locations are often used for such experimentation, such as in reaches where embankment heights are low.

b. An inspector should be familiar enough with the materials at a job site to recognize when the soils are too dry, too wet, or at optimum water content. To gain needed familiarity with site materials, an inspector should spend time in the field laboratory performing compaction tests and index tests such as Atterberg limits so as to become familiar with differences in appearance and behavior of site fill materials.

c. A trained inspector should be able to pick up a handful of soil and make a reasonable estimate of its water content relative to optimum by feel and appearance. Experienced inspectors can often estimate deviation from optimum water content to within 1 percent. Material may be examined by rolling a small amount on a clipboard or between the hands to get an indication of how close to the plastic limit the soil is. Comparison with the plastic limit is a good rule-of-thumb because there is often good correspondence between optimum water content and the plastic limit of a soil. However, after the inspector has made visual and contact examination, a water content test should be performed on the material in question for confirmation of water content.

d. In addition to having a feel for how a soil looks and feels when it is at the proper density, a penetration resistance index test is often devised by inspectors. The resistance index test itself can range from the use of a Proctor needle (Proctor penetrometer) to that of a common spade. Many inspectors, in fact, have had success in judging density by noticing the resistance of the compacted soil to penetration by a spade.

e. Proper lift thickness is fairly easy to estimate when the inspector's judgement has been calibrated by actual thickness measurements. However, many contractors are interested in placing lifts as thick as they can get by with, and conflict often arises on this point. Therefore, control of lift thickness by visual observation alone is not sufficient and must be supplemented with measurements. Contractor behavior dictates the level of force that must be exercised to maintain proper lift thicknesses. As a minimum practice by the inspector, it is necessary to make measurements on the same point on the construction surface after every few layers.

f. Much useful information can be gained by observing the action of compacting and heavy hauling equipment on the construction surface. If the water content of the fill material is uniform and the lift thickness is not too great, the action of the roller will indicate whether water content of the material is satisfactory and good compaction is being obtained. For example, it is likely that soil-water content is too high if on the first pass of a rubber-tired roller the tires sink to a depth greater than or equal to half the tire width, after several passes, excessive rutting of the soil surface is observed, the surface ahead of the roller shows signs of weaving or undulating (as opposed to "springing"). It should be noted that the characteristics just described may sometimes be caused by tire pressure which is too high, but in most instances they are caused by water content which is too great. On the other hand, if the roller tracks only vary slightly or not at all and leave the surface hard and stiff after several passes, the soil is probably too dry. For most soils with the proper water content, the roller will track nicely on the first pass and wheels will embed 3 to 4 in.; there should always be some penetration into soil at its proper water content, although penetration will decrease as the number of passes increases. After several passes of a sheepsfoot roller, the roller should start walking out of the fill if adequate and efficient compaction is being obtained. Walking out means that the roller begins bearing on the soil through its feet with the drum riding a few inches above the soil surface. If the roller walks out after only a few passes, the soil is likely too dry. If the roller does not walk out but continues churning up the material after the desired number of passes, either the soil is too wet or foot contact pressure is too high. Another significant observation during compaction by sheepsfoot roller is whether or not the feet are coming out clean. Soil is generally too wet when large amounts of material are being picked up by the feet and knocked off by the cleaning teeth. If soil is at the proper water content, only a small amount of sticking should occur.

g. At a proper water content there will always be a noticeable "springing" of the embankment surface as it reacts to the passage of any heavy construction equipment; the amount will depend largely on soil type. However, a sudden sinking or rising of the surface under the weight of the passing equipment is a good indication that a soft layer or pocket exists below the surface; if there is no spring at all, it is probable that several lifts of fill have been placed too dry. If such a condition is noticed, it should be checked by the laboratory and the condition corrected if the underlying layers do not meet specifications.

5-10. Field Control Testing and Sampling

a. General. Field control testing (field density tests) and record sampling of compacted fill are conducted for two basic reasons: to ensure compliance with design requirements, and to furnish a permanent record of as-built conditions of the embankment. Field control testing consists largely of determinations of the water content, density, and classification of the field-compacted material. Record sampling consists of obtaining undisturbed samples (often with companion disturbed bag samples) at selected locations in the embankment during construction.

b. Field density testing and record sample programs.

(1) Frequent control tests should be performed at the start of fill placement; after rolling requirements have been firmly established and inspection personnel have become familiar with material behavior and acceptable compaction procedures, the amount of testing can be reduced. Many factors influence the frequency and location of control tests and record samples. Frequency of testing will depend on the type of material and how critical the fill being compacted is relative to the overall job (for example, an impervious core will naturally require more control than will a random berm). Sampling should be carried out at locations representative of the area being checked. It is vitally important in control tests that soil specimens be properly sized; specimens that are too small yield inaccurate and misleading results. Guidance regarding proper specimen sizing is given in EM 1110-2-1906 and by Gilbert (1990).

(2) A systematic testing and sampling plan should be established at the beginning of the job. Control tests are usually designated as routine and are performed at designated locations, no matter how smoothly the compaction operations are being accomplished. A routine control test should be performed for every 1,000 to 3,000 cu yd of compacted material and even more frequently in narrow embankment sections where only a small volume of material raises the section height considerably. In the first lift above the foundation, tests should be made more frequently to

ensure that proper construction is attained in this important area. The locations of record samples should be at the discretion of the design engineer and should also be stated on a predetermined plan of testing. A rough guide for taking record samples is one for every 30,000 cu yd of core fill and every 30,000 to 50,000 cu yd of compacted material outside the core. Since the record samples are taken primarily to determine the shear strength of the fill, it may be more important in many dams to concentrate more tests in the material outside the core because this is where a major portion of the resistance to sliding is developed. For dams with narrow central plastic clay cores placed wet of optimum water content for impermeability and flexibility, flanked by large lean clay zones, record samples should be taken mainly in the clay shells.

(3) In addition to routine 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 special compaction procedures are being used (power tampers in confined areas, etc.), where instruments are located, and adjacent to abutments.

c. Record samples. Undisturbed record samples may be obtained by carefully carving out about a cubic foot block of the compacted fill. The sample is then sealed in wax and encased in a wooden box or protected by other methods of packaging against disturbance or water loss. Undisturbed record samples are also taken by trimming around a large steel cylinder as it is pushed into the fill (e.g., the Fort Worth district has used a sampler 7-1/2 in. in diam by 10 in. high). Details for obtaining and preserving record samples are described in EM 1110-2-1907. Undisturbed record samples are subjected to shear and perhaps consolidation testing by the division laboratory, and the material from trimmings and unused portions of the record samples or of the companion bag samples are used for laboratory compaction, gradation, specific gravity, Atterberg limits, and other laboratory tests. Undisturbed record samples and bag samples must be tested promptly if the results are to be useful in construction control.

d. Field density tests. Field density determination consists of volume and weight measurements to determine wet density of in-place fill and water content measurement to determine fill water content and dry density. Volume and weight measurement can be determined by direct or indirect methods. In direct measurements, weight of the material removed from a hole in the fill and hole volume are used to determine wet density. Direct water content determination involves drying the soil in an oven at 110 ± 5 °C, then weighing the dry soil to determine water loss. Determining density and water content by indirect methods involves measuring a characteristic of the material that has been previously correlated with density and/or water content. As a rule, field density tests should be taken one lift thickness deep.

(1) Direct methods.

(a) Direct methods of measuring volume include sand displacement, water balloon, drive cylinder, piston sampler, and water displacement. Apparatus, procedures, and guidance in obtaining satisfactory results for the sand displacement, water balloon, drive cylinder, and piston sampler are given in EM 1110-2-1907. The sand displacement and water balloon methods are the most widely used for measuring in-place density because of their applicability to a wide range of material types and good past performance records. Apparatus for these two methods is shown in Figure 5-7. Sand displacement is the most reliable and most frequently used method; it should be the referee test for all other control methods. The drive cylinder and piston sampler are good for obtaining samples from which the density can be ascertained, but are limited to moist fine-grained cohesive soils containing little or no gravel and moist fine sands that exhibit apparent cohesion. The water displacement method is generally used for testing gravelly soils where holes as large as one cubic yard are needed to obtain accurate results. A water-displacement density test is shown in Figure 5-8. A thin plastic sheet is necessary to line the hole to prevent leakage, and special equipment is often required for handling and weighing the large volume of excavated material and measuring the large volume of water. A 3-to-5-ft-diam steel ring with a height about equal to the compacted lift thickness is often used where the fill surface is rough and uneven. The volume of water required to fill the ring with the plastic liner in place is determined, the water and liner removed, and then the hole is dug without moving the ring. The liner is then placed in the hole, and the volume of water required to fill the hole to the top of the ring is determined. The difference between the two volume measurements is the in-place volume of excavated fill material. Apparatus and procedures for large volume water displacement tests are described by Hammer and Torrey (1973) and by Gordon and Miller (1966).

(b) Water content measurement is required to control placement water content and to determine dry density for field tests. Methods for direct water content determination include conventional oven drying, hot plate or open flame drying, drying by forced air, and drying in a microwave oven. In conventional oven drying, a soil specimen is dried to a constant weight in an oven maintained at a temperature of 110 ± 5 °C and the weight loss determined. Conventional oven drying is the standard for accuracy in water content measurement; details of the test are described in EM 1110-

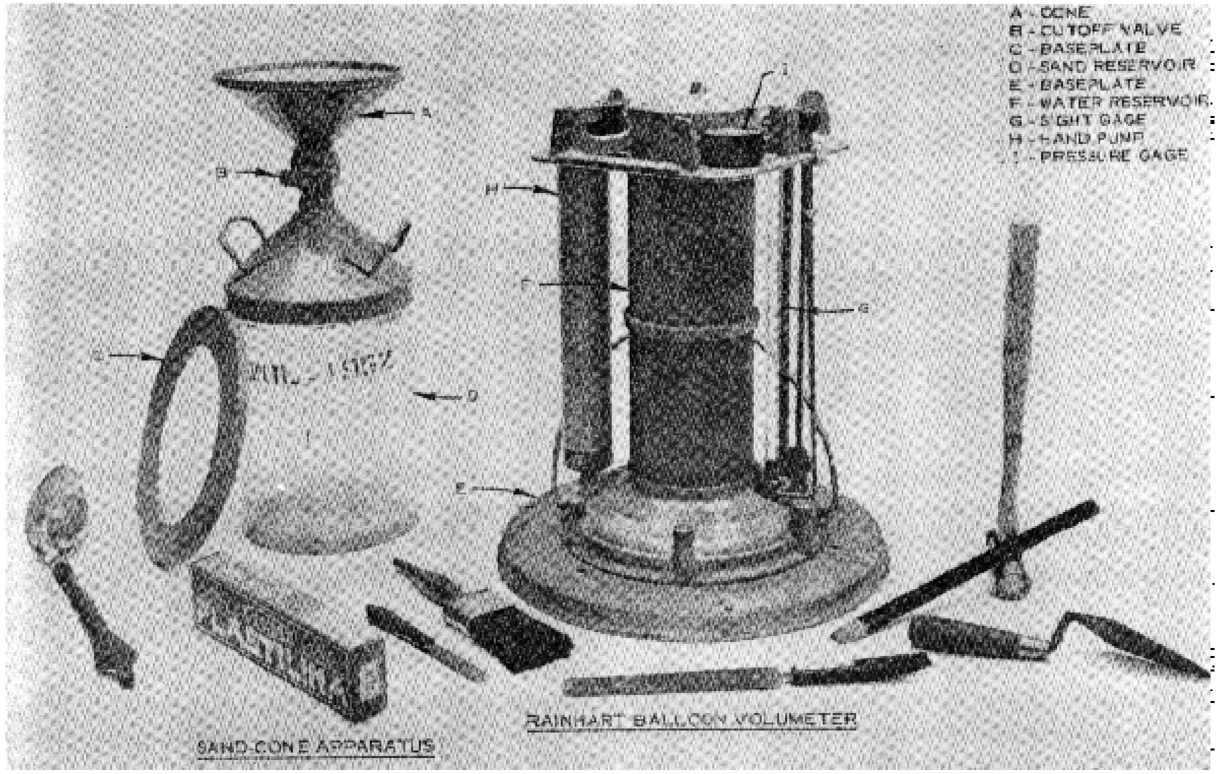

Figure 5-7. Displacement density apparatus

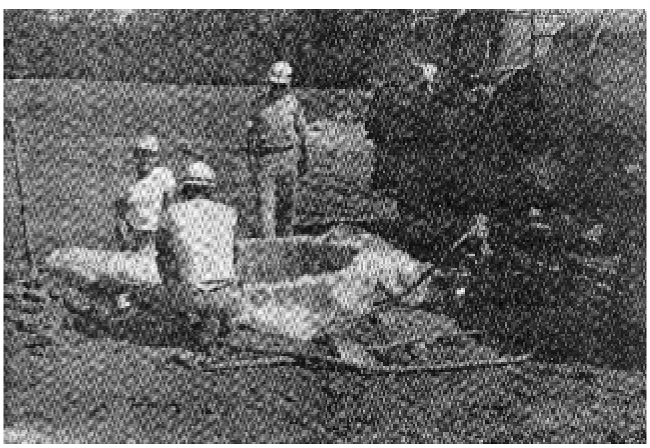

Figure 5-8. Large-scale water displacement density test in progress at New Hope Dam, North Carolina

2-1906. The hot plate method utilizes a small tin pan and a hot plate, oil burner, gas burner, or some other device to apply high temperature quickly; the test is performed by weighing a sample of wet soil, drying the soil on a tin pan over high heat, and weighing again to determine how much water was lost. Hot plate drying is fast but can result in inaccuracy in water content because high uncontrolled temperature applied to the soil can drive off adsorbed water and burn or drive off volatile organic matter, neither of which should be removed in a normal water content test. In the forced hot air or "moisture teller" procedure, a specimen is placed in a commercially available apparatus containing an electric heater and blower. Hot air at 150 to 300 °F is blown over and around the specimen for a preset time. A 110- or 230-V source is required for the apparatus, which can accommodate specimen masses from 25 to 500 g. Drying times will depend on specimen size and material type but are estimated to vary from 5 min for a sand to as long as 30 min or more for a plastic clay. Care must be exercised when using this method also, since the soil may be overdried or underdried with a resulting inaccuracy in water content.

(c) Microwave oven. A Computer Controlled Microwave Oven System (CCMOS) has been developed at WES and demonstrated to be an acceptable and useful piece of equipment for rapid determination of water content for compaction control. The principal of operation of the system is that water content specimens are weighed continuously while being heated by microwave energy; a small computer monitors change in water content with time and terminates drying when all "free" water has been removed. CCMOS is essentially automatic; after the operator has placed a specimen in the oven system, the controlling computer performs all required tasks (including calculations) through software, and returns the final water content with no additional input required from the operator. A water content test in the CCMOS typically requires 10 to

15 min; the system has been field-tested at the Yatesville Lake and Gallipolis Lock projects in the Ohio River division. At the projects, companion tests were performed in a conventional oven at 110 ± 5 °C and in CCMOS. Data returned from the projects are shown in Figure 5-9; statistical analysis of the data shows that CCMOS produces water contents that are within 0.5 percent of the conventional oven water content. Special procedures must be used when drying materials which burst from internal steam pressure during microwave drying (which includes some gravel particles and shales) and highly organic material, which requires a special drying cycle. CCMOS will not produce correct water contents in soils with high gypsum content; therefore, no attempt should be made to use the system to dry such materials. (However, it must be noted that a special drying procedure is required to dry gypsum rich soils in the conventional constant temperature oven). CCMOS and its operation and use are described by Gilbert (1990). Components of the system are shown in Figure 5-10.

(d) Pressure tester methods. The pressure tester method for water content determination involves combining moist soil in a sealed chamber with calcium carbide (these react with water in the soil to release gas) and relating the resulting gas pressure to soil water content. Accuracy can be a problem when using this technique since soils and especially fine grained clays bind and hold water at different energy levels. Consequently, there is no assurance that calcium carbide will react correctly with bound or adsorbed water; calibration tests must be performed to correlate pressure tester water content with conventional oven water content. Special care should also be taken in using the pressure tester technique with organic soils, since accuracy is affected by the presence of organic matter in soils. The pressure tester technique is most effective and accurate on relatively dry soils (less than 20 percent water content) which readily disaggregate; the technique becomes cumbersome and possibly dangerous when testing excessively wet soils, as very high gas pressure may develop in the test chamber. The American Society for Testing and Materials (ASTM) has recently prepared a standard for the calcium carbide pressure tester method of water content determination (ASTM D 4944). The procedure states that uncertainty and sources of error in using the procedure arise from the fact that water entrapped in soil clods does not react correctly or completely with calcium carbide; additionally, some soils contain chemicals which react unpredictably with the reagent to give erroneous results. It is important to realize that when calcium carbide reacts with water, acetylene gas is released which is highly flammable to the point of being explosive; additionally, the gas is irritating to the skin and eyes. Therefore, appropriate safety measures must be exercised when using this procedure.

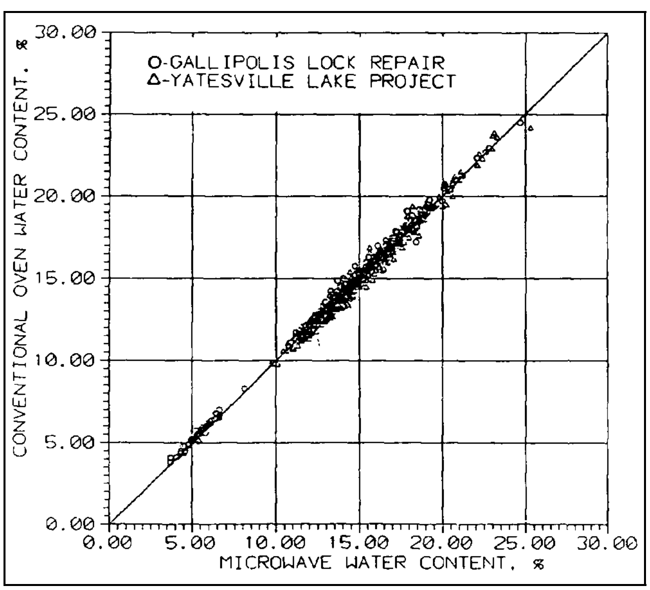

Figure 5-9. Conventional oven versus CCMOS water content data

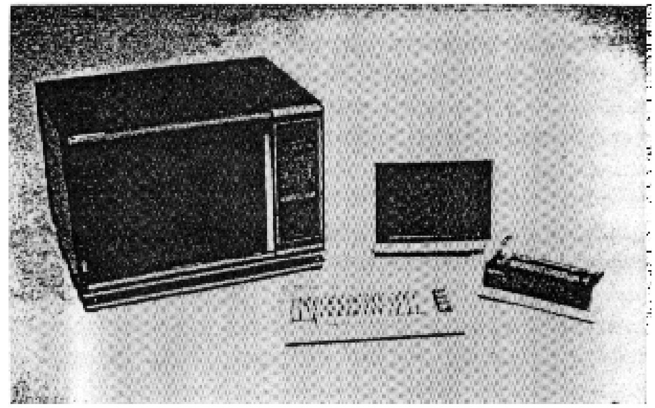

Figure 5-10. Components of the microwave drying system

(2) Indirect methods. Indirect methods can often be successfully used to measure density and water content; however, indirect methods should never be used instead of direct methods or without careful calibration and correlation with results obtained from direct methods. Additionally, indirect measurement results should be periodically checked against direct measurement results during construction. Indirect methods include the use of the nuclear moisture-density meter, the Proctor penetrometer (often called the "Proctor needle") and the pressure tester method of water content measurement.

(a) Proctor penetrometer. The Proctor penetrometer is generally accurate only under ideal conditions; it requires careful calibration using soils of known density and water content and considerable operating experience. Even then the results may be questionable due to the significant influence of nonuniform water content or variation due to the influence a small piece of gravel can have on the penetration resistance. The Proctor penetrometer is, therefore, not recommended for general use in compaction control; it 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 for determining the relation between wet unit weight, penetration resistance, and water content is described in the ASTM Standards, Designation D 1558-63.

(b) Nuclear method.

- The nuclear method is an expedient means by which both water content and density determinations can be made more rapidly than by conventional direct methods. Improvements in the design of nuclear equipment and a better understanding of the nuclear principles have led to increasingly widespread use of nuclear gauges. The nuclear method is not permitted as a primary control, but is used to supplement direct methods. A 1969 survey of Corps of Engineers use of nuclear gauges showed 13 Corps offices were using such instruments in various applications. A 1990 survey of nuclear density gauge use in earthwork construction within the Corps showed that seven districts were using nuclear instruments to supplement other methods of density and water content determination. Guidance given by Webster (1974) and by Rosser and Webster (1969) requires that before a nuclear density gauge is used on a Corps of Engineers job, results obtained using factory curves must be compared with density and water contents determined by conventional methods. Based on this comparison, corrections may be required to the factory curve or a new calibration curve may have to be developed. It should be noted here that recent research has shown that the calibration of nuclear gauges is highly nonlinear in determination of water content or soil density at water contents greater than about 40 percent, and steps should be taken to account for this nonlinearity.

- Most nuclear gauges are built to measure density by one or more methods, classified as the direct transmission, backscatter, and air-gap density methods as shown in the schematics of Figure 5-11; however, all nuclear gauge methods are based on the principle of using gamma radiation to establish a density relationship. The direct transmission method is reported to yield the best accuracy, in that material composition and surface roughness influences are minimized. The backscatter method avoids the need to create an access hole in the compacted soil because the unit rests on the surface. The air-gap method (shown in Figure 5-11c) raises the device above the surface to lessen composition error, but accuracy will still not match that of the direct transmission method. Moisture measurements utilize a method based on the principle of measuring the slowing of neutrons emitted into the soil from a fast neutron source, usually using the backscatter method. Generally, the density and water content measuring devices are incorporated into a single self-contained unit. Both surface-type nuclear gauges, which test materials at depths greater than 1 ft, are now available. Descriptions of gauges available from a number of manufacturers are given by Smith (1968). Modern nuclear gauges contain a microcomputer which processes gauge readings to directly calculate and display wet density, dry density, degree of compaction, and water content.

- No license is required by the Atomic Energy Commission (AEC) for using nuclear gauges when the radiation-emitting source is a naturally occurring radioactive nuclide. A license is needed when the radiation-emitting source is a by-product radioactive nuclide. All Corps applications for AEC licenses, renewals, amendments, and correspondence thereto must be forwarded through normal Corps channels to HQDA (CESO-ZA), Washington, DC 20314, for processing. AEC standards are contained in Title 10, Part 20, Code of Federal Regulations (Atomic Energy Commission 1966). Full time radiation inspectors with special training must be present on Corps projects where nuclear gauges are used. This requirement can be a barrier on small jobs or jobs with marginal funding.

- The advantage of the nuclear method is the speed with which density and water content determinations can be obtained as compared with conventional methods. An in situ density and water content determination can be made in approximately 15 min as compared with a period as long as 24 hr for conventional methods when oven drying is used. In addition, the possibility of human error is minimized. However, the field density and water content must still be related to a compaction curve or to maximum and minimum densities, as is the case with data obtained by conventional methods. Consequently, it is necessary to obtain a sample of the material at the location of the nuclear test in order to relate the field and laboratory date.

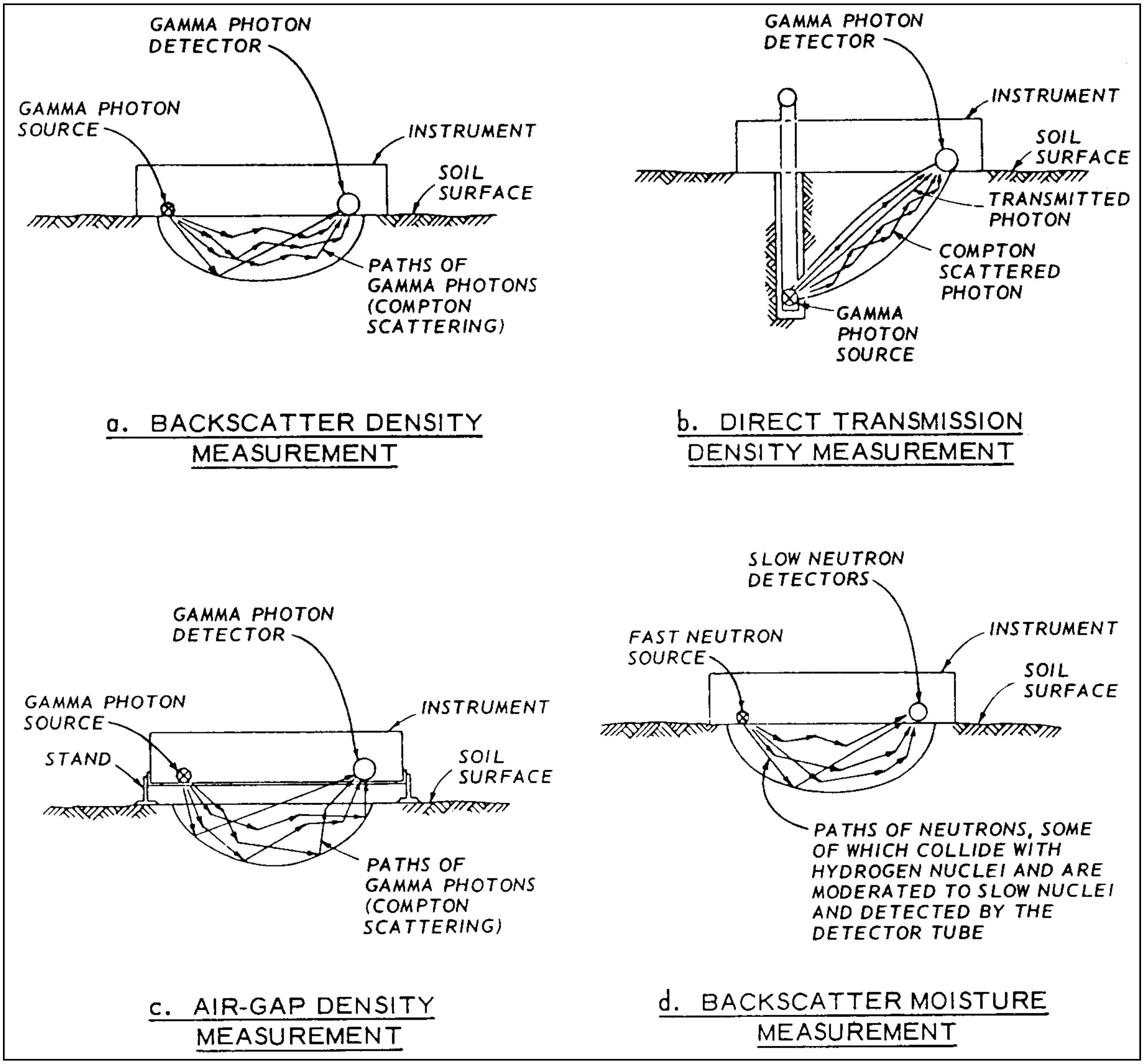

Figure 5-11. Schematic diagrams of density and moisture measurements

- The operating principle of the nuclear moisture gauge is, very basically, that neutrons from a radioactive source are released into a soil/water mixture then detected some distance away after they have traveled through the soil. The (initial) statistical energy spectrum of the released neutrons is known; after reacting with the soil/water medium for a period of time, the neutrons reach a state of energy equilibrium which is detected and measured by a probe. Detected energy level is then related to soil water content through calibration. Neutrons lose energy primarily by colliding with chemically bound hydrogen present in the (soil-water) medium, and neutrons are absorbed by certain elements which may be present in the soil. Therefore, some of the factors that adversely affect water content measurement using this procedure may be more clearly visualized: (1) *All* chemically bound hydrogen causes neutron energy loss, including that in organic matter, adsorbed water, and structurally bound water as well as "free" water. Only free water should be included in a normal water content determination; the gauge cannot discriminate between hydrogen in free water and hydrogen in other sources. (2) Certain elements (such as iron, potassium, manganese, boron, and chlorine) are highly absorptive of neutrons. The presence of these elements in soils will cause erroneous water content determination using a nuclear gauge. Because of the possible presence of generally unknown quantities of organic matter, adsorbed water, structurally bound water, and highly absorptive elements, water content measured by the nuclear gauge must be frequently checked against that determined in the conventional oven to account for the factors which are known to influence nuclear gauge results. In addition, nuclear gauges react with and are affected by other nuclear gauges in close proximity; therefore, a nuclear gauge should not be used within 30 to 40 ft of another nuclear gauge in use in the field. A major disadvantage of nuclear gauges is that specimen size is unknown and can never be established with certainty; the volume "probed" by a nuclear gauge is determined by water content, soil mineralogy, grain-size distribution, and geometry of the test configuration (for example, results determined in a narrow utility trench may be in considerable error relative to results obtained on a flat, obstruction-free soil surface).

- Additional disadvantages of nuclear methods for determining field densities and water contents are general lack of understanding of the method as well as factors affecting the results and, consequently, lack of confidence in the results; calibration curves must be developed and/or verified by field tests for each instrument; and although the proper use of nuclear gauges presents no health hazards, rigid safety regulations and documentation requirements must be met. For this last reason, field parties are sometimes reluctant to use nuclear equipment.

e. Test pits. It is sometimes desirable to excavate deep test pits to determine the overall condition of the compacted embankment. Field density tests can be made and undisturbed record samples can be obtained at various elevations as the pit is being dug, and the degree of uniformity or water content with depth can be obtained by testing samples at frequent depths. An important advantage of the test pit is that it allows a visual inspection of the compacted fill; soft spots can be detected, and it can be determined whether or not successful bonding of the fill lifts has been accomplished. Large-diameter bucket auger holes (30 to 36 in.) can also be utilized effectively for this purpose. All tests and visual observations should be thoroughly documented, including numerous photographs. Test pits must be backfilled with properly compacted soil.

f. Methods of relating fill density and water content to maximum density and optimum water content.

(1) The fill density and water content must be related to laboratory values of maximum density and optimum water content of the same material in terms of percent compaction and variation of fill water content from optimum. For this comparison to be meaningful, valid laboratory values must be selected.

(2) Performance of the standard five-point compaction test on the field density test material is ideal, as it gives the correct values of maximum dry density and optimum water content directly. However, the five-point test is time-consuming and generally not possible on material from each field density test.

(3) There are other, less time-consuming methods based on identification of the field density material with one of the soils on which standard compaction tests have been performed in connection with design studies and during construction. The means of identification are as follows:

(a) Two-point compaction test.

(b) One-point compaction test.

(c) U.S. Bureau of Reclamation (USBR) rapid compaction control.

(d) Atterberg limits correlations.

(e) Grain-size distribution correlation (sometimes used for coarse-grained soils).

(f) Visual comparison.

These methods are discussed in detail in Appendix B. The two-point and one-point methods follow essentially the same procedure as the five-point method, but are quicker since fewer points need to be run. It should be noted that the five-point method requires wetted soil cured overnight prior to compaction to allow uniform distribution of added water. In the one- and two-point methods, whether adding water to or drying back the fill material, thorough mixing is required to obtain valid results. Water contents and dry densities from the one- and two-point methods are plotted on the same plot as the five-point laboratory compaction curves used for control. The curve best fitting the plotted points is selected, and the field values are compared with the maximum density and optimum water content of that curve. Atterberg limits correlations are based on correlations of liquid limit, plastic limit, or plasticity index with optimum water content and maximum dry density. In the USBR rapid method, a wet density compaction curve is developed from three wet density compaction points, and the percent of maximum dry density and deviation from optimum water content are computed without having to perform water content tests. The visual method consists of establishing by visual examination that the field density material is the same as one of the materials on which laboratory compaction curves were developed. It is a frequently used method, but is the least desirable because materials that look very much alike and have the same soil classification can have widely varying compaction characteristics.

g. Procedures for gravelly soils. Results of the five-point, two-point, one-point, and visual methods are usually correlated directly with field density test results if appropriately sized compaction molds are used (see EM 1110-2-1906). However, the Atterberg limits correlations and USBR rapid methods are based on the minus No. 4 sieve fraction; consequently, the field density test results must be corrected to obtain the water content and density of the minus No. 4 fraction. Corrections must also be applied to the field results if the laboratory compaction curve is based on a scalped material (corrections would not be made if particles larger than 2 in. are replaced with an equal weight of particles from 2 in. to the No. 4 sieve and tested in the laboratory in a 12-in. compaction mold). The equations necessary to make these corrections and procedures for applying them are given in Appendix B.

h. Evaluation of test results and subsequent actions to be taken. As soon as field test results are obtained, they must be compared to appropriate values of maximum dry density and optimum water content to determine if specification requirements have been met. If measured values match or exceed specification requirements, the next lift can be added. If test results show that specifications have not been met, corrective measures must be taken immediately. A lift must be rejected if the material is too wet or too dry. If density is too low but water content is acceptable, additional rolling is all that is required. If, however, water content is outside specifications, the entire lift should be reworked and rerolled. A lift that is too wet should be worked by disking until the water content is lowered to an acceptable value and then recompacted. A lift that is too dry should be disked, sprinkled, and redisked until the additional water is uniformly distributed, then recompacted. It is important when reworking a rejected lift that the full lift depth be reworked, not just the upper portion. All reworked lifts should be retested for density and water content. It is desirable to determine the reason(s) for an unsatisfactory lift in either borrow or fill operations, so that conditions causing the problem may be corrected on future lifts.

5-11. Operations in Adverse Weather

a. Cold weather.

(1) Research (Sherards et al. 1963) has shown that good compaction is not obtained on frozen soil or on soil at temperatures near freezing. Contractors will often want to keep working as long as possible in cold weather, and the Resident Engineer may be faced with a difficult problem in deciding exactly when it becomes too cold for further fill placement. There are no definite criteria for establishing the temperature below which satisfactory work is impossible. The rate at which unfrozen soil loses heat and freezes depends on the size of the construction surface and the rate of fill placement. In cold weather it is important to keep the construction surface “active,” i.e., fill placement must continue without lengthy interruptions. Work has been continued at some dam sites in 20 to 30 °F weather 24 hr a day, 7 days a week to keep the construction surface active. Work must be terminated whenever water in the soil freezes quickly and equipment operation becomes awkward. Underwater dumping in water with floating ice should not be allowed because of the possibility of entrapping ice in the fill. Construction in cold weather must be limited to special situations and always performed under close observation with extreme care.

(2) Protecting the construction surface during the winter when operations are shut down is another problem. The degree of protection required depends on the severity of the winter. In most parts of the United States, it is not necessary to use any protection if the embankment surface has been properly seal-rolled; the worst damage is a heaving and loosening of the upper few inches of the embankment fill by frost action. Before construction starts again in the spring, the surface material should be excavated to a depth below the line of frost action. The depth at which to excavate is best determined by visual examination of shallow test holes. In colder climates where the embankment freezes to a depth of several feet, it may be desirable to protect the construction surface during winter with several feet of loose material. Other methods of protection have been used in extremely cold areas, such as ponding water over the construction surface and even using some type of heating coils on foundations for structures (spillway, outlet works tower, etc.).

b. Wet weather.

(1) Maintaining proper water content during periods of high precipitation is always a problem. Impervious materials should never be placed on embankments during rain, although construction operations can often be continued

successfully between rains. Water content of material spread on embankments can be reduced somewhat during periods between rains by plowing or disking before rolling.

(2) It is desirable to compact fill material as soon as possible after spreading to minimize the time loose fill is exposed to precipitation. Rubber-tired rollers are superior to sheepsfoot rollers when rains are frequent because they leave a relatively smooth compacted surface, whereas the sheepsfoot roller leaves a loose rough surface that readily soaks up rain water. If a sheepsfoot roller is used for general compaction, smooth-wheel rollers (steel or rubber) can be employed to seal the surface when rain is imminent. In any event, the construction surface should be kept sloped to allow the water to run off instead of standing in puddles and soaking in. After a rain, if some ponding does occur, it is usually easy for the contractor to install a few small ditches to drain these areas.

(3) It is often necessary after a rain to scarify and work the construction surface to a depth below that of excessive moisture penetration until it is dried to a satisfactory water content or, to remove and waste all affected material. If procedures to facilitate runoff are followed (sloping the surface, sealing the surface with smooth rollers, etc.), the depth of moisture penetration will be kept to a minimum.

c. Dry weather.

(1) If material being dumped on the fill is too dry for proper compaction, water must be added by sprinkling after it is spread and before it is rolled. The amount of water added and the blending required will depend on grain size and plasticity of the soil, fine-grained soils of high plasticity requiring the greatest amount of blending. Soil must be worked with disks to thoroughly blend and homogenize added water into the soil. The importance of uniform moisture distribution cannot be overemphasized; if pockets of wet and dry soil are allowed in uncompacted material, very poor compaction will result.

(2) Sprinkling the soil can be accomplished by hosing from a pipeline, located along either the embankment toe or the crest, or by the use of water trucks. The latter method is the most effective and the most commonly used today. Pressure sprinkling systems on trucks are superior to gravity systems and should be employed if at all possible. Water sprays must not be directed on the soil with such force as to cause fines to be washed out. Until the inspectors and contractor personnel have gained a "feel" for the amount of water needed, rough computations of the number of gallons to add for a given area should be made, and water applied accordingly. After a few trials, a feel for the proper amount will develop. The coarser and less plastic the soil, the more easily water can be added and worked uniformly into it. It is very difficult to obtain uniform water content distribution in plastic clays containing lumps without a "curing" period of a few days; this is, of course, not practical on the embankment surface. Consequently, disking followed by addition of water and then thorough mixing with a heavy rotary pulverizer may be required to obtain uniform distribution of water in such soils.

5-12. Compaction in Confined Areas

a. Confined areas are those where normal rolling operations with heavy equipment are restricted or where heavy equipment cannot be used at all and hand compactors must be used. Compaction with hand compactors should be avoided and heavy equipment used in these areas if at all possible. Confined areas, where heavy equipment can often be used on a careful basis if maneuvering room is available, include fairly smooth abutments (rock or earth), conduit barrels, towers, etc. Confined areas where hand compactors often must be employed are adjacent to thin concrete structures, such as wing walls, guide walls, etc., where heavy equipment might damage the structure; adjacent to rough, irregular rock abutment slopes where heavy equipment cannot get in close enough to the surface to squeeze the fill into all the irregularities and openings in the rock; and around seep rings or plugs where maneuverability is a problem.

(1) Heavy equipment. When conditions are such that heavy compaction equipment can be used to compact the soil against rock abutments or walls of concrete structures, the construction surface of the embankment should be sloped at about 1V on 6H for a distance of 8 to 12 ft away from the rock or concrete. This will allow the roller to act more directly in compacting the soil against the abutment or structure. The area can then be rolled perpendicular to the face of the abutment or structure by heavy pneumatic equipment or a sheepsfoot roller or by heavy pneumatic equipment in a direction parallel to the face.

(2) Hand compactors. If heavy rollers cannot be used in this manner, the roller should be allowed to work as close as possible, and the portion of embankment directly against the rock or concrete should be compacted with smaller equipment in thinner lifts. Smaller equipment refers to hand-operated power tampers, as shown in Figure 5-12, or power tampers mounted on small tractors. These tampers are usually gasoline-operated or operate on compressed air. Hand-operated power tampers (sometimes called rammer compactors) are probably the most widely used equipment for compacting fine-grained soils in confined areas. A loose lift thickness of not more than 4 in. should be employed in conjunction with these power tampers. Hand compactors should have a minimum static weight of 100 lb, and the

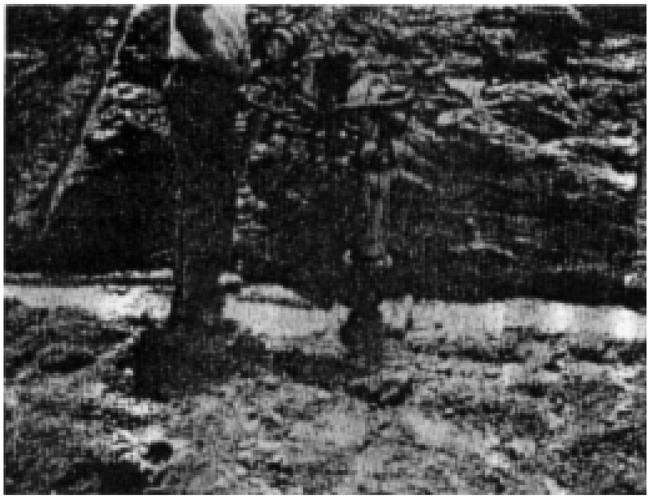

Figure 5-12. Compacting against rock abutment with a hand-operated power tamper, Green River Dam, Kentucky

inspector should carefully check to ensure that the manufacturer's recommended air pressure is being developed. Experience has shown "two-by-four" wood rammers, or single-foot compressed air tampers (commonly referred to as "powder puffs" or "pogo sticks") do not produce adequate compaction. It is important that zones of hand compaction and compaction by heavy equipment overlap so that no uncompacted material exists between them.

b. Where impervious material is to be placed adjacent to abutments or concrete structures, it should be as fine-grained as practicable. Soil must be plastic enough to penetrate all irregularities in the abutments and to form a well bonded seal.

c. Close compaction control must be exercised in these areas since they are generally more critical with respect to seepage and damaging settlements causing cracking and piping than the main embankment. A special sampling program should be established, and an inspector must watch operations involving the use of power tampers at all times.

Section IV
Pervious Fill

5-13. Definition

Pervious fill material as used in this manual is defined as free-draining cohesionless sand and/or gravel, containing less than approximately 5 percent passing the No. 200 sieve.[1] Standard impact compaction tests on such materials do not yield well-defined values of optimum water content and maximum dry density, and field densities are related to maximum and minimum density determinations made according to the relative density procedures in EM 1110-2-1906 rather than to maximum dry density as determined in the standard compaction test.

5-14. Compaction Equipment

a. Vibratory steel-wheel rollers in the weight range of 5 to 10 tons are the best equipment for compacting pervious sands and/or gravel. It should be noted that compaction equipment has been steadily increasing in weight and it is not uncommon to find steel-wheel roller compactors with a weight of 15 or more tons. Drum-drive self-propelled vibratory rollers have been found to be effective on fine uniform sands when other vibratory rollers were not. Rubber-tired rollers are sometimes specified, and crawler tractors are sometimes used if they can produce required densities. Crawler tractors may be effective for compaction in rough or hilly areas where a vibratory roller cannot operate well—for example, in compacting a horizontal drainage layer on an undulating foundation. The contact pressure of the tractor should be at least 9 PSI, and the tractor should operate at that speed which imparts the greatest vibration to the fill.

b. Where free-draining pervious material is placed as backfill against concrete walls and around concrete structures such as outlet conduits, small compaction equipment is needed because of restricted area or because heavy equipment is not allowed close to the walls. Two common types of vibratory compactors are a small steel-wheel vibratory roller and a "vibrating plate" compactor. Air-operated concrete vibrators have also been used successfully in densifying narrow, relatively deep zones of pervious backfill. Figure 5-13 shows pervious backfill being placed against a concrete wall with a hand-operated compactor in the background. Vibratory-type units should be checked frequently to ensure that they are operating at a frequency level giving the highest possible density. For cohesionless materials, the frequency of vibration should generally fall between 1,100 and 1,500 vibrations/cycles per minute.

[1] Outer embankment zones of some dams composed of coarse-grained soils containing appreciable amounts of fines (i.e., greater than 5 percent) are sometimes designated as "pervious zones." The compaction equipment, procedures, and control for materials comprising the pervious zones referred to here are those presented in *Section III* on impervious and semipervious fill.

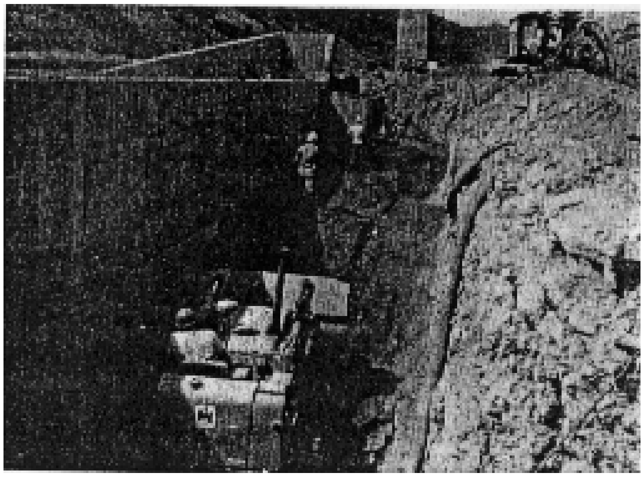

Figure 5-13. Placement of pervious material adjacent to stilling basin wall, Brookville Dam

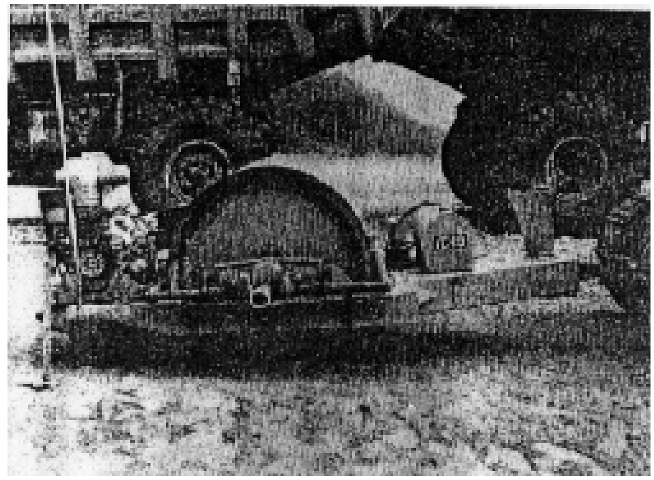

Figure 5-14. Sprinkling system built on frame of vibratory roller (feeder pipes are shown above frame, spray bars are attached below) used at DeGray Dam, Arkansas

5-15. Material Gradations

Gradations of materials to be placed in large pervious embankment zones are generally not specified except to restrict the maximum size and/or the percentage by weight of particles smaller than the No. 200 sieve. On the other hand, a particle-size distribution within limits defined by roughly parallel gradation curves on the standard grain-size (semi-log) plot is specified for select pervious materials to be used in horizontal and inclined drainage layers and in pervious transition layers.

5-16. Water Content Control

Water content control is unnecessary in gravel, and the material may simply be compacted in its as-received condition. If the material is sand or contains a significant proportion of sand sizes, the material must be maintained in a high degree of saturation during compaction using water trucks with pressure spray bars, hoses connected to header pipes laid along the embankment, or other approved methods of water application. If pervious sand is compacted at a low degree of saturation (with insufficient water), surface tension between the water present and the sand grains will cause the moist soil to "bulk," and in this state it will not densify efficiently under an applied compactive effort; the result will be a poorly compacted weak layer which may cause problems. It is therefore imperative that sand be in a high degree of saturation as the roller passes over it, but it is often difficult to achieve a high degree of saturation because surface tension will also prevent water from flowing freely through sandy soils. Figure 5-14 shows the unique wetting system used to saturate the sand for the vertical sand drain at DeGray Dam. The entire spray system was attached to the frame of the vibratory roller itself. The water was fed to the system by means of a long hose connected to a water truck which moved as necessary to accommodate the roller. Very good results were achieved with this arrangement. If a so-called pervious material contains appreciable fines (say, more than 5 to 10 percent passing the No. 200 sieve), it is probable that water content control must be exercised to ensure that the water content is within a range that will permit desired compacted densities to be obtained.

5-17. Lift Thicknesses and Number of Passes or Coverages

These will be established in the specifications. Pervious fill is commonly placed in 6- to 15-in. lifts when it is to be compacted by three or four passes of a vibratory steel-wheel roller or a 50-ton rubber-tired roller, or in 6- to 8-in. loose lifts when it is to be compacted by three to six coverages by a crawler tractor. A note of clarification is necessary here. Guide Specification CE-1306 calls for a specified number of "complete passes" of a rubber-tired roller or a vibratory steel-wheel roller, where a "complete pass" is defined to be complete areal coverage of the lift. This concept does not retain the same meaning in a crawler tractor where the tracks (because of their wide separation) do not make complete areal coverage of the lift. Therefore, when compaction by a crawler tractor is specified, the specification should require coverages by the *tracks* of the tractor. In confined areas where small vibratory rollers or hand-operated vibrating compactors are required, material is normally placed in 2- to 3-in.-thick layers with vibratory compaction applied until densities comparable to those required for areas compacted with heavy equipment are achieved.

5-18. Density Requirements

Compaction equipment and procedures are normally specified without field densities being specified. The expectation is that the prescribed field compaction methods will produce the desired densities. If these are not achieved in the field, then the contractor is paid for additional rolling. Requirements established by the Office of Chief of Engineers are that the average in-place relative density of pervious fill zones should be at least 85 percent and that no portion of the fill should have a relative density less than 80 percent.

5-19. Construction Control

a. Simple control procedures.

(1) Checking lift thicknesses of pervious fill can be accomplished by the simple procedures described for impervious and semipervious materials, except that in using a shovel or rod it is often difficult to determine when the top of the underlying compacted layer is reached. This procedure is also not practical in fills containing large gravel particles. In some cases, it is possible to excavate a small hole in the loose material to the top of the underlying layer, which is identified by a relatively higher resistance to digging.

(2) The inspector must make certain that the embankment is always graded so that surface waters will not wash fines from impervious or semipervious fill materials into the pervious fill. During construction of earth dams, placement of filter materials for drainage layers should be kept higher than adjacent fill containing fines in order to prevent spillage of fine-grained soil onto the pervious material or to reduce the washing of fine-grained soils into the materials by surface runoff. The inspector should be trained to recognize the appearance of pervious material meeting specifications so that he can more easily detect, without the delay of testing, the presence of excess fines. A good indication of excessive fines is when the hauling and compacting equipment sinks in and causes ruts in the fill surface. This usually indicates that water applied during compaction is not draining through the material as it should because of clogging by excess fines.

(3) In general, a vibratory roller should push only a small amount of material ahead of it and leave a smooth surface behind on the first pass. If the roller sinks in and pushes a large amount of material in front of it, either the frequency of vibration is not correct for the particular soil being compacted or the material contains too many fines.

(4) It is more difficult to judge the compacted density of pervious material than that of fine-grained material. Resistance to penetration of a shovel or a reinforcing steel rod often is not a suitable way of checking density, and it is necessary for the inspector to rely more heavily on field control tests. Some inspectors can judge the compaction obtained in pervious fill by walking over it and feeling the reaction of the material. The uniformity of particle-size gradations in the lift should be observed. Too much vibration may cause segregation of the fill material, causing the fines to settle to the bottom of the lift. Conversely, if particles are being crushed during compaction, a layer of fines will develop in the upper few inches of the lift.

(5) The inspector should observe loading, dumping, and spreading operations, particularly if the pervious fill is well-graded material, to ensure that undesirable segregation of particles is not occurring as a result of such operations.

(6) The particular importance of horizontal and inclined drainage layers to the function of a dam, and the fact that these features are so limited in thickness, justify the special attention of inspectors to see that gradations and densities of the in-place filter materials meet the specifications.

b. Gradation. Gradation tests should be performed to ensure that the material being placed is within specification limits. The number of gradation tests needed will, of course, depend on the variability of natural pervious material as obtained from the borrow areas. Complete gradation tests should be performed on material for which the entire range of particle sizes is specified. For those materials for which only the percent finer than the No. 200 sieve or some other sieve is specified, the material should be soaked and then washed over the No. 4 and the designated lower-limit sieve in accordance with procedures given in EM 1110-2-1906. Gradation tests should also be performed on compacted material especially when it is suspected that there has been contamination with fines from surface waters or when the fill material may have been degraded by breakage of particles during compaction.

c. Field density testing and relative density determinations.

(1) The water balloon and sand volume density test methods described in paragraph 5-10*d*(1) can be used to determine the in-place density of pervious fill. It is, of course, more difficult to dig holes in pervious materials. When the fill material contains high percentages of large particles, it may be necessary to increase the volume of holes substantially and to line the holes with plastic film so that the volume may be determined by the quantity of water or oil needed to fill it. The nuclear density meter can be used for supplementary density determinations under the conditions stated in paragraph 5-10*d*(2)(b). The density of

free-draining pervious fills and filter materials cannot be related to standard impact compaction test results since water content/density relations are not valid for such materials, as they are for materials having varying degrees of plasticity. Field densities must be expressed in terms of maximum-minimum densities as determined by laboratory tests described in EM 1110-2-1906. Field densities are expressed in terms of their relation to these laboratory values, i.e., in terms of relative density. The percent relative density, D_d, of the in-place material can be computed by the equation:

$$D_d = \frac{\gamma_d - \gamma_{min}}{\gamma_{max} - \gamma_{min}} \times \frac{\gamma_{max}}{\gamma_d} \times 100$$

where

γ_d = dry unit weight of the pervious fill in place (the in-place density), pcf

γ_{min} = minimum density, pcf, from laboratory tests

γ_{max} = maximum density, pcf, from laboratory tests

(2) Field density determinations using the water balloon or sand volume procedures should be made for every 1,000 cu yd of pervious fill placed at the beginning of the job and for every 3,000 cu yd thereafter, with more frequent determinations desirable for testing in drainage layers. These tests generally should be taken one lift thickness deep, especially in sands. Although the performance of maximum and minimum density determinations on material from each field density test would give the most accurate determination of the relative density of the in-place material, this is frequently not feasible because of time and manpower restrictions. Therefore, it is often advisable to attempt to develop correlations between the gradation data and the maximum-minimum density values on materials representing the range of gradations to be expected from the sources of supply. Figure 5-15 is an example of a correlation between the percent finer than the No. 16 sieve and the maximum-minimum density values. Where a good correlation like this is developed, a simple determination of the percent finer than the No. 16 sieve is all that is needed to obtain the appropriate maximum-minimum density values in the in-place material. In other instances, good correlations may be developed between maximum-minimum density values and the percent of material passing other sieve sizes or the coefficient of uniformity. Correlations developed between minimum and maximum density values can be used to obtain minimum density after the performance of a maximum density test alone. Caution should be exercised in using such correlations for uniform sands, since the spread between the maximum and minimum density is very small and large errors may result.

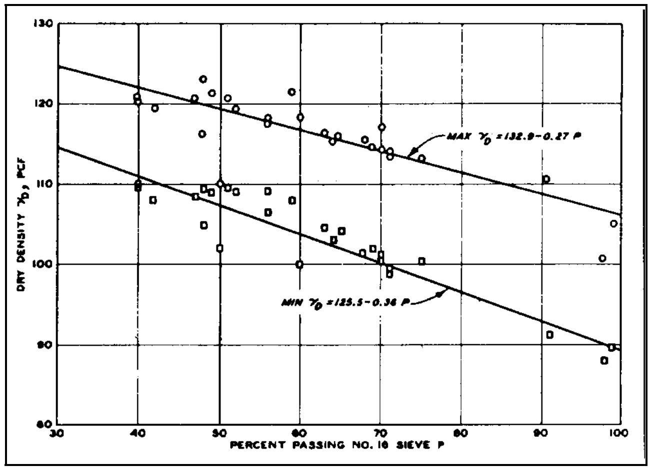

Figure 5-15. Correlation between density and percent passing No. 16 sieve

(3) Correlations such as those described above should be used only on materials from the particular sources for which the correlations were developed. Application to materials from other, geologically different sources may lead to considerable error because of differences in particle shapes and degradation characteristics. The selection of maximum-minimum density values by visual comparisons of field density test material with samples of materials on which maximum-minimum density determination have previously been made is generally not a good procedure; small differences in particle sizes that cannot be adequately detected by visual comparisons have significant effects on these density values.

5-20. Test Results and Actions to be Taken

Assume, for example, that it has been established that a lift has in-place relative densities between 80 and 85 percent. A review must be made of the relative densities of all previous lifts to ensure that a minimum average of 85 percent relative density will be maintained if the questionable lift is to be accepted. The intent of the relative density criteria is that the relative density of the material measured immediately after compaction must conform to the requirements stated in paragraph 5-18 without any consideration of increase in density caused by the placement and compaction of subsequent lifts.

Section V
Rock Fill

5-21. General

a. Embankments with large rock-fill zones are becoming more common. This is primarily due to the necessity of using sites where rock foundation conditions are unsuitable for concrete dams, the suitability of modern construction equipment to handle rock, the increasingly higher dams being constructed, and the economic benefit obtained by the maximum use of rock from required excavation.

b. Rock for construction purposes falls into two categories, soft rock and hard rock. Soft rocks such as shales, mudstones, siltstones, claystones, chalk, earthy limestones, weakly cemented sandstones, and badly weathered igneous and metamorphic rocks break down in varying degrees during compaction, some into tight compact masses similar to impervious soils. Soft rocks are generally susceptible to further softening by exposure to air and water. Conversely, hard rocks do not readily break down during handling and compaction, and their use results in a pervious to very pervious fill depending on the amount of fines present.

c. There are no well-established criteria for construction methods best suited to either type of rock. The breakdown of most types of rock is very unpredictable, and this fact has led to the widespread use of test quarries and test fills for large rock-fill dams.

5-22. Hard Rock

a. Specifications. The specifications for pervious rock-fill sections generally require that the rock be sound, well graded, and free draining. Gradation is not usually specified, but the maximum permissible size is normally specified together with lift thickness. Rock fill is usually required to be placed by dumping from trucks, with bulldozers spreading the material to the desired lift thickness. The required placement and spreading operations should be that segregation of rock sizes is avoided. This is discussed in more detail in the following paragraphs. The type of roller, lift thickness, and number of passes will be specified, preferably based on results of test fills.

b. Placement operations.

(1) When rock is dumped on the fill surface and pushed into place by a bulldozer, the fines are moved into the upper part of the lift, thereby creating a smoother working surface for the compacting equipment. If, however, a layer of fines of such a thickness as to choke the upper part of the lift and prevent distribution of the fines throughout the lift is produced, it is necessary to specify that the rock be dumped directly in place.

(2) All oversized rock must be removed prior to compaction. This is usually done with bulldozers, crawler tractors fitted with special “rock rakes,” or cranes. Oversized rocks are often pushed into a specified zone in the outer slopes. Excessively large rocks are sometimes hauled off to be dumped elsewhere, or they are broken up with a drop weight or explosives and used in the rock fill or riprap zone. Oversized rocks should never be pushed to accumulate along the contact slope of a closure section.

(3) Close inspection is also required to ensure that the material does not contain excessive fines, which can cause excessive post-construction settlements when the reservoir is filled. It is difficult to define a limiting amount of fines in the specifications and, consequently, this is rarely done. However, the design office should provide some guidance to field personnel, based on results of rock tests and fill studies, which will aid in determining when excessive fines are present. The inspector must be alert for material variations that could result in undesirable changes in gradation of the material being brought to the embankment. Such changes should be called to the attention of the contractor so that quarrying techniques can be changed.

c. Compaction.

(1) With the introduction of smooth steel-wheel vibratory rollers to this country in the last 20 years, current practice is to compact all sound rock fill, using these rollers, in comparatively thin lifts of unsluiced rock. Vibratory rollers having static weights of 5, 10, and 15 tons have been used to construct several Corps rock-fill dams.

(2) The lift thickness specified is dependent on the size and type of rock and the type of compaction equipment to be used, and is usually determined from results obtained during construction of a test fill. Generally, specified lift thickness will be no thicker than 24 in. unless test fills show that adequate compaction can be obtained using thicker lifts. Maximum size rock should not exceed 0.9 of the lift thickness.

(3) Scarification of compacted lift surfaces is not necessary and should not be allowed because it disturbs the compacted mass.

5-23. Soft Rock

a. The use of soft rocks in the past has been dictated by their availability in large quantities from required excavations. The main concern about these materials is their tendency to weather and soften with time when exposed to air and water. However, cases in which large portions of embankments were composed of soft rocks have shown that they can be used satisfactorily in random and semipervious zones, attaining adequate shear strength and experiencing no appreciable softening after placement. Where soft rocks will constitute a significant structural portion of a fill, their properties and the best methods of compaction should be determined by means of a test embankment constructed during the design studies.

b. Some types of soft rock have been compacted by first rolling over the loose lift with a heavy tamping roller equipped with long spike or chisel-type teeth ("shell breaker"), and then compacting the lift with conventional tamping or rubber-tired rollers. A summary of this technique is given by Bennett (1958).

Section VI
Semicompacted Earth Fills

5-24. Uses

Spoil berms, channel fillings, and low levees to protect farmlands are often constructed of semicompacted fills.

5-25. Specifications

Semicompacted fills are those specified to be compacted by the routing of hauling and spreading equipment over the spread layer. Lift thickness is specified, but the range of placement water contents is either not specified or permitted to vary widely.

5-26. Construction Control

Inspection of semicompacted fill is usually entirely visual, although a few density tests may be made for record purposes. The primary concern of the inspector is to ensure that the specified lift thickness is not exceeded, suitable materials are being used, and hauling and spreading equipment covers the fill uniformly.

Section VII
Sequence of Placement and Measurement of Quantities

5-27. Schedule of Construction

The schedule for construction of an earth or rock-fill dam may require stage (or phase) construction. In a wide flat valley, the embankment on one side of the river may be constructed to the full height under one contract, with subsequent portions constructed during following years. Where foundations are soft, the embankment may be constructed to a specified elevation and further fill placement deferred for a year or more to permit dissipation of foundation pore pressures or to achieve an adequate degree of consolidation. In a narrow steep valley with rock foundations, the entire embankment may have to be completed to a stipulated elevation by a certain date to prevent overtopping during the flood season. The construction schedule is developed to make maximum use of available borrow and excavation materials, considering river diversion requirements, foundation conditions, and seasonal weather conditions. The contractor is responsible for constructing the particular stage or section of embankment within the time limit specified. The inspection force is responsible for determining that each stage or section of embankment is being built in proper sequence and also that each stage or section is constructed using proper placement sequence. Changes in sequence or timing of stages should not be made without approval of the design engineer.

5-28. Placement Sequence

a. It is usually required that the embankment be brought up fairly uniformly over the entire width and length of the section under construction. Interim embankment crests should be crowned slightly to provide surface drainage during wet weather. Specified transverse slopes of interim crests may range from 1 to 5 percent. During periods of dry weather, the fill heights of central impervious zones are sometimes allowed to exceed the heights of adjacent pervious zones by as much as 5 ft to permit continuous placement of impervious material. However, special precautions such as sloping the impervious fill material away from the pervious zone are required to keep impervious material out of inclined filter zones.

b. Placing material in a cutoff trench should be accomplished by dumping and spreading the first lift of the downstream filter zone material (if such a filter is required at the downstream trench slope) and then dumping and spreading the first lift of impervious material. This should be followed by compaction of both zones concurrently, with separate equipment being used on each zone. Dumping and spreading filter layers first will help to maintain the specified width of the filter zone. A downstream horizontal drainage zone should be completely placed and covered by two lifts of downstream shell materials as soon as possible to prevent contamination of the blanket by exposure to surface waters carrying fines.

5-29. Measurement of Quantities

Measurement of excavated materials is usually based on cross-section surveys of the area before and after excavation, using the average end area method for computing quantities. For embankment fill, a cross-section survey of the outer boundaries and average end area method are used in computing quantities. For separate zones within an embankment, the theoretical quantities are computed from the lines and grades shown in the construction drawings. Inspection personnel should be completely familiar with provisions of the specifications and lines and grades shown on construction drawings so that instances of overexcavation or fill placement outside contract lines and grades are recorded. This will assist in preventing possible errors in measurement and certification of payment for quantities in excess of contract provisions.

Section VIII
Slope Protection

5-30. Areas to be Protected

Slope protection is required to protect upstream slopes against damage from wave erosion, weathering, ice damage, and damage from floating debris. Upstream slope protection of earth dams usually consists of riprap, although soil cement, concrete paving, and asphalt paving have been occasionally used when riprap was not economically justified. Dams with outer shells of sound, durable, large rock may not require further protection. Downstream slope protection is required to protect against damage from surface erosion by wind and rain. Downstream slope protection includes gravel for dry climates, turf in humid climates, riprap where tailwater may create wave action, and waste rock. Proper field construction procedures and enforcement of specifications are particularly important in obtaining slope protection that will remain in place and in minimizing maintenance during the life of the dam.

5-31. Upstream Slope Protection

Placement of upstream slope protection may be accomplished either as the embankment is being built or after the embankment is completed. This depends on the elevation limits of slope protection, the schedule for impounding reservoir water, and the type of slope protection. The best procedure is to require that the slope protection construction not lag behind earth-fill construction more than 10 ft in elevation.

a. Riprap. Riprap is the most commonly specified type of upstream slope protection. Properly graded riprap, placed to provide a well-integrated mass with minimum void spaces so that underlying bedding cannot be washed out, provides excellent slope protection. Two primary factors govern successful construction and are discussed below.

(1) Loading from the quarry to provide a good mixture of different sizes within the required gradation in each load. Proper loading from the quarry requires that blasting operations produce proper sizes and that the inspector be experienced in inspecting the loading operations.

(2) Placing loads on the slope to provide uniform distribution of different sizes without segregation and rearrangement of individual rocks to provide a rock mass without large voids. A gradation test (performed by weighing a sufficient quantity) should be made for each 10,000 cu yd of placed riprap. Two ENG forms for plotting gradations curves are available. These forms are ENG Form 4055 dated April 1967, “Riprap Gradation Curves” and ENG Form 4056 dated April 1967, “Gradation Curves for Riprap, Filter, and Bedding”. Placement should be accomplished by placing loads along the slope against previously placed riprap; this will reduce segregation of sizes that would otherwise occur if loads were dumped in separated piles. The best method of placement to avoid segregation is to use a skip as shown in Figure 5-16a. Dumping rock at the top of the slope into a chute should never be allowed since this will result in segregation. If dumping is done from trucks, it is usually necessary to winch load haulers down the slope to the placement location. Dumping should proceed along horizontal rows and progress up the slope; loads should not be dumped to form rows up the slope. If very large (4 to 5 ft diam) rock is specified, a crane with an orange peel attachment (Figure 5-16b) operating on a platform built up on the slope can be used. Other equipment such as Gradalls, cranes with clamshell buckets, and rubber-tired front end loaders, can be used to place riprap. These are preferable to dumping from haulers. Close visual inspection after dumping and spreading is required to determine the degree of uniform distribution of different sizes and close-knit arrangement of individual pieces. Reworking, generally by hand, will almost always be required; however, reworking can be kept to a minimum if care is taken when loading to ensure that each individual load has the proper amount of each size rock (i.e., the proper gradation). Supplemental gradation checks might be made by the photogrid method, described by Curry (1964), in which a 10-ft-by-10-ft aluminum pipe form containing a 1-ft-by-1-ft grid or rope is placed on the riprap and photographed. From the photograph, the number and size of stones visible at the surface are determined. However, for materials that have been selectively arranged, as by hand, this may not provide an accurate determination of size distribution. Firm enforcement of specifications is required, especially during early stages of riprap placement

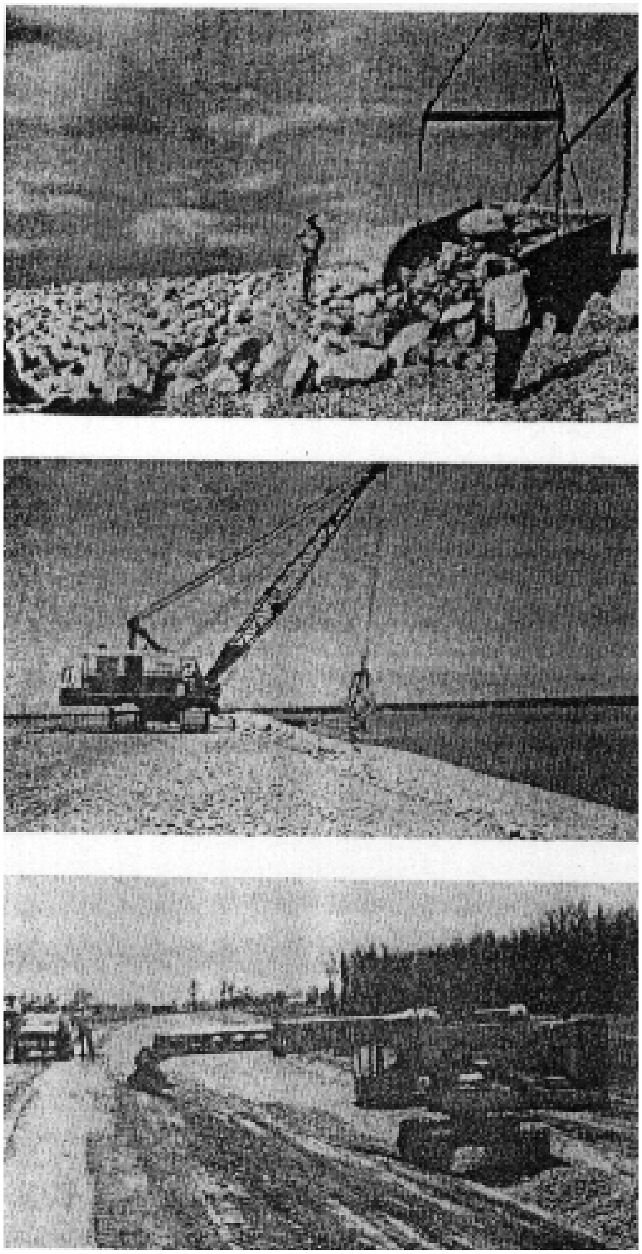

Figure 5-16. Placement of riprap and bedding material. (a) Dragline with skip placing riprap at Texarkana Dam, Texas; (b) Dragline with orange peel attachment placing riprap at Lavon Dam, Texas; (c) Gradall used to place bedding material, main stem levee, Chariton River Project, Missouri

to ensure a well-graded mass having no large voids.

(3) A bedding layer or layers must be provided between the riprap and embankment material (except in the rare case that the latter is highly cohesive) to protect the embankment material from eroding by wave action and to provide a stable base for riprap. Placement is shown in Figure 5-16c. Many riprap failures have occurred because the bedding material was not large enough to preclude being washed out by wave action through interstices of the riprap. Removal of the bedding causes settling and dislodging of overlying riprap, further exposing bedding and embankment material to direct wave action. It is, therefore, necessary that bedding material meet specifications relating to gradation and layer thickness. It is good practice to place rock spalls or crushed stones of like size between the bedding and riprap if they are available from quarry or required excavation. The term spalls refers to the finer materials resulting from rock excavation for materials such as riprap. Spalls must be durable fragments of rock, free of clay, silt, sand, or other debris. The gradation of spalls will vary and must be specified for each particular job. The use and minimum and maximum size of spalls or equivalent crushed stone should be established in the design memo and should be specified if it is appropriate. In some cases, spalls may replace graded bedding material.

b. Soil cement. Soil-cement slope protection has not been used for Corps of Engineers dams in the past, but may be used in the future if riprap would be excessively expensive. The recommended method is to use plant-mixed rather than mixed-in-place soil cement. Inorganic sandy or gravelly soils with not more than 35 percent finer than the No. 200 sieve are suitable for soil cement use. The plasticity of the fines should be low. Soils classified as GW-GM, GP-GM, GM-GC, SW-SM, SP-SM, and SM-SC would be suitable. The amount of cement and water added to the soil is based on laboratory tests to determine compaction properties and resistance to freezing and thawing cycles. Plant-mixed soil cement is usually spread in 6-in. horizontal lifts along the slope in a strip, 7 to 10 ft wide (depending on the slope angle and specified thickness perpendicular to the slope), and compacted by sheepsfoot or rubber-tired rollers. Succeeding lifts are stairstepped up the slope. Control of cement and water content, uniformity of mixture, and density tests are required, as well as measurement of both lift thickness and lift width. Bonding of the compacted layers is important, and scarifying is usually specified on surfaces of compacted layers prior to placing the next lift. Curing is also important, and in dry climates special measures may be needed to prevent drying of compacted layer surfaces. Reference material on construction operations can be obtained from the Portland Cement Association. Another source of information is the U. S. Bureau of Reclamation, which has used soil-cement slope protection extensively.

c. Other upstream protection. Monolithic concrete, hand-placed riprip paving (grouted and ungrouted), and asphalt paving are other methods of protection for upstream slopes. These methods have been used infrequently, if at all, for Corps of Engineers dams in the past.

5-32. Downstream Slope Protection

a. Grass turf. Grass turf for protection of downstream slopes is usually specified in humid climates for earth embankments. Where the downstream embankment zone is composed of pervious material, sufficient fine-grained soil or topsoil must be placed to support vegetation growth. The method usually specified consists of clearing the slope of any roots and stones, tilling to a depth of at least 4 in., fertilizing, seeding or sprigging, compacting, watering, and maintaining as required to establish the turf. Temporary or permanent protection should be established on completed portions of the embankment as soon as possible. The usual practice of waiting until near the end of construction and trimming slopes by filling erosion channels with loose material and then fertilizing and seeding has resulted in continuing maintenance problems at several projects. Specifications usually provide detailed instructions with which inspection personnel should be familiar. Frequent inspection should be made to ensure the following:

(1) That the soil is properly tilled and not allowed to migrate down the slope during tilling, which might create depressions or undulations.

(2) That the specified type, quality, and quantity of fertilizer and seed are used.

(3) That turfing operations are conducted during good weather conditions, and necessary interim precautions are taken to prevent erosion, such as mulching with hay or burlap for a protective covering.

b. Riprap. Riprap placed on the lower downstream slope to protect against wave action from tailwater should be controlled in the same manner as upstream riprap. Above the elevation needing such protection, dumped rock (usually waste rock) is used only when readily available from required excavation or stripping operations. (Control should conform with specification requirements).

c. Gravel. Gravel or rock spalls (depending on available material) are sometimes used for downstream slope protection. Where the outer downstream shell contains random granular materials, it is often specified that cobbles and rocks be pushed out to the edge and used in the slope protection. In this case, it is desirable that placement of downstream slope protection be kept 5 to 10 ft behind embankment placement. The gravel or spalls are usually dumped and spread horizontally along the outer slope to depths of at least 1 ft measured perpendicular to the surface.