RECLAMATION

Managing Water in the West

Design Standards No. 13

Embankment Dams

Chapter 10: Embankment Construction
Phase 4 (Final)

U.S. Department of the Interior
Bureau of Reclamation

May 2012

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Acknowledgments

The U.S. Army Corps of Engineers manual, *Construction Control for Earth and Rockfill Dams*, EM 1110-2-1911, dated January 1977 [1], was used extensively to develop this design standard. Additions have been made and passages edited to reflect current Bureau of Reclamation practice.

Design Standards Signature Sheet

Design Standards No. 13

Embankment Dams

DS-13(10)-16: Phase 4 (Final)
May 2012

Chapter 10: Embankment Construction

Foreword

Purpose

The Bureau of Reclamation (Reclamation) design standards present technical requirements and processes to enable design professionals to prepare design documents and reports necessary to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Compliance with these design standards assists in the development and improvement of Reclamation facilities in a way that protects the public's health, safety, and welfare; recognizes needs of all stakeholders; and achieves lasting value and functionality necessary for Reclamation facilities. Responsible designers accomplish this goal through compliance with these design standards and all other applicable technical codes, as well as incorporation of the stakeholders' vision and values, that are then reflected in the constructed facilities.

Application of Design Standards

Reclamation design activities, whether performed by Reclamation or by a non-Reclamation entity, must be performed in accordance with established Reclamation design criteria and standards, and approved national design standards, if applicable. Exceptions to this requirement shall be in accordance with provisions of *Reclamation Manual Policy*, Performing Design and Construction Activities, FAC P03.

In addition to these design standards, designers shall integrate sound engineering judgment, applicable national codes and design standards, site-specific technical considerations, and project-specific considerations to ensure suitable designs are produced that protect the public's investment and safety. Designers shall use the most current edition of national codes and design standards consistent with Reclamation design standards. Reclamation design standards may include exceptions to requirements of national codes and design standards.

Proposed Revisions

Reclamation designers should inform the Technical Service Center (TSC), via Reclamation's Design Standards Website notification procedure, of any recommended updates or changes to Reclamation design standards to meet current and/or improved design practices.

Chapter Signature Sheet
Bureau of Reclamation
Technical Service Center

Design Standards No. 13

Embankment Dams

Chapter 10: Embankment Construction

DS-13(10)-16:[1] **Phase 4 (Final)**
May 2012

Chapter 10 – Embankment Construction is an existing chapter within Design Standards No. 13 and was revised to include:

- Experience and information that have been gained since the initial version of this chapter was published
- Technology development
- Equipment development
- Additional construction photographs
- Additional tables and figures
- Appendices

[1] DS-13(10)-16 refers to Design Standards No. 13, chapter 10, revision 16.

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Chapter 10

Embankment Construction

10.1 Introduction

10.1.1 Purpose

The purpose of this chapter is to present construction concepts that embankment dam design engineers should consider during design and construction of a new embankment dam or modification to an existing embankment dam.

10.1.2 Scope

This design standard covers construction concepts and details that are important to ensure that design assumptions, field conditions, and construction practices are compatible.

10.1.3 Deviation from Standards

Rationale for deviation from the design standard should be presented in technical documentation for the dam and should be approved by appropriate design managers.

10.1.4 Revisions to the Standards

This standard has been in use for two decades and was submitted to a consultant review during its early years. The original issue was on July 1, 1991, with no subsequent editions. This current version is the result of an in-house review during 2011-12. It will be revised periodically as dictated by changes in construction concepts and technology. Comments and/or suggested revisions should be sent to the Bureau of Reclamation, Technical Service Center, Attn: 86-68300, Denver, CO, 80225.

10.1.5 Applicability

The construction concepts presented herein apply to the design and construction of earth and rockfill dams.

10.2 General Design Considerations

10.2.1 Design Involvement

The design of an earth or rockfill dam continues through construction and operation until it is proven that the dam is operating as intended by the designers. Timely participation of appropriate members of the design team can be invaluable in anticipating, preventing, and solving problems during construction and in ensuring construction of a quality embankment within budget. Designers must ensure that foundation conditions, embankment materials, and construction practices are as assumed during design. If these conditions are not consistent with design assumptions, the dam may not function as intended. In some cases, this may lead to serious economic loss, structural failure, and loss of life. Therefore, it is imperative that the designers of a dam be intimately involved with its construction.

During construction, design engineers and geologists should work closely with construction field staff to frequently reassess design concepts and assumed foundation conditions as compared to actual foundation conditions observed at the site. This involves establishing open and frequent communication between construction and design staff, including frequent design staff visits to the project to observe actual foundation conditions and construction procedures to determine if changes may be required to accommodate site conditions.

Additional information concerning the characteristics of the foundation and abutments is obtained during clearing, stripping, and required excavation and may confirm or contradict design assumptions based on earlier geologic investigations. For this reason, dams are sometimes constructed in phases so that the design can accommodate observed foundation conditions. Operations in borrow areas and in required excavations also provide information on the characteristics of the fill material and the excavated slopes. Weather conditions during construction and ground water conditions may significantly affect the water content of fill material or create seepage and/or hydraulic conditions, which may necessitate modifications to the design. Details of contractor operations, methods, and equipment determine the quality of the product. Design and construction staff need to work together to avoid potential deviations from design intent, which may result from contractor performance.

Design evaluation must also include evaluation of compaction control results. The designers may need to reanalyze stability conditions based on: (1) results of laboratory tests on record samples and additional foundation samples, and (2) field observations of pore water pressures, settlements, and lateral displacements. A high degree of coordination between design and construction staff is mandatory.

10.2.2 Coordination Between Design and Construction Staff

Involvement of designers during construction of the dam can create difficulties at times because design philosophy is often somewhat different from construction philosophy, even though the goal of both the designers and the construction staff is a high quality job. Designers want to ensure absolute compatibility with design intent, which includes an assessment of field conditions and may result in design changes that possibly result in construction delays and affect the budget. The contractor is interested in maintaining schedules and making a profit. The construction administration staff is caught in the middle of these conflicting goals. The designers, the construction staff, and the contractor are all trying to perform a high quality job compatible with their best interests. However, the interests of each group may differ and result in conflicts that require resolution.

Some of the potential problems that could occur during construction can be reduced by clear, concise specifications and clear, concise instructions to contract administration personnel regarding design assumptions and reasons for design requirements. This information is usually conveyed in the construction considerations document that is prepared by the design staff for the construction staff. Because most of this information is also valuable to the contractor, the current policy is to include construction considerations and the basis for various assumptions in applicable sections of the specifications. For example, geologic and engineering reasons for specifying excavation to particular surfaces for the foundation of the dam should be included in the specification section on foundation excavation. Confidence in the information on which the requirements are based should also be conveyed in the specifications. When this type of information is provided in the applicable technical paragraphs of the specifications, it gives prospective bidders a clearer, more informed basis for preparing their bid and, therefore, a better opportunity for a more responsive bid, which results in less likelihood that claim situations will develop. It also minimizes the possibility that the contractor will deny lack of knowledge of information that was essential to preparation of the bid.

Designers can convey information that is not needed by, or that is inappropriate for, the contractor to the contract administration staff by letter, memorandum, or meetings. However, it should be understood that the contractor is privileged to any information. Quality assurance sampling and testing frequency for various embankment zones is an example of information that could be transmitted to the Project Construction Engineer (PCE) separately and not be included in the specifications.

Designers and geologists should schedule briefings with the PCE's staff prior to and during construction. One such meeting is the construction readiness review, and another is the constructability review. A third possible briefing would be the preconstruction meeting with the contractor. The construction readiness meeting is a briefing by the design staff to the PCE and PCE's staff and may include the contractor's staff at the discretion of the PCE. This briefing generally is a discussion of the construction considerations. If the PCE staff desires, additional briefings should be held with the contractor's staff to discuss design requirements and answer questions, so that all persons concerned have a clear understanding of anticipated conditions, design intent, and requirements. The ultimate goal is to provide both the Bureau of Reclamation (Reclamation) construction and contractor staff with a clear understanding of the requirements, reasoning, and uncertainties in the specifications. A clear understanding of design intent and reasoning will promote good construction, contract administration, and inspection and will ultimately result in a smoother running contract and a better product.

The designers and geologists, especially the Principal Designer (PD) and Principal Geologist (PG), should establish good rapport with the construction staff as early as possible during the design data collection phase of the project, if the construction staff is onsite at that time, or as soon as possible thereafter. This promotes a better understanding of each other's needs, fostering trust and free exchange of information. Such a relationship will prevent many misunderstandings.

The Construction Liaison Engineer (CL) is the link between design and construction staff, helping to coordinate and resolve design and construction issues and promoting good relations. The PD and PG should ensure that all discussions with the construction staff have CL involvement. The CL should have a good construction background, in addition to a good understanding of design requirements. Because the CL can facilitate discussion between the design and construction staff, the CL is an asset to promoting understanding between them. The PDs and PGs should take full advantage of this expertise in their discussions with project and regional offices.

10.3 Foundation Treatment

10.3.1 Foundation and Abutment Treatment

Preparation of the foundation and abutments for an earth or rockfill dam is a critical phase of construction; the thoroughness with which it is done is reflected in the operational performance of the structure. It is often difficult and costly to correct foundation and abutment deficiencies that show up after construction is underway or completed. The primary purposes of foundation and abutment treatment are: (1) to provide positive control of underseepage, (2) to prepare the foundation contact for placement of the overlying compacted fill, (3) to minimize differential settlements and thereby prevent cracking of the embankment, and (4) to prevent migration of embankment material into fractures or openings in the foundation.

The work is intended to ensure that: (1) foundations and abutments are stripped to depths sufficient to remove soft, organic, fractured, weathered, or otherwise unsatisfactory materials; (2) depressions and fractures in rock surfaces are cleaned and adequately filled with grout, dental concrete, or other suitable material; (3) rock surfaces are made relatively smooth and uniform by shaping and filling with dental concrete as necessary; (4) subsurface cavities and fractures are detected and grouted; and (5) cutoffs extend to suitably impervious materials. Figure 10.3.1-1 shows excavation to competent rock at Ore Knob Dam in North Carolina.

Figure 10.3.1-1 Ore Knob Dam, North Carolina. A back hoe being used to excavate to remove weathered rock. Competent rock is indicated by refusal of the bucket to excavate further. Note the “smoke” (rock dust) being produced by the scraping of the bucket teeth on the hard rock.

During this phase of construction, close liaison must be maintained between construction and design staff, since most discrepancies between design assumptions and actual field conditions are detected during foundation excavation and treatment. Few dams are constructed without encountering some unexpected foundation conditions that were not discovered in exploration for design, such as ancient stream channels filled with sands and gravels, large boulders, more extensive zones of rock weathering or fracturing, cavities, soft soil areas, abandoned pipes or drains, and debris. For this reason, inspection trenches are generally required beneath the impervious zone of a dam, when cutoff trenches are not specified. These inspection trenches provide access for careful examination of the foundation along the entire length of the dam to ensure that undesirable foundation conditions are detected and corrected. Design Standard No. 13, Chapter 3, "Foundation Surface Treatment," gives specific details on foundation treatment. Chapter 2, Embankment Design, and Chapter 8, Seepage, give specific information on cutoff trenches, as well as a brief treatise on grouting with references to more detailed information. Chapter 15, Foundation Grouting, gives design and construction information on grouting, and Chapter 16, Cutoff Walls, gives design information on cutoff walls.

Careful inspection by both the construction and design staff is important during the foundation and abutment treatment phase of construction. Open communication between the design and inspection staff is important to ensure that design intent and requirements are clearly understood. Inspectors must be vigilant for conditions that are different from those which were anticipated by the designers and geologists and make sure that these differences are brought to the attention of the PCE, PD, and PG. The PD and PG should visit the site frequently during this phase of construction, so that they can personally inspect the foundation and its treatment and communicate directly with the inspection staff. The construction readiness review should include discussions of anticipated foundation conditions and design intent regarding acceptable foundation treatment prior to beginning this phase of construction. The requirement and procedure for accomplishing foundation acceptance are conveyed in paragraph 175.4.1 of the *Reclamation Instructions*, appendix A, and should also be discussed during the construction readiness review meeting.

Figure 10.3.1-2 shows foundation cleanup of a rock foundation that is beneath the Spring Canyon Dam embankment at Horsetooth Reservoir in Colorado. A backhoe, hand labor, compressed air and water, and a vacuum truck were used in the foundation cleanup. If irregular foundation conditions occur beneath an impervious zone 1 or the filter or drainage zones of the embankment, shaping of the rock surfaces to improve their contours and smoothness would be required to facilitate compaction of embankment materials on the rock foundation. This shaping can be achieved by a combination of line drilling, jack hammering, smooth blasting techniques, and dental concrete placement. No loose soil or rock should remain on the foundation surface. The final cleanup prior to placement of embankment materials should be accomplished by the use of hand labor and pressurized air or water, or air and water together. Figure 10.3.1-3 shows final cleanup of a sandstone foundation. Care should be exercised so that the air/water pressure does not loosen the foundation rock. It is desirable that the foundation surface be damp just prior to fill placement; however, there should be no standing water on the foundation surface.

Figure 10.3.1-2 Horsetooth Dam Modification, Spring Canyon Dam, Colorado. Foundation cleanup for placement of embankment materials on the foundation. USBR- 2001-03

Figure 10.3.1-3 Final foundation cleanup using pressurized air and water to remove loose sandstone and other rock and soil particles.

Figure 10.3.1-4, at Bonneau Dam, Montana, shows final cleanup of a shale foundation using pressurized air, and figure 10.3.1-5 shows dental concrete being placed on the Bonneau Dam foundation to prevent the shale from weathering. An outlet conduit was constructed on this foundation. The foundation for Zone 1 and filter/drain at Bonneau Dam were similarly cleaned, but usually did not require dental concrete placement because very little shaping of the foundation was required and the embankment materials could be placed quickly enough to prevent the shale from weathering.

Figure 10.3.1-6 shows severe seepage, manifested by sand boils, near the toe of the embankment at Lake Alice Dam in Nebraska. This is an indication of inadequate control of seepage through the foundation of the dam. This seepage is the result of improper treatment of the foundation at Lake Alice Dam during original design and construction, as well as an improperly designed seepage collection system. The dam was later modified with an inverted filter and drainage berm over the sand boil area. The filter and drainage blankets were weighted by earthfill. The purpose of this modification was to safely collect and convey seepage from beneath the dam and to increase slope stability. During construction of the modification, the original toe drain was recovered. It was completely full of soil that had been piped into it from the Brule Formation, which was the foundation, and from the embankment.

Figure 10.3.1-4 Bonneau Dam Modification, Montana. Foundation cleanup for placement of dental concrete. Rocky Boys Indian Reservation, Montana. USBR 2004

Figure 10.3.1-5 Bonneau Dam Modification, Montana. Protective dental concrete being placed over easily weathered shale to prevent the foundation from weathering. Rocky Boys Indian Reservation, Montana. USBR 2004

Figure 10.3.1-6 Lake Alice Dam, Nebraska. Sand boils downstream of the embankment near the toe of the dam. USBR 1982

10.4 Dewatering and Unwatering

10.4.1 Dewatering and Drainage of Excavated Areas

Inadequate control of ground water seepage and surface drainage during construction can cause major problems in maintaining excavated slopes and foundation surfaces and in compacting fill on the foundation and abutment slopes. This lack of control may cause unstable slopes, sloughing of slopes, wet and muddy foundation surfaces, and a wet and boggy foundation. These will all contribute to a poor embankment foundation contact and may cause construction delays. Seepage control and surface drainage systems should control seepage and hydrostatic uplift in excavations, as well as provide for collection and disposal of surface drainage. In order to properly design dewatering systems, adequate, accurate field data must be collected. Inspections and observations must be made to ensure that dewatering and drainage control systems are installed correctly and are functioning properly. More information is provided in Design Standard No. 13, Chapter 21, “Dewatering.” Proper surface drainage should be provided for in the specifications.

10.4.1.1 Surface Erosion

Surface runoff may cause erosion of slopes excavated in silts, fine sands, lean clays, dispersive clays, and soft rocks. Eroded material will wash down and fill the excavation at the toe of the slope. The cut slope can become deeply scoured and rutted, making it necessary to smooth the slope prior to placing embankment against it. Figure 10.4.1.1-1 shows surface erosion on an unprotected excavation at Virginia Smith (Calamus) Dam, Nebraska.

The best way to minimize surface erosion of temporary excavation slopes is to minimize exposure time by backfilling against the slope as soon as possible. This often cannot be done, however, and it becomes necessary to take other measures. A good means of protection is to leave the surface high by underexcavating the surface and then excavate to the final foundation grade just prior to fill placement against the surface. Grass cover on the slopes is a good means of preventing surface erosion if it can be readily established, and if the slopes are to remain exposed for a season or two. Geotextiles can be placed on the slope to mitigate slope erosion. Other slope protection measures, such as riprap or asphaltic treatment, are rarely justified for construction slopes; thus, it is necessary to keep as much water off the slope as possible. Most slopes can withstand rain falling directly on them, with only minor sloughing. If surface water from outside of the excavation were to flow into the excavation, perimeter ditches and/or dikes at the top of the slope can be used to carry surface water away from the excavation. Ditches may be required at several elevations along the excavation slope to collect and drain surface water. In some cases, such surface drainage protective measures that are used during construction can be incorporated into the final surface drainage scheme.

Figure 10.4.1.1-1 Virginia Smith (Calamus) Dam, Nebraska. Erosion of cutoff trench excavation. USBR 1981

10.4.1.2   Springs

Springs are often encountered in rock foundations and abutments. These springs should be well documented and located (coordinates, elevation, flow rate, etc.) for future reference during operation of the dam. Where seepage rises through rock fractures, the effect of placing impervious fill on the foundation is to create a mud hole, impossible to compact, with fill material piping out as it is placed. Where the water is under a low head and has a single point of issue, a standpipe can usually be installed. A corrugated metal or high density polyethylene pipe with a diameter that varies based on the size of the spring is placed over the spring area, and a damp mixture of quick-setting cement, sand, and gravel is packed around the outside of the standpipe base. Earth is then compacted around the outside of the pipe in conjunction with embankment lift placement and compaction above the base. Water inside the standpipe is kept pumped down as an impervious seal is achieved outside the pipe and until enough pipe sections have been added to retain the head of water in the pipe. The standpipe can be filled with gravel to prevent collapse. A grout pipe must be installed to the base of the gravel for grouting after the head of water is controlled. The area should then be continuously examined for evidence of new springs, which often appear after an old spring is plugged. Construction of the fill continues to the top of the standpipe, at which time the gravel is grouted, using low pressures so that the fill is not hydrofractured or lifted off of the foundation. If the pipe was not filled with gravel, it can simply be filled with vibrated concrete. Fill placement then continues across the top of the pipe.

The above procedure can also be used to treat springs that are encountered on the abutments when the embankment fill reaches the same elevation as the spring. To temporarily control spring water that occurs on an abutment above the elevation of the embankment construction, a small pipe can be grouted into the source of seepage and discharged away from the embankment construction. If the springs are not localized in area, more extensive methods (described in paragraph 10.4.1.3 to 10.4.1.6) may be required.

10.4.1.3 Dewatering

When excavating the dam foundation below ground water through surficial deposits, deep wells or well points, or a combination of both, are usually required to control seepage into the excavation, especially where the excavation is through pervious to semipervious soils. It is preferred to draw water down below the excavated surface with the use of dewatering.

The dewatering system must be properly designed for site-specific conditions. This requires knowledge of geotechnical conditions at the site. The design of wells and well point systems is beyond the scope of this chapter. Design Standard No. 13, Chapter 21, “Dewatering,” provides specific guidance on this subject. The designer should also refer to Chapter 5, “Protective Filters,” and Chapter 8, “Seepage,” for general guidance on seepage and seepage control. Also see references [2], [3], [7], and [8] for excellent guidance for design of dewatering systems.

Inspection of the installation and operation of the dewatering system is extremely important and is a responsibility of both the design and construction staff. Potential problems can often be detected in early stages by visual observations of increased seepage flow, piping of material from the foundation or slopes, development of soft wet areas, uplift of excavated surfaces, settlement of adjacent areas, lateral movements of slopes, or failure of piezometer water levels to drop sufficiently as pumping is continued. Water pumped from dewatering systems must be observed daily at the discharge outlet; if the discharge water is muddy or contains fine sand, fines are being pumped from the foundation. (This can also be observed by obtaining a jar of the water and noting sediment [soil particles] settling to the bottom). Pumping of fines from the foundation can cause internal erosion channels (piping) to develop in foundation soil deposits, and it is imperative that corrective measures be taken. Wells or well points from which fines are being discharged must be abandoned, sealed, and replaced with wells having adequate filters. Piezometers should be installed with dewatering systems to monitor drawdown levels in the excavation area. Piezometers should be read daily, and the readings should be plotted to enable continuous evaluation. Survey points may be installed in areas adjacent to dewatering and near excavated areas to monitor for movement. Daily pumping records should also be kept and evaluated to determine the quantity of water removed by dewatering systems and sump systems. These records are valuable for detecting inadequate seepage control and evaluating claims by the contractor of changed conditions from what is conveyed in the plans and specifications. References [2], [7], and [8] give a detailed description of various types of dewatering systems, installation procedures, and performance evaluation. Figure 10.4.1.3-1 shows a sketch of a single-stage, well point dewatering system, and figure 10.4.1.3-2 shows a combination multistage well point and deep well dewatering system used at Virginia Smith (Calamus) Dam.

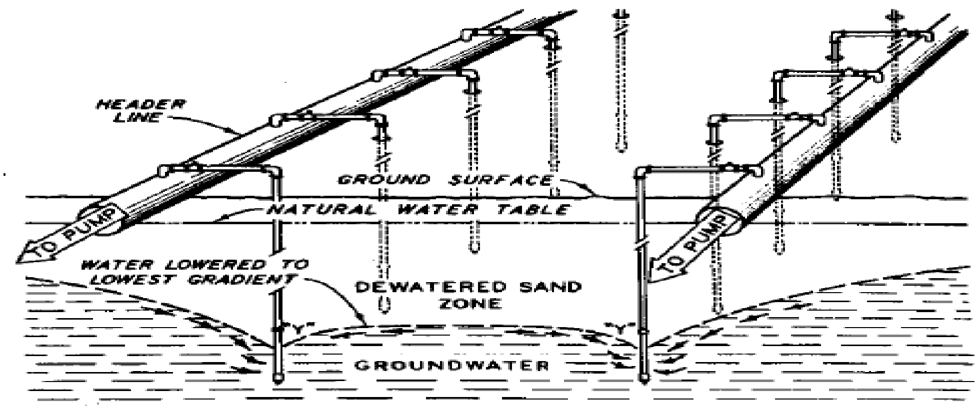

Figure 10.4.1.3-1 Sketch of a single-stage, well point dewatering system [1].

Figure 10.4.1.3-2 Virginia Smith (Calamus) Dam, Nebraska. Multistage well point and deep well dewatering system used for dewatering the stilling basin for the outlet works. USBR 1982

Failure of a dewatering system can result in serious problems that often require extensive and costly remedial work. To prevent failure of the dewatering system, all power sources should be backed up by standby gas- or diesel-powered pumping or generating equipment, and standby pumps should be available. This is critical if a dewatering system is being relied upon for slope stability of an excavation or preventing blowout near the toe of a cut slope or dam.

When excavations are founded in impervious material, unrelieved artesian pressures in underlying pervious strata can cause heaving of the excavation bottom. Should the impervious stratum rupture under these pressures or blow out, boils (violent emission of soil and water) will develop and cause loss of the underlying foundation material, resulting in extensive damage to the construction and, possibly, expensive modifications to the excavation.

Figure 10.3.1-6 shows sand boils that developed in a permanent toe trench at Lake Alice Dam in Nebraska. They are not under high hydrostatic head, but they are a concern and illustrate what happens if seepage is not adequately controlled. Similar or more violent boils could develop on the bottom of an excavation from excessive artesian pressures in underlying strata. Failure of excavation slopes may also occur because of excessive artesian pressures.

10.4.1.4 Other Seepage Control Measures

Certain soils cannot be effectively dewatered. Clay soils cannot be dewatered using well points. With those types of soils, the only adequate method is long-term drainage in drainage trenches. This may require phasing construction. Other means of stabilizing excavation slopes and preventing seepage from entering an excavation, such as jet educators, electro-osmosis, freezing, sheet piling, soil-bentonite cutoffs, and grouting, have all been used for structure excavations. These methods are not economically feasible for extensive foundation excavations for dams, but they might be used in more concentrated structure excavations where conventional dewatering methods are not suitable for various reasons. Design Standard 13, Chapter 21, “Dewatering,” should be consulted for a more detailed treatise on dewatering.

10.4.1.5 Sumps and Ditches

While it is preferred for the dewatering system to control the ground water levels below excavated surfaces, this is not always possible for an entire excavation. There are likely to be bed areas or point sources of intense discharge that necessitate the use of ditches and sumps for complete water removal. Thus, when an excavation such as a cutoff trench is extended to rock or to an impervious stratum, there will usually be some water seeping into the excavation and/or "wet spots" in the bottom of the excavation, even with deep wells or well point systems in operation. Water seeping into the excavation from the upstream and downstream slopes of a long cutoff trench can usually be collected by excavating narrow, longitudinal toe trenches and/or constructing French drains at the intersection of the slopes and the bottom of the excavation. Trenches can sometimes be formed by using sandbags. Sumps are usually needed for pumping the water and should be appropriately located. Trenches at the upstream and downstream limit of the impervious foundation should be attempted prior to excavating any ditches within the impervious foundation. If the bottom of the excavation does not dry out, smaller ditches can be cut through the problem areas and sloped to drain to the side trenches. Regardless of the method used, care should be taken to prevent movement of materials out of the foundation.

Extreme care must be used in conjunction with sumps and ditches to ensure that the contact zone between the impervious zone and its foundation is not short circuited. Gravel-filled ditches or surface drains should never be allowed to traverse in an upstream/downstream direction for a distance of more than approximately one-third of the width of the impervious embankment/foundation contact. The perpendicular distance between ditches or drains entering from opposite edges of the impervious zone should be separated by a distance that is equal to at least two-thirds of the width of the impervious zone. Ditches should be aligned parallel to the dam axis to the extent possible.

To keep the bottom of the cutoff trench dry while placing backfill, the drainage ditch system can be filled with gravel so that the system can continue to function even after being covered with earthfill. The gravel should be uniformly graded with a maximum size of 1.5 inches so that high pressures are not required to grout the drain. The volume of grout used to seal the drain should be measured and compared to the volume of grout required to fill the voids, which can be computed. These gravel-filled ditches should constitute only a very small portion of the overall area being drained to preclude the necessity of later grouting large portions of the bottom of the cutoff trench containing gravel. Gravel should not be placed in gravel-filled ditches until all foundation cleanup using wash water has been completed. The surface of the gravel can be covered with a layer of nonwoven geotextiles or equivalent material, or by a layer of stiff concrete to prevent migration of fines from the earthfill material into the gravel drain. The ditches are blocked at each end of the excavation by concrete plugs, but with riser pipes from each sump to the surface. Water can then be pumped from one or more riser pipes, as necessary, with the remaining riser pipes serving as vent pipes.

After the earthfill reaches the height that will counteract the hydraulic head, the gravel-filled ditches are grouted. Cement grout is introduced under gravity through one riser pipe, with the vent pipes serving as an escape for air and water in the gravel. When grout issues from the vent pipes, the vent pipes are shut off, and a slight pressure is maintained in the system until the grout has set. Following grouting, earthfill operations can continue. If only one sump is used in the drainage system, a separate vent pipe must be installed at an appropriate location before earthfill placement continues.

After the drains are no longer needed, extreme care should be exercised to ensure that the grouting system used to seal the drains is absolutely effective. Vent pipes/grout return pipes should be spaced no further than 20 to 30 feet on center so that grout return is guaranteed. A general rule is to space the vents no further apart than the amount of embankment covering the French drains at the time of grouting. The gravel ditch must be effectively sealed so that grout is contained within it and does not damage the surrounding earthfill. Grouting pressures must be controlled so that the earthfill is not jacked away from the foundation or hydrofractured. Grout pressures should be that imposed by gravity or only slightly above. A general rule is to limit grout pressures to less than ½ pound per square inch (lb/in^2) per foot of overburden, at the level of grout injection. A positive factor of safety of grouting pressure, as compared to the effective pressure of the earthfill, should be maintained at the elevation of the drainage ditch. The grout mix should have a water cement ratio, by volume, that is not thinner than about 2 to 1. It should be as thick as possible, but still flow effectively through the gravel drain.

Basic details of French drains and ditches should be shown on the drawings or described in the specifications; however, sumps and ditch systems are generally designed by the contractor during construction. Specifications must provide for review and approval by the government/owner/engineer before the system is installed, and the contractor is generally required to submit his design/plan for approval. However, telling contractors to submit a "plan" does not provide a basis for the plan or grounds for acceptance or rejection of the plan. Specifications need to specifically state what information the contractor must submit and the level of performance that must be demonstrated. The review must be sufficiently thorough so that the integrity of the foundation contact is ensured after the system is sealed by grout. Additionally, thorough inspection is required during installation, earthfill placement, and grouting of the system to ensure that requirements of the design are properly executed during construction. Figure 10.4.1.5-1 shows sumps that were successfully used at Horsetooth Dam, and figure 10.4.1.5-2 shows a drainage system that was successfully used at Ridgway Dam.

Figure 10.4.1.5-1 Horsetooth Dam, Colorado. Sumps used to dry the foundation for placement of embankment materials on the foundation. USBR 2001

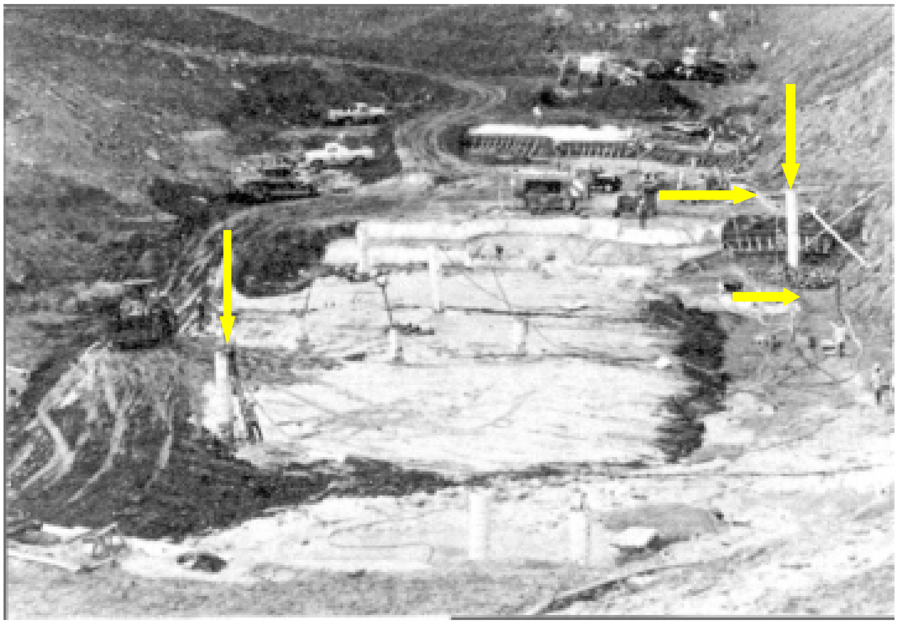

Figure 10.4.1.5-2 Ridgway Dam, Colorado. Sumps (vertical arrows) and drains (horizontal arrows) that were used for drying the impervious foundation in the cutoff trench. USBR 1982

10.4.1.6 Impervious Barriers

In many cases where a dewatering system is being used, a 4- to 5-feet-high impervious blanket with a stable slope could be placed at the toe of the cut slope to prevent minor seepage flow that might otherwise occur, thus providing a dry bottom. The blanket should be constructed of highly plastic soil and be of sufficient thickness to prevent seepage. This procedure requires a slope stability analysis to evaluate the slight rise in the phreatic surface within the slope caused by the impervious blanket.

10.5 Borrow Areas and Quarries

10.5.1 Equipment Earthfill – Excavating, Handling, and Hauling

Over the past several decades, significant improvements have been made to earth-moving equipment. While the basic types of equipment have remained virtually the same, the speed, power, and capacity have continuously increased. Some of the basic principles of the more common units are discussed in the following paragraphs.

10.5.1.1 Excavation Equipment

10.5.1.1.1 Unsubmerged Borrow Areas

Excavation is usually accomplished with hydraulic excavators such as front-end loaders, backhoes, power shovels, draglines, scrapers, wheel excavators, or side-delivery loaders. Each equipment type offers certain advantages and disadvantages; therefore, several types of excavators are frequently used on the same job. Figures 10.5.1.1.1-1 through 10.5.1.1.1-3 show some typical excavating and hauling equipment.

Figure 10.5.1.1.1-1 New Waddell Dam, Arizona. A 12-cubic-yard front-end loader, loading a 30-ton end dump truck with alluvium containing sand, gravel, cobbles, and boulders that will be processed into filter and drain material. USBR 1990

Figure 10.5.1.1.1-2 Virginia Smith (Calamus) Dam, Nebraska. A Holland wheel loader excavating a vertical face mixing silt and fine sand deposits for impervious fill at Reclamation's Virginia Smith (Calamus) Dam, September 1983

Figure 10.5.1.1.1-3 Jordanelle Dam, Utah. Two model 992C Caterpillar front end loaders loading zone 4 (gravel and cobble fill) from borrow into a model 540 Dart belly dump truck. This type of loading operation, with steep face of the borrow area, can be used to get a well-mixed fill from a layered deposit. August 1990

10.5.1.1.2 Submerged Borrow Areas

Although rarely used in Reclamation, dredging may be employed to move material from borrow areas to the dam site. Dredges are particularly suitable for use when large quantities of material are to be obtained from borrow areas submerged in rivers, lakes, etc. The two basic types of dredges are the bucket dredge and hydraulic dredge. Bucket dredges have a common limitation: the discharge is alongside the place of excavation. They can best be used for localized dredging or where the borrow area is so located that the material can be economically transported by trucks or barges to the dam site. All hydraulic dredges have a centrifugal pump and a suction line through which the pump is supplied with material. They differ in how they loosen and pick up material. An advantage of hydraulic dredges is that they can transport material without rehandling for almost unlimited distances with the aid of booster pumps. In the past, this feature has been particularly desirable in the construction of temporary dikes, and possibly permanent structures, by the hydraulic fill method. Dredges have been used in both sands and stiff clays to construct levees and low impoundment dikes. This type of operation is very economical in the right circumstances. Hydraulic fill methods should never be used to construct permanent embankments. Hydraulic fill embankments are particularly susceptible to failure in areas of high seismic activity, and some have failed during construction, on existing slide surfaces (for example, at Fort Peck Dam in Montana).

10.5.1.2 Hauling, Handling, and Separating Equipment

When scrapers (or certain types of dredging procedures) are used to excavate borrow material, additional hauling and handling equipment may not be required. When other types of excavation equipment are used, hauling and handling equipment are required. Regardless of the type of excavation equipment used, the borrow material may require separation according to size or soil type. Some of the equipment used for hauling, handling, and separating borrow materials are discussed in the following paragraphs.

10.5.1.2.1 Trucks

Trucks of many types, some with capacities up to 50 tons being commonplace, are used to transport embankment material from the borrow pit to the dam site. Bottom dump trucks (belly dumps) have capacities as great as 100 to 120 tons. Trucks can be categorized according to the method of unloading as bottom dump, end dump, or side dump. Figure 10.5.1.1.1-1 shows an end dump truck used at New Waddell Dam, and Figure 10.5.1.1.1-3 shows a bottom dump at Jordanelle Dam. Additional considerations are presented in Section 10.5.1.4.2, "Hauling Equipment."

10.5.1.2.2 Belt Conveyors

Belt conveyors are used to transport material from the borrow area to the dam site when large quantities of material must be moved under difficult conditions. Belt conveyors are most suitable for moving large quantities of material over rough terrain where there are large differences in elevation between borrow pits and the dam site, and where the costs of building and maintaining haul roads would be high or environmentally unacceptable. Conveyor systems are adaptable to different types of automated processing procedures such as screening plants, crushing plants, blending operations, water addition, etc. Transfer points (where the material is transferred from one belt to another) are usually required. Automatic facilities for loading trucks at the terminal points can be easily provided, or sometimes the material can be dumped directly from the belt onto the embankment, spread with dozers or graders, and compacted. Depending on material type, segregation could be a problem, especially if the materials are moved a significant distance by the spreading equipment.

An example of processing procedures and belt conveyance is Reclamation's 538-foot-high Trinity Dam, completed in 1962 in northern California. Impervious material was excavated by scrapers and transported to drive-over belt loading stations, where the loads were dumped. Grizzly bars (bar racks) at these loading stations were set at 24 inches to remove oversized material.

Material over 8 inches was crushed to minus 5 inches in roll crushers. A flight of conveyor belts transported the crushed material and minus 8-inch material to the dam site. The belts were 48 and 42 inches wide, the total flight length was 10,415 feet, and the drop in elevation was 1,000 feet. The capacity of the system was 1,850 cubic yards per hour. The longest flight length was 1,895 feet. Trucks were used to transport the materials from three truck loading bins to the embankment.

If loading towers and belt conveyors are located on the earthfill, a problem with overcompaction of the earthfill can occur. The continual routing of haul traffic under the load tower may create a zone of overcompaction in the embankment. It is preferable to locate the truck loading tower off of the embankment fill. If the loading tower must be located on the dam, it should be located in a noncritical area. If it must be located on the impervious zone, its location must be moved frequently.

10.5.1.2.3 Separation Plants

Separation or screening plants, as noted previously, are employed where it is desirable to separate different particle sizes of a material. Generally, the purpose is to remove oversize rocks or cobbles to facilitate compaction or to remove fines from filter or drainage materials. There are four principal types of screening plants:

- **Horizontal or Sloping Stationary Screens.** Screens retain the coarser particles and allow the finer material to drop through by gravity.

- **Shaking or Vibrating Screens.** Screening separation process enhanced by vibration or shaking.

- **Trommels.** Rotating cylinders of perforated metal or screen.

- **Wobblers (or Rotating Cams).** Rotating action of the cams causes the fines to fall through and the rocks to discharge over the front end.

Various plants have capacities ranging from 100 to 2,000 cubic yards per hour; however, most plants process 300 to 500 cubic yards per hour. Wet materials containing appreciable clay content are the most difficult to process because the clay tends to clog openings in the screens. Additional details are provided in section 10.5.1.4.3, Processing Equipment. Figure 10.5.1.2.3-1 shows a processing plant used to produce filter drainage material at New Waddell Dam in Arizona.

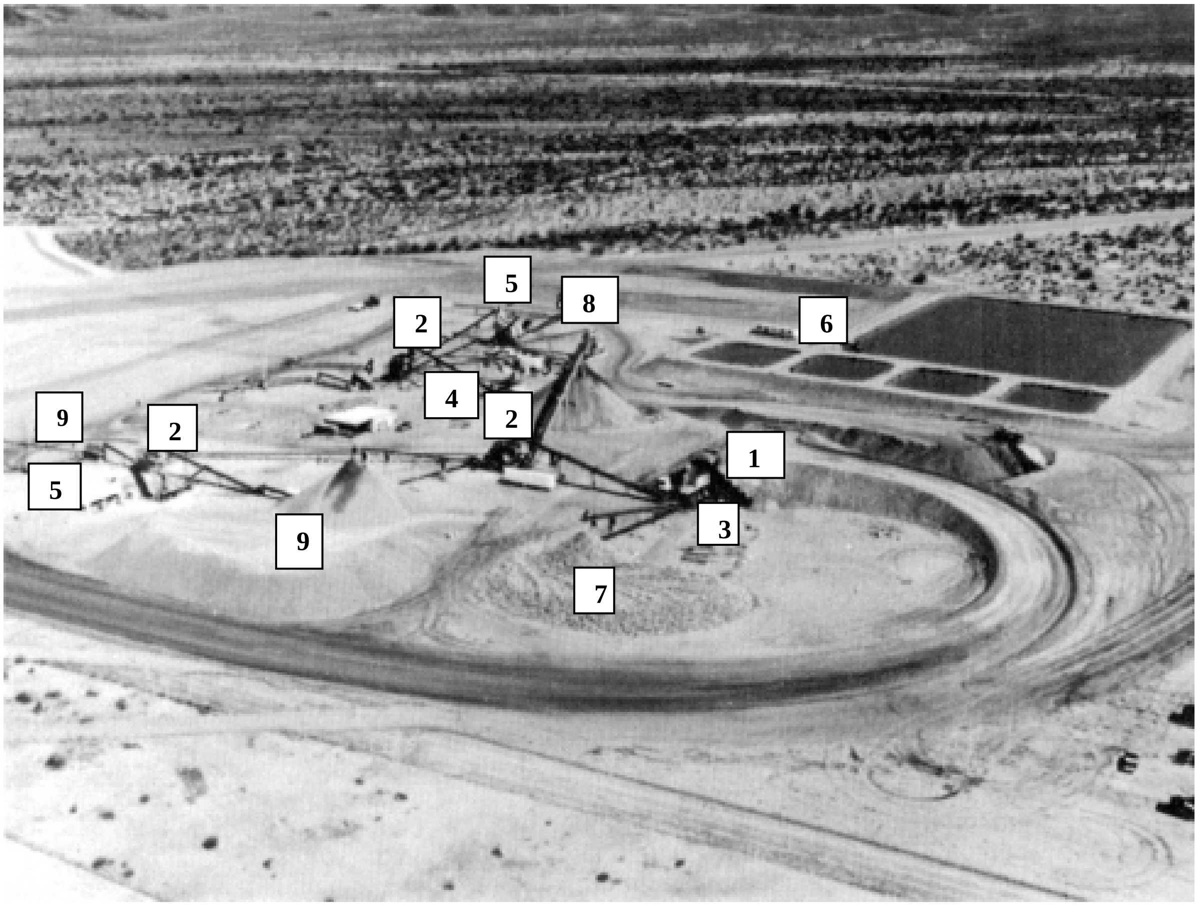

Figure 10.5.1.2.3-1 New Waddell Dam, Arizona. Photo of the processing plant used to produce filter and drainage material. (1) Grizzly, (2) vibrating screen, (3) rock crusher, (4) sand screw (wet), (5) articulating conveyor stacker, (6) settling ponds for cleaning processing water, (7) oversize material, (8) filter material, (9) drain material. USBR 1990

10.5.1.3 Borrow Area Operation

10.5.1.3.1 Plans for Development

Specifications should require the contractor to submit, prior to construction, plans detailed for material production for the development of borrow areas and quarries and operation of separation plants. These plans and their modifications should be thoroughly reviewed prior to approval. However, telling a contractor to submit a "plan" does not provide a basis for the plan or grounds for acceptance or rejection of the plan. Specifications need to specifically state what information the contractor must to submit, or the level of performance that must be demonstrated. Once approved, the plan should be carefully followed during construction. If conditions change or are not as anticipated, the plan can be modified during construction.

10.5.1.3.2 Inspection

Inspection of borrow pits is a function of the construction staff; however, the designer should be aware of the inspector's responsibilities. Inspection of borrow pits includes observing and recording all earthwork operations performed in the borrow pit prior to placing material on the embankment. The borrow pit inspector should observe areas excavated, depth of cuts, and adequacy of contractor equipment for the tasks being performed. The inspector should inform the chief inspector of conditions that deviate from the plans and specifications, so that corrective action can be taken if necessary. These deviations include:

- Borrow materials are different from those expected to be obtained in the borrow area.

- Borrow excavation operations are not producing the desired blend or type of material required. If separation or blending is required, the inspector should perform gradation tests to ensure that the soil type and gradation of the processed material meet the specification requirements. A typical impervious core requirement is that the materials contain a minimum of 25 percent passing the standard U.S. No. 200 sieve.

- Borrow materials are too wet or too dry for proper compaction. During excavation and processing, the inspector should observe all adjustments made to the water content of the material.

10.5.1.3.3 Water Content Control

Water content changes occur in the borrow pit because of rain, evaporation, and borrow area operations. However, specifications should require that the water content of the excavated materials be as close as possible to the desired water content prior to hauling to the embankment.

a. Dry Soils

- For most clay, it is not practicable to produce uniform moisture distribution by adding more than 1 to 2 percent of water on the fill. Reclamation guide specifications do not allow adding more than 2 percent of water on the fill. In arid regions, the average natural water contents of soils in borrow areas may be 5 to 10 percent below the desired value for compaction. Under such conditions, irrigation or prewetting of borrow materials results in more uniform moisture distribution and is the most economical method of adding water. For clay soils dry of optimum water content, wetting should be sufficient to be able to remold dry clods of the clays. Borrow areas are frequently ripped and wetted to depths of 5 to 15 feet by surface irrigation.

- Borrow pits are irrigated by ponding water on the surface with low dikes or with a pressure sprinkler system. Irrigation by ponding is most suitable in low-lying flat areas and for low permeability soils for which long periods of wetting are needed. While sprinkling can be used to irrigate low, flat areas, it is especially advantageous on sloping ground and in large borrow areas where only relatively shallow wetting is needed. In some borrow areas, it has been found desirable not to strip the topsoil before irrigating because the stripping operation tends to seal the natural holes and cracks in the ground surface that allow water to penetrate. However, in other borrow areas, ripping of tight surface layers has proven effective in speeding up the wetting process. When sprinkling is used on hillside borrow areas, it is often desirable to use contour plowing to prevent surface runoff. Good judgment should be used in prewetting steep hillside borrow areas so that landslides are not induced. The length of time required for moisture conditioning the soil may vary from a few days to several months, depending on the permeability of the soil and the depth to which moistening is desired. After irrigation, a curing period is desirable to allow the added water to be absorbed uniformly by the soil. The time needed to moisture condition the soil, and the best method for adding moisture to the soil, can be determined by experimentation with test areas during exploration or the early stages of construction.

- In some cases where general borrow pit irrigation is impossible or not satisfactory, supplemental water can be added by sprinkling the excavated surface during excavation of the material. With this procedure, the water is mixed into the soil by the excavator and blends with the loosely excavated soil as it is being hauled, dumped, and spread. If the soil is being processed through a screening plant to remove oversize cobbles, a considerable quantity of water can be blended into the soil by sprinkling within the plant.

b. Wet Soils

- It is generally easier to add water to dry soil than it is to reduce the water content of wet soil. The difficulty in lowering the water content of a soil deposit depends on the permeability of the soil and on the amount and type of rainfall that occurs during construction. The rainfall pattern is important; for example, infrequent cloudbursts are less harmful than the same amount of precipitation falling as rain over a longer period of time. It is practically impossible to dry out borrow material to any extent without substantial effort and cost unless there is a dry season of sufficient length to accomplish this. The first step toward drying out or maintaining the *in situ* water content of borrow material is to provide surface drainage in the borrow area. This is done by cutting ditches in the borrow area and by sloping surfaces to drain to these ditches. This will minimize absorption of subsequent rainfall. Wet soils can sometimes be dried by ripping, plowing, or disking, thus aerating the soils to a depth of several inches or, in some cases, a few feet. In addition to climatic conditions, the time required for drying depends on the soil permeability and the depth to which the soil can be aerated. This procedure is repeated after removal of the dried soil layers by elevating graders or scrapers. This is a relatively dependable method for drying of silty and sandy soils; however, it is not very effective for drying clayey soils. It should be noted that drying only occurs in the plowed layer. The mulching effect of the plowed layer will prevent capillarity and, therefore, impede drying below the plowed layer, especially in clays. In dry climates, if the water content of high plasticity clays is lowered by aeration, the clay tends to dry into hard, dry chunks that are difficult to process. In some sandy and silty soils, open ditches in a borrow area with a high water table will drain off some excess water and lower the water table.

- During the construction of Dorena Dam (Oregon) by the U.S. Army Corps of Engineers [1], disking of the borrow areas did not break up and mix the clay material enough to obtain uniform moisture conditions. This problem was solved by using a heavy rotary pulverizer pulled by a crawler tractor after disking. Shortly after being pulverized, the material was at or near placement moisture, was easy to load, and was in excellent condition for compaction.

- In very wet climates, it may be possible only to prevent the material from getting any wetter during construction. This is done by providing surface drainage in the borrow areas and by using excavation equipment that minimizes the opportunity for the borrow material to soak up additional water. Excavation with power shovels on a vertical face is an example of this method. An extreme case was the construction of Mud Mountain Dam, where soil was dried in kilns.

10.5.1.3.4 Blending Soil Layers with Excavating Equipment

Blending of two or more soil types may be required where different soil strata are present in borrow areas or required excavation. Reasons for blending soils are: (1) to obtain borrow materials having acceptable characteristics for a particular embankment zone, (2) to use borrow materials so stratified *in situ* that it would not be feasible to load and place material from individual soil strata, and (3) to produce adequate quantities of suitable materials.

Where materials to be blended occur as horizontal strata, shovels, draglines, wheel excavators (see figure 10.5.1.1.1-2), or, in some cases, scrapers have been used to blend them during excavation. Excavation with a power shovel on a vertical cut will blend the materials. Where more extensive mixing is required, it can be achieved by running the open bucket through the mixture several times before loading. Construction control, in this case, will require maintaining the height of cut necessary to obtain the desired proportions of each type of material and to ensure that the materials are blended thoroughly. Blended soil should be tested more frequently to ensure that good results are obtained.

Blending of different materials from different borrow sources can be accomplished by stockpiling one layer from each source upon the other, so that excavation can be made through the two materials as in a stratified natural deposit. However, this procedure is expensive and is seldom used.

Scrapers have been used to blend stratified deposits by developing the excavation in such a way that the scraper is loaded on an incline, either uphill or downhill, cutting across several horizontal strata of different materials; however, mixing by this method is not as effective as using an excavator or dragline. Uphill loading may require more equipment, such as push dozers to assist excavation. However, the extra effort associated with uphill loading results in larger, more compact loads.

10.5.1.3.5 Selection of Materials Intended for Different Embankment Zones

The embankment or borrow pit inspector should ensure that materials intended for a certain embankment zone are within specification limits. Selection of materials will, to a large extent, be accomplished on the basis of borrow area investigations and design studies (i.e., borrow areas for the various zones will be specified by the designers). Borrow area investigations should have provided data on the nature of the materials and the expected ranges of variation in material types. Field personnel should review results of all investigations and become familiar with acceptable materials. The inspector should be able to identify these materials visually with a minimum of index tests.

The use of proper equipment by the contractor will also aid in preventing undesirable mixing of soil types. For instance, thicker stratified deposits of distinct soil types with fairly large areal extent may be kept separate, if desired, by excavating with a scraper because scrapers excavate by cutting relatively thin strips of soil, thereby avoiding mixing of strata. These stratifications of soil deposits are very difficult to separate. A scraper will not be able to separate thinly stratified deposits. These soils should probably be blended. Screening or crushing plants are sometimes employed to obtain required gradations. Although screening or crushing of natural materials for major embankment volumes is an expensive process, it may not be excessive when compared with the benefits. The use of screening or crushing plants may prevent major placing problems, allow steeper embankment slopes, and enable the use of less material. Screening and crushing are most often used in connection with production of uniformly graded filter or drainage materials.

The design staff should provide exploratory and laboratory information on borrow area material in the specifications; however, the designers should be careful not to misrepresent the borrow area. The designers should convey the basis for selecting various borrow areas for specific embankment zones, as well as their confidence in the quantity of material available and the quality of the material in the specifications. If zones will be encountered in the borrow area that will not meet requirements for construction of the embankment, this should be noted in the specifications. For example, if impervious material overlies a shale formation, it may be difficult to accurately locate the shale/soil contact. (Reclamation or American Society for Testing of Materials [ASTM] standards for soil classification must be followed [6].)

A rule of thumb for borrow investigation is to find two to three times the quantity of material required for the embankment. Material quantities that may not be sufficient for embankment construction should be noted in the specifications so that these materials can be conserved.

10.5.1.3.6 Oversized Materials

The maximum diameter of stone or cobble material allowed in compacted fill is generally limited to about 75 percent of the thickness of the compacted layer. Where a high percentage of oversized cobbles or stones are present, oversize material should be removed and used in the outer zones of the embankment. Oversize materials can be removed on the fill surface using hand labor or by using special rock rakes mounted on tractors, or they can be removed by screening in the borrow areas. Removal of oversized rock is generally more efficiently accomplished in the borrow areas where rock separation plants are usually used for this purpose. The exception to this is in the removal of rock from impervious fill. It is difficult, as well as expensive, to remove oversize rock from impervious fill. All other methods should be attempted first. Hand picking and rock raking on the fill generally work as well as processing in the borrow area to remove oversize rock from impervious zones. Processing methods are discussed further in Section 10.5.1.4, Quarries and Rock Excavations.

10.5.1.3.7 Stockpiling

Contractor use of stockpile areas should be anticipated as part of the project design. When the excavations of fill material from borrow sources, including required excavation, progress at a faster rate than the material is placed in the embankment, the material can be stockpiled. This involves expensive rehandling and is generally done only on large projects where borrow is to be used from an excavation made prior to embankment construction, where borrow areas will be flooded during construction, or when material must be stockpiled close to the construction site for rapid construction of a closure section. Unless stockpiling is a specified item, its use is at the expense of the contractor. Stockpiling may also be useful where borrow must be transported over long distances, moved by belt conveyors, or for specific site requirements.

Filter/drainage materials are often stockpiled when it is necessary to obtain such materials from commercial sources or to manufacture them on the site. In some cases, separate specifications have been issued in advance of the dam construction for procurement and stockpiling of filter/drain materials. When stockpiling filter/drainage materials, the contractor should be careful to avoid segregation, contamination, and particle breakage. Stockpiling and rehandling of filter/drain material, or any soil material, cause breakdown of the individual particles. Excessive rehandling of materials should be avoided. Fines content (minus standard U.S. No. 200 sieve material) of filter/drain material should be specified for in-place, compacted material.

When placing filter/drainage material in a stockpile, drop heights should be kept to a minimum. To prevent contamination, the filter/drainage material stockpile should be located away from other types of material stockpiles, and operation of heavy equipment on the stockpile should not be permitted. The area should be sloped so that water drains away from the stockpile. The stockpiling may result in a greater percentage of waste because of contamination at the ground contact. Gradation tests should be performed on samples of filter/drainage material from a number of locations in the stockpile, as well as after it has been placed in the embankment to ensure that specifications are met. Because of the difficulty in sampling stockpile material, the results should be analyzed over a period of time to establish a composite evaluation. Consult the ASTM standards, as well as Reclamation's *Concrete Manual*, for information on sampling of aggregate stockpiles [19]. For any type of material stockpiled, the importance of controlling stockpile quality should be emphasized, particularly if another contractor will ultimately use the stockpile. Design Standard 13, Chapter 5, "Protective Filters," should also be consulted for precautions and methodology concerning stockpiling of filter/drainage material.

10.5.1.3.8 Cold Weather Operations

Borrow area operations can often continue into freezing weather without loss of quality of embankment fill. Except in extremely cold climates, frost penetration of *in situ* fine-grained soil is a slow process, and the soils will not become frozen if borrow operations are continuous. Material satisfactory for fill placement in freezing conditions can be obtained if the *in situ* water contents do not require adjustment on the fill. Sands and gravels can generally be excavated and handled effectively, even at very low temperatures, but the addition of water on the fill for compaction may present problems. Borrow area excavation in cold weather is usually limited by fill placement requirements but, in any case, should be limited to special situations, and then used only with considerable caution. Frozen materials shall not be placed in the embankment, nor shall any material be placed over already frozen embankment or ground.

10.5.1.4 Quarries and Rock Excavations

Experienced geologists, engineers, and blasting experts can rely on knowledge acquired from previous quarries to develop drilling and blasting plans that will optimize the quarry rock product. However, even experienced geologists and engineers may have difficulty predicting how rock obtained from a quarry or excavation will break down during and after blasting. The most frequent problem occurs when the quarried material is shot in a manner in which it either contains more quarry fines and dust, or more oversized material, than anticipated in the design. It is sometimes necessary to make major design changes because rock behavior or breakdown was different than that anticipated by the designers. The contractor's plan for drilling and blasting should require approval, and test excavation blasting may be required to demonstrate that specified rockfill will be produced. However, telling a contractor to submit a "plan" does not provide a basis for the plan or grounds for acceptance or rejection of the plan. Specifications need to specifically state what information the contractor must submit or the level of performance that must be demonstrated.

10.5.1.4.1 Loading Equipment

Front-end loaders are used for loading trucks or other vehicles in rock excavations or quarries. Power shovels are used occasionally, but large front-end loaders have gained prominence because of the development of more powerful units with large capacity buckets. In a high face (deep) quarry, specifications should provide for the walls and face to be carefully scaled and cleaned after each shot to prevent rock fall accidents.

The power shovel, either electric or diesel, is still sometimes preferred for loading directly from the muck pile, although front-end loaders are used more often. The power shovel is sometimes desired because of its large capacity, its powerful bite, and its efficiency in getting the load from the bucket to the hauling equipment.

Front-end loaders are used almost exclusively to load processed material from stockpiles. A front-end loader may be either tracked (crawler) or rubber tired. The crawler type was often used in the past, but the four-wheel-drive, rubber-tired loaders have recently become popular. Although the rubber-tired loader lacks the traction of the crawler loader, it is faster and usually has sufficient traction on most surfaces to load a full bucket efficiently.

For riprap quarries, front-end loaders equipped with slotted rock buckets are often the preferred loading equipment. Shaking the rock in the bucket allows the smaller rock and fines to separate. This is an effective method in processing riprap and is often all that is necessary.

10.5.1.4.2 Hauling Equipment

Trucks are generally used as prime haulers of rockfill. The three basic truck types are the end dump, the bottom dump, and the side dump. Side dumps are rarely used for the construction of compacted rockfill dams; they are more useful for building out the edges of fills. Bottom dumps are more frequently used, but they have definite limitations; they are somewhat unwieldy, and oversized rock has a tendency to become trapped in their discharge gates, requiring bulldozers to push them off the rock, thus losing time and disrupting the hauling schedule. End-dump trucks are probably the most used vehicles for rock hauling because of their speed, mobility, and generally lower initial cost to the contractor. End dumps vary in size from the light "dump truck" to semitrailer types with capacities in excess of 100 cubic yards. Because, in most cases, hauling from rock excavations and quarries is "off-the-road" hauling, these trucks are not subject to size and weight limitations imposed upon carriers that travel on public highways, thus allowing the large capacities.

10.5.1.4.3 Processing Equipment

It is desirable, but usually difficult, to obtain the specified gradation of rock directly from piles of blasted rock. When it is impossible to obtain specified sizes or gradations of rock by blasting, it becomes necessary to process the blasted rock. This may involve removing oversized or undersized material (fines) from the blasted rock or obtaining a specific size range for use in particular zones of the embankment. The use of a processing plant may be necessary. For large riprap, processing may be done with equipment and acceptance based on visual examination.

The production of filter and drainage zone material, whether from a quarry or borrow area, will, in most cases, also require the use of a processing plant. This production and stockpiling is usually necessary to ensure a supply of properly graded materials during the wet season when screens tend to clog up.

There are several types of separation or processing plants; the one used depends on the end product desired. Figure 10.5.1.2.3-1 shows the processing plant used to produce filter and drain material at Reclamation's New Waddell Dam. This plant was used to produce material from an alluvial borrow area, but equipment used in a rock quarry would be similar. Some of the more common components of a processing plant are briefly discussed in the following paragraphs.

- **Grizzlies**. The grizzly is probably the most commonly used rock separating device. The grizzly is used only for separating oversized rock from material. In many cases, this is all that is needed to obtain the specified gradation. A grizzly is a grating made of heavy bars, usually built on a slope, across which the material to be processed is passed. The bars are wider at the top than at the bottom, so that the openings between bars increase in width with depth and, therefore, are not clogged by particles caught partway through. The grizzly is often constructed with a sloping, vibrating grating or with rotating cams (wobblers), so that oversized material is dumped over the end of the grizzly, while the desired size of material passes through. Although there are many ways to construct a grizzly, all of them employ some type of heavy grating.

- **Trommel.** A trommel is a more sophisticated separating device consisting of a rotating cylinder of perforated sheet metal or wire screen. It, too, is used for eliminating fairly large-sized material, but it can also separate the remaining material into several size fractions. The trommel is open at one or both ends, and the axis of the cylinder is horizontal or slightly inclined, so that the material is advanced by the rotation of the cylinder. The perforations in the sheet metal or the size of openings in the screen can be varied to obtain more than one fractional size. As the raw material is fed into the rotating cylinder, the oversized material moves through and is discharged at the other end, while each of the fractional sizes passes through its respective opening and is usually caught in hoppers or transported to stockpiles by conveyor belts.

- **Shaking or Vibrating Screen.** This device is generally used to obtain sizes of material. It consists of a metal screen, or screens, with desired opening sizes, mounted either horizontally or inclined on a rigid frame and given either a reciprocating motion (in the case of a shaking screen) or a vibrating motion (in the case of a vibrating screen). Material retained on a given screen passes to one end of the screen, where it is discharged into a hopper or onto a belt. More than one size can be separated using screens of successively smaller openings below the initial screen.

- **Rock Crusher Plants.** Rock crusher plants are not generally used for processing rockfill because of high operational costs. They are used extensively, however, when production of filter and drainage material is required. These are usually materials that need to be clean (less than 3 to 5 percent passing a standard No. 200 sieve) and uniformly graded (coefficient of uniformity between 1.5 and 8). There are several kinds of crushers. The most common types are jaw crushers, impact crushers, cone crushers, and roll crushers. In general, jaw and impact crushers are for primary crushing, cone crushers are for secondary crushing, and roll crushers are for tertiary crushing. However, these uses can change depending on size, shape, fracturing, and hardness of material being crushed. Also, there are other kinds of crushing equipment that are used for special purposes. The design of a crushing plant depends on site-specific conditions. It is usually prudent to consult with equipment manufacturers for advice on site-specific needs.

- **Washing Equipment.** Washing is not generally necessary for production of rockfill material, but it is commonly required for producing filter and drainage material where the amount of fines is to be limited to a very small fraction, such as 2 to 3 percent minus standard U.S. No. 200 sieve material. Washing is usually accomplished during the screening process by directing water from spray bars, under pressure, at material on a screen. Spray bars should be mounted so that spray is with the flow of the material. Using high-pressure spray perpendicular to the screen surface will only drive near screen size material into the screen surface, causing binding. The washing process takes place near the end of the screening process.

10.5.1.5 Test Quarries

Test quarries aid designers in determining the sizes, shapes, and gradations of rock produced after excavation and handling. Test quarries are usually operated in conjunction with a test fill, so that all phases of the rock behavior, from blasting to compaction, can be evaluated. Variables in the quarrying operation include drilling and blasting techniques, and loading, processing, and hauling procedures and equipment. A properly executed test quarry program will: (1) provide designers, geologists, and field personnel with valuable information pertinent to excavation design, effect of geologic structure on product, and best blasting techniques and rock fragmentation control to be used; (2) provide representative materials for test fills; (3) give prospective bidders a better understanding of the drilling and blasting behavior of the rock; and (4) determine what processing, if any, of the rock will be required.

Even though test quarries are usually established during design, separate contracts are sometimes let to obtain data for use in the preparation of the design and for inclusion in the specifications for use by the contractor in preparing the bid. It is desirable, if possible, that construction personnel assigned to the test quarry are assigned to the dam construction. These personnel will have gained valuable insight on construction procedures and material behavior and form an important nucleus when staffing for dam construction.

Construction control ensures that the different test methods and procedures called for in the plans and specifications for a test quarry are followed, so that comparisons of the test methods and analyses will be meaningful. It is imperative that comprehensive and accurate records be maintained throughout the job. Records should include types of drilling equipment used; rates of drilling in each type of rock; hole diameter, depth, pattern, and spacing; types of explosive, powder factor, and spacing; stemming material and procedures; time sequence of firing; photographs; location and geologic sections/descriptions; and details of results obtained.

10.5.1.6 Obtaining Specified Rockfill

Specifications provide the gradations of rockfill to be placed in the various zones. It may be possible to obtain acceptable material directly from blasting; however, rock may require processing to obtain the required gradation. The contractor's method or operation has a significant effect on the gradation of rockfill obtained. Therefore, the designer should be familiar with methods or operations that influence rockfill production.

10.5.1.6.1 Drilling and Blasting

Refer to Reclamation's *Engineering Geology Manual*, Volume II, Chapter 19, "Blasting Design" [20].

The contractor's drilling and blasting methods have a significant effect on the gradation of rock obtained. It is, of course, most desirable to obtain the correct gradation of rock directly from the piles of blasted rock. However, this is not always easy to do, and, generally, some experimentation on the contractor's part is necessary. The first experimental shots should provide criteria for establishing a satisfactory drilling and blasting pattern. Spacing of boreholes and the intensity of the charge depend on the *in situ* rock condition.

Rock is excavated or quarried either by the "bench method" using vertical holes or by "coyote holing." The coyote method involves firing large charges of explosives placed in tunnels driven into a rock face at floor level. It is initially cheaper than the bench method, but it frequently results in an excess of fines and oversize rocks that require secondary blasting. As a general rule, the coyote method should be prohibited when quarrying for rockfill structures or for riprap.

In quarry experimentation, the material broken by the first blast should be removed, not only to determine if the correct gradation has been achieved, but to examine the excavation rock face and the condition of the excavation floor. The power shovel has already been mentioned as the best means of loading blasted rock in quantity, but it must be operated from a relatively level floor. Loading procedures that will help ensure a uniform distribution of sizes in each load, if the rock is used in a specific zone without processing, are usually necessary.

In a normal shot, the coarser materials will be to the outside, away from the face, and on top; the finer materials will be concentrated toward the working face and at the bottom. The operator of the loading equipment should be cautioned and instructed on correct loading procedures that will help ensure a uniform distribution of sizes in each load if the rock is used in a specific zone without processing. In many quarries, a layer of fines will become concentrated on the quarry floor as loading progresses and must either be used elsewhere or wasted.

10.5.1.6.2 Processing

If the contractor cannot obtain the rock sizes using blasting, or if special treatment is required in the specifications, processing will be required. The amount of processing required will depend on the results of the blasting unless processing procedures are specifically provided in the specifications. The different types of separation equipment and their purposes were discussed previously.

The degree of processing will vary from using equipment to sort the shot rock to using a simple grizzly to remove oversized rocks, or washing to remove excess fines, to running the material through a rock crusher plant. Rock crusher plants are not generally used for processing rockfill due to high operational cost. They are, however, sometimes used to produce select filter and drain materials, bedding materials, and transition materials.

10.5.1.7 Final Condition of Borrow Areas, Quarries, and Spoil Areas

Generally, no treatment is required for borrow areas, quarries, or spoil areas located in the reservoir below minimum operating pool elevation unless there is a stability concern. However, for borrow areas, quarries, or spoil areas located above minimum operating pool elevation and borrow areas, quarries, or spoil areas located downstream of the dam, some treatment is generally required to eliminate unsightly scars. Treatment of these borrow areas, quarries, or spoil areas usually involves stockpiling topsoil when the borrow pit or quarry is first opened. In a borrow pit, the contractor should not be allowed to excavate to bedrock, but should be required to leave a foot or two of soil over rock. After all usable borrow has been removed, the surface should be graded to drain, and the previously stockpiled topsoil should be spread over the surface. The quarry or borrow area should then be graded to a smooth, uniform surface that will drain. If steep slopes are present, benches or terraces may be specified to help control erosion. As a final step, the entire area should be fertilized and seeded. These procedures are intended to prevent erosion and restore the borrow area, quarry, or spoil area to a pleasing aesthetic appearance and, possibly, make it available for future use.

Abandoned quarries are not only unsightly, but they may be a hazard. Insofar as practicable, old quarries should be drained and provisions made to prevent any future ponding of water in them. All slopes should be scaled and trimmed back to eliminate the possibility of falling rocks or debris. All areas that can support vegetation should be seeded. In some cases, fencing may be required to restrict access to the area.

Specific areas must be provided for the disposal of waste or spoil materials. These areas should be shown on specification drawings. Unsuitable material is first used to fill and shape depressions such as ditches, sloughs, etc., located outside the limits of the embankment. Suitable waste materials in excess of that required to fill these depressions may be used upstream to reinforce seepage blankets or as berms to increase the stability of the structure. Waste areas located downstream of the embankment must be carefully selected to avoid interference with any component of the structure or creation of undesirable areas requiring excessive maintenance or remedial work. Waste materials should never be permitted to block seepage from drains, pervious zones, or rock toes, nor should the disposal area be located where it could cause contamination of ground water. Generally, compaction of material in waste areas is not needed other than that produced by hauling equipment, except on the finished outside slopes. Surfaces should be left reasonably smooth and sloped to provide drainage away from the embankment and construction activities. Outside slopes of waste areas composed of easily erodible materials should be compacted or track-walked to reduce erosion. If possible, the areas should be fertilized and seeded to improve their appearance and to prevent erosion, thus possibly making them suitable for recreational or other purposes.

10.6 Embankment Construction

10.6.1 Fill Processing and Compacting Equipment

10.6.1.1 Heavy-Compaction Equipment

The four principal types of heavy equipment used to compact embankment fill are the sheepsfoot or tamping roller shown in figure 10.6.1.1-1, the padfoot roller shown in figure 10.6.1.1-2, the rubber-tired or pneumatic-tired roller shown in figure 10.6.1.1-3, and the vibratory, smooth drum, steel wheeled roller shown in figure 10.6.1.1-4 . Other general-purpose equipment that is sometimes used to compact fill includes the hauling and spreading equipment, which are routed over the fill to be semicompacted, and tracked, crawler tractors, which sometimes can produce adequate compaction of pervious, cohesionless materials, when tracked to gain complete coverage of the fill. Figure 10.6.1.1-5 shows construction of a dam in the early 1900s; comparatively, figure 10.6.1.1-6 shows a modern day dam under construction. Excellent guidance on constructing and compacting embankments can be found in two publications by Jack W. Hilf [15, 18].

Figure 10.6.1.1-1 Carrion toothed roller, which is similar to a sheepsfoot or tamping type roller. These type rollers are generally used in more clayey or plastic soils.

Figure 10.6.1.1-2 Vibratory, padfoot roller. These type rollers are generally used in more silty soils.

Figure 10.6.1.1-3 Pneumatic (rubber-tired) roller. Pneumatic tired rollers are sometimes used on impervious fill with scarification of the top surface of the lift after the lift is compacted.

Figure 10.6.1.1-4 Vibratory, smooth drum, steel-wheeled roller. Good for rolling gravel and rock fill.

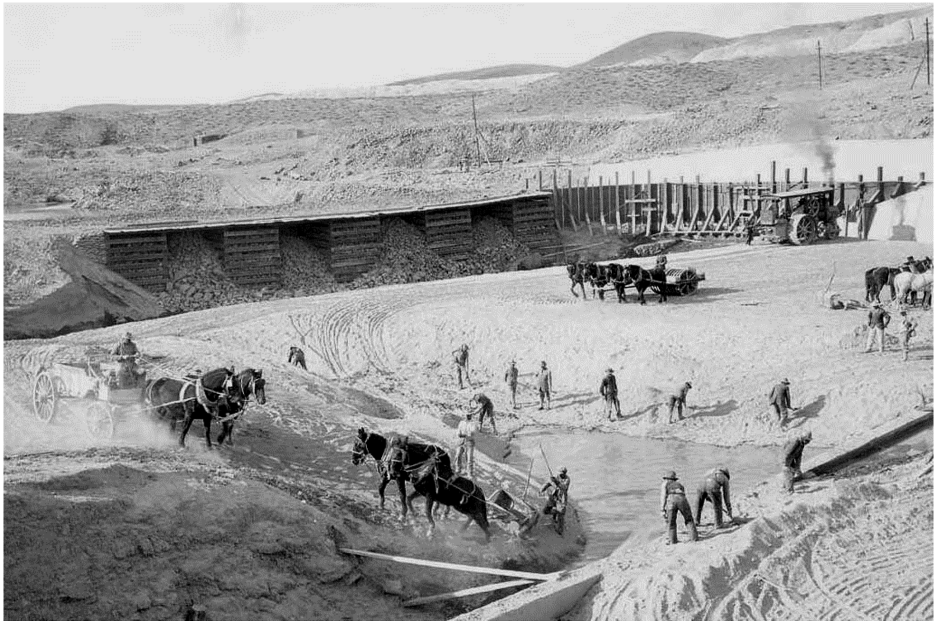

Figure 10.6.1.1-5 The cut and fill method is being used here to construct Lahontan Dam in Nevada, circa 1911.   A horse drawn scraper (Fresno) is seen at the bottom center of the picture excavating fill above bedrock, which is being placed on the embankment near the right side of the picture and compacted by a horse drawn compacter. USBR 1911

Figure 10.6.1.1-6 Slickrock Creek Dam, Iron Mountain Mine, California. Embankment core material is being spread and compacted. Note that the truck crossing over the sand filter and gravel drain material has a geotextile cover to protect them from contamination. Also, fiber concrete has been placed on the rock abutment visible in the background to prevent seepage transport of the core and sand filter into the abutment rock.

10.6.1.2 Hand-Operated Compaction Equipment

Wherever possible, heavy pneumatic tired wheel rolling with construction equipment should be used to compact against abutments or concrete structures. However, use of hand operated compaction equipment in lieu of wheel rolling is sometimes necessary. For compacting in restricted areas (such as those immediately adjacent to concrete walls, around conduits, or in depressions in rock surfaces), hand-operated, powered tampers weighing at least 100 pounds or hand-operated, vibrated plate compactors are used. Vibrated plate compactors are effective only in clean cohesionless material. To aid compaction against rock or concrete surfaces, more plastic impervious material should be placed 1 to 2 percent wet of optimum moisture content. Figure 10.6.1.2-1 shows hand compaction against a steep surface at Ridgway Dam, Colorado.

Figure. 10.6.1.2-1 Ridgway Dam, Colorado. Hand compaction along formed dental concrete on an impervious foundation. Notice that this fill has been previously rolled against the foundation by a rubber-tired piece of equipment. The hand compaction is supplemental. USBR 1983

10.6.1.3 Spreading and Processing Equipment

Spreading and processing equipment commonly used on embankment fills are discussed below. Global Positioning System (GPS) technology can be used on this equipment to ensure that specified lines and grades are being achieved and that the required lift thicknesses are spread prior to compaction. Use of this GPS-assisted equipment is strongly encouraged, and, in some cases, it may be desirable to specify its use.

10.6.1.3.1 Crawler and Rubber-Tired Tractors and Dozers

These tractors are used to tow compactors (now days most compactors are self-propelled), disk plows, harrows, etc., and when equipped with dozer blades, to move and spread material, as shown in figure 10.6.1.3.1-1 and to remove oversize rocks from embankment fill. When dozers with blades are used to tow compactors, the blades should be physically modified so that they are not useable.

Figure 10.6.1.3.1-1 Dixon Canyon Dam, Horsetooth Dam Modification, Colorado. Crawler tractor spreading a lift of rockfill. USBR 2002

10.6.1.3.2 Motor Graders (Road Patrols)

Graders are used to spread and mix material; to dress up interfaces between different zones, such as core, transition, and filter zones; to remove oversized particles; and to scarify surfaces of previously compacted lifts.

10.6.1.3.3 Disk Plows

Disk plows, towed by rubber-tired or crawler tractors, are used to scarify surfaces of previously compacted lifts and to aerate or blend water into uncompacted lifts prior to compaction. Scarification is done by cutting through the current loose lift into the previously compacted lift. The diameter of the disk (36 inches is preferred) and weight of the plow should allow the disk to cut 1 to 3 inches into the previously compacted lift. Scarification should generally be longitudinal or parallel to the dam axis direction. Figure 10.6.1.3.3-1 shows a disk plow that was used at New Waddell Dam. The depth and angle of the plow should be adjustable from the operator's seat on the towing equipment.

Figure 10.6.1.3.3-1 New Waddell Dam, Arizona. Disk plow used for conditioning and scarifying impervious fill.

10.6.2 Test Fills

10.6.2.1 Rock Test Fills

In the design of rockfill dams, construction of test embankments can often be of considerable value, and, in some cases, it is absolutely necessary [1, 9, 10]. 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 on the placement of rockfill. A properly executed test fill program should determine: (1) the most effective type of compaction equipment, the lift thickness, and the number of passes; (2) maximum rock sizes; (3) the amount of degradation or segregation occurring during hauling, placing, and rolling; and (4) physical properties of the in-place fill such as density and grain-size distribution. Knowledge gained and consequent improvement of the design can significantly influence the cost of the structure.

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

Construction control of a test fill should be very exacting; otherwise, data obtained may be of questionable value. Plans and specifications for the test fill are prepared by the design engineers to evaluate construction procedures and material behavior, so that results of the test fill can be used in the design and construction of the prototype. The test fill contract should be administered by the construction staff, but the design staff should remain involved in the actual construction of the test fill.

Records should be kept up to date, and data should be plotted daily, as changes in the test program may be necessary to obtain the desired information. The type of records and data required should be established by the designers. It is important that all observations are recorded no matter how insignificant they may seem at the time. Photographs and records of visual observations are extremely important because they often provide answers to perplexing questions that would otherwise go unanswered. Designers should actively participate in test fill construction so that required data is collected.

Gradation tests should be performed on the rock before and after compaction has been completed. A comparison of 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 (ring density tests USBR 7220 or 7221; ASTM D 4914 or D 5030) or indirectly by observing and measuring settlement of the fill. The latter method is generally used because conventional density tests in rockfills 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 the settlement measured is, in fact, that of the layer in question and does not include settlement of the foundation or underlying layers. Survey equipment is required for this activity. Settlement in the foundation and within lifts can be determined from settlement plates. If necessary, a few conventional density tests may also be made to supplement the settlement data.

Test trenches should be excavated through the completed test fill for visual observation of compacted lift thicknesses and distribution of fines, and to determine distribution of density. Test fill operations, including inspection of test trenches, should be thoroughly documented with measurements, photographs, and written results of visual observations.

10.6.2.2 Earth Test Fills

Test fills for earth embankments are often necessary to establish the appropriate loose lift thickness and the number of passes required to compact soils to specified densities for which there is no previous compaction experience. Test fills may be used to determine the best procedure and equipment for moisture conditioning of the soil to obtain the specified water content uniformly throughout the lift. Test fills are constructed (at the contractor's expense) when the contractor wants to use equipment other than that permitted by the specifications. The contractor must prove that the specified density can be obtained with the proposed equipment. Test fills are also used to determine if the specified densities can be economically obtained in the field. A test fill may be made part of the embankment, and if satisfactory results are achieved, the compacted fill can remain part of the embankment fill. These test fills are usually located in noncritical areas of the embankment.

10.6.3 Impervious and Semipervious Fill

10.6.3.1 Definition

Impervious materials include clays (CH and CL), silts (ML), clayey sands or gravels (SC or GC), and silty clays (CL-ML); semipervious materials include silty sands or gravels (SM or GM). Clayey soils are preferred for the impervious, water barrier zones of dams, but silts, silty sands, and silty gravels are sometimes used in the impervious zones and generally perform adequately. Increasing the fines content of a soil increases its imperviousness. In general, materials can be considered impervious if they have at least 25 percent passing the standard No. 200 sieve (in some cases, 10 to 15 percent passing is the minimum considered necessary for adequate impervious fill). These soils are controlled by the Proctor and rapid compaction tests, and moisture is critical to achieve compaction. 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. Impervious (Zone 1) soils are used in the impervious core, impervious seepage blankets, and other impervious zones of a dam.

Note that sands with borderline gradations classifying as SW-SM, SW-SC, SP-SM, or SP-SC; 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."

10.6.3.2 Compaction Specifications

Requirements for the more important compaction variables (such as water content limits, layer thickness, compaction equipment, and number of passes) will be contained in the specifications and will be observed by the inspection staff to ensure compliance. Figure 10.6.3.2-1 shows compaction of impervious (Zone 1) fill. The designer should include additional requirements for compaction of specific zones or features of the work such as filters, drains, or Zone 1 impervious core.

Specifications will generally state the type and size of compaction equipment to be used and require that the contractor furnish the Government the manufacturer's data and specifications for the equipment. The manufacturer’s information should be checked against the job specification requirements, along with a visual inspection of the equipment to ensure that the equipment’s condition will enable it to achieve the specified 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 the yoking arrangement. For a rubber-tired roller, the tire inflation pressure, spacing of tires, and the empty and ballasted wheel loads should be checked.

Figure 10.6.3.2-1 Horsetooth Dam Modification, Colorado. Impervious material being dumped, spread by a tracked dozer, and compacted by a tamping or sheepsfoot type roller. USBR 2002

The compacted lift thickness is specified. The specified lift thickness is based on the type of material and the compacting equipment being used. Impervious or semipervious materials are commonly compacted to approximately 6- to 9-inch lift thicknesses with 8 to 12 passes of a sheepsfoot or padfoot roller. A sheepsfoot roller usually works better in clay soils, while a padfoot roller generally works better in silty soils. If the material is in the impervious zone, a maximum compacted lift thickness of 6 to 9 inches and a minimum density are specified. Table 7.6 in *Compacted Fill,* by J.W. Hilf, gives guidance on equipment and lift thickness [15]. In all cases, the contractor must demonstrate that the required density is being obtained with the roller and lift thickness that are being used. When using any roller that leaves a smooth surface after compaction, scarification of the surface of the compacted lift prior to placing the next lift is specified in order to ensure a good bond between the lifts. In confined areas where hand-operated, powered tampers must be used, the fill is commonly compacted to a maximum compacted lift thickness of 4 inches and to a specified density. Scarification of hand-compacted surfaces by hand-operated tools, such as a rototiller, is usually necessary because compacted surfaces are almost always smooth.

In-place water content and density must be related to optimum water content and to maximum density in order to judge whether a compacted soil is suitable or unsuitable. Desired minimum densities are normally established during design, in terms of a certain percentage (> 95 percent) of maximum dry density,[2] and an allowable range of placement water content is given in the specifications in relation to the optimum water content of the soil being compacted. Each soil type has a different maximum density and optimum water content for a given compactive effort, and it is necessary for in-place field densities and water contents to be compared with laboratory-determined optimum water contents and maximum densities of the same soils. If the material being compacted in the field cannot be related to available laboratory compaction data, a compaction test should be performed on that material. It is recommended that verification compaction tests be performed on the soil to be placed in the embankment prior to fill placement to ensure consistency of this material with the optimum values obtained by laboratory testing during design for the same soil.

Assumptions are made during design regarding shear strength, permeability, and deformation characteristics of the embankment fill. These properties vary according to the density and water content of the compacted soil. This is why the soil must be placed as specified; otherwise, design assumptions may not be met, and distress might occur in the structure. Thus, the desired density and the placement water content range are not arbitrarily established; they are specified for very definite reasons. 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 specified density is not obtained, even though the water content is within the specified limits, a decision has to be made whether to require additional passes. In some cases, where the fill is extremely out of specification limits on moisture/density, the material should be removed, replaced, and recompacted. Prior to beginning fill placement, construction and design staff should establish guidelines for removal and replacement of out of specification materials. Procedures for performing tests to determine field densities and water contents, and the applications of these tests to compaction control, are covered in the *Earth Manual* [6] and ASTM volumes 04-08 and 04-09, *Construction, Soil and Rock* [4] and *Compacted Fill* by J.W. Hilf [15]. There is also a new publication from ASTM on *Quality Control of Soil Compaction using ASTM Standards* [14]. Virtually all Reclamation test methods in the *Earth Manual* that are used for earthwork construction control have ASTM equivalents. Reclamation traditionally has performed its own quality assurance testing, and the *Earth Manual* and ASTM are cited in construction specification paragraphs in that case. If the contractor is to perform quality control testing, the ASTM standards are used.

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

10.6.3.3 Compaction Fundamentals

For a specific soil containing a significant percentage of silty or clayey fines, there exists a specific maximum density to which the soil can be compacted by a given amount of compactive effort. In order to obtain this maximum density, it is necessary for the soil to be at specific water content. The water content existing at maximum density is termed the "optimum water content." The maximum density and optimum water content are determined in the laboratory by compacting five or more specimens of the same soil at different water contents and plotting a curve. This is a Proctor compaction test. Figure 10.6.3.3-1 shows Proctor compaction curves for several Reclamation dams [18]. Other examples can be seen in "Compacted Fill" [15]. There are two compaction test efforts for the Proctor compaction test. The first test uses effort or energy termed "standard compaction effort" (ASTM D 698 and USBR 5500). A second test was developed using higher energy for airports and heavily loaded roads, termed "modified effort" (ASTM D 1557). Reclamation has used the standard effort test for most embankment dam construction. An exception was the construction of New Waddell Dam, where the level of effort was increased to have a more rigid core and to save compaction water. Table 10.6.3.3-1 gives the degree of compaction requirements for embankment dams based on "standard" compaction effort.

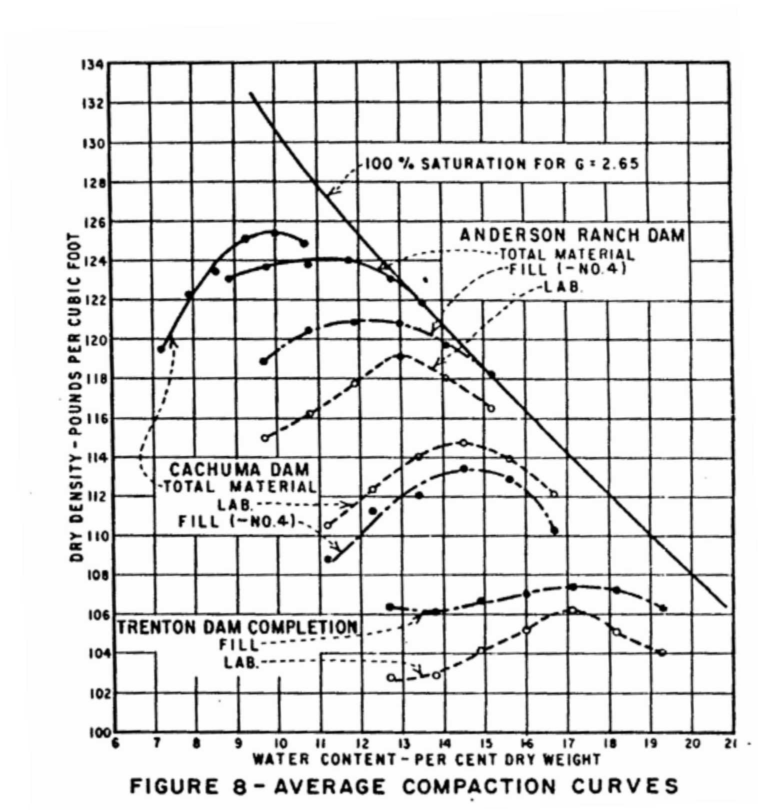

Figure 10.6.3.3-1 Laboratory compaction (Proctor) curves for several Reclamation dams. USBR, 1941-53

Table 10.6.3.3-1 Criteria for Control of Compacted Dam Embankments (Control of Earth Construction, Part 1 [6])

Type of material	Percentage of + No. 4 fraction by dry weight of total material	Percentages based on minus No. 4 fraction					
		50 feet or less in height			Greater than 50 feet high		
		Minimum acceptable density	Desirable average density	Moisture limits $w_o - w_f$	Minimum acceptable density	Desirable average density	Moisture limits $w_o - w_f$
Cohesive soils controlled by the Proctor test	0 - 25	D = 95	D = 98	-2 to +2	D = 98	D = 100	2 to 0**
	26 - 50	D = 92.5	D = 95		D = 95	D = 98	
	More than 50*	D = 90	D = 93		D = 93	D = 95	
Cohesionless soils controlled by the relative density test	Fine sands with 0 - 25	D_d = 75	D_d = 90	Soils should be very wet.	D_d = 75	D_d = 90	Soils should be very wet.
	Medium sands with 0 - 25	D_d = 70	D_d = 85		D_d = 70	D_d = 85	
	Coarse sands and gravels with 0 - 100	D_d = 65	D_d = 80		D_d = 65	D_d = 80	

Note: $w_o - w_f$ is the difference between optimum water content and fill water content in percent of dry weight of soil.
D is fill dry density divided by Proctor maximum dry density in percent.
D_d is relative density as defined in section10.6.4.7.3.

* Cohesive soils containing more than 50-percent gravel sizes should be tested for permeability of the total material if used as a water barrier.
**For high earth dams, special instructions on placement moisture limits will ordinarily be prepared.

Two variables that greatly influence fill densities are field compactive effort (that effort applied by the passage of a given piece of equipment, a given number of times, on a given thickness of lift) and placement water content. When the water content of a soil being compacted with a specific compactive effort deviates either greater than or less than the optimum water content for that compactive effort, densities less than maximum density will result; the greater the deviation from the optimum water content, the lower the resulting density. For a soil with a water content on the dry side of optimum or at optimum, an increase in compaction effort will generally increase the density. For a soil with water content considerably greater than its optimum water content, an increase in compactive effort will tend to shear the soil but not increase its density because of the small volume of compressible air filled voids.

Compactive effort can be increased by increasing the contact pressure of the roller on the soil, by increasing the number of passes, or by decreasing the lift thickness. The combination of variables for use on any given job will depend on the difficulty of compaction, the degree of compaction required, and economic considerations.

10.6.3.4 Simple Control Procedures

Simple controls using both visual observations and rough measurements are the primary means by which construction control is performed. These simple controls must not be used as the sole means of construction control, however, but must be supplemented by an extensive program of laboratory testing. For any estimation of material properties to be meaningful and accurate, the observer's eyes and hands should be calibrated to all conditions expected to be encountered. The designer should consider specifying construction of small test sections prior to the beginning of major fill placement so that inspectors, designers, 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.

Designers should encourage the inspection staff to become thoroughly familiar with the fill material prior to the start of fill operations. It is beneficial to spend time in the field laboratory performing a few compaction tests to become familiar with the differences in appearance and behavior of the various fill materials and to recognize when they are too dry or too wet, as well as when they are at optimum water content. Also, Atterberg limits on fine-grained soils and the appearance and feel of the soils when they are at the plastic limit help gauge when the soil is near optimum water content.

A trained inspector should then be able to grab a handful of soil and make a reasonable estimate of the relationship of its water content to its optimum water content by feel and appearance (experienced inspectors often can estimate deviation of water content from optimum within +/- 1 percent). A soil should be evaluated for specified water content prior to rolling, and check moisture tests should be made for confirmation. A simple test is to roll out a small amount of the material on a clipboard, or between the hands, and evaluate how close the moisture content of the material is to the plastic limit. This is generally a good indicator because there is often only a very small difference in the optimum water content and the plastic limit of a soil.

In addition to knowing how a soil looks and feels when it exists at the specified moisture and density, some method of penetration resistance is often used as a guide. The method could range from the use of a Proctor needle to a common spade. Many inspectors in the past have had good success in estimating density by simply observing the resistance of the compacted soil to penetration by a spade or by observing the way a sheepsfoot roller walks out of the fill. The Proctor needle is difficult to calibrate and use, so its use has mostly been discontinued. See USBR testing procedure 1410-89 [6].

Specified lift thickness is fairly easy to estimate once the observer’s judgment has been calibrated by actual measurements of thickness. A simple measurement for lift thickness is to work a "sharpshooter" spade through the loose lift until the surface of the last compacted layer is encountered. Some inspectors also use a steel rod or a lath to determine lift thinness. The shovel, rod or lath is marked for various depths, and the thickness of the layer can be read directly from the spade. This is done just prior to the first pass of the roller and is generally quick and accurate enough for control purposes. However, because many contractors are naturally interested in placing thicker lifts, arguments frequently arise. It is for this reason that control of lift thickness by visual observation alone should not be used; it must be supplemented by measurements. Reclamation specifications require the contractor to excavate test pits and, in many cases, exposure of the lifts may show that the lifts are too thick and compaction is not being achieved. The use of GPS-controlled construction equipment can help to ensure consistent lift thicknesses. Another reliable method for determining lift thickness is by obtaining the elevation of the embankment at predetermined stations every 3 to 5 days, recording the number of lifts, and computing the average lift thickness. It is normal practice for the inspection staff to keep records of the number of lifts and to use level surveys for control during construction for part of the permanent record and documentation history.

Additional 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 the water content of the material is satisfactory and if good compaction is being obtained. For instance, if on the first pass of a rubber-tired roller, the tires sink to a depth equal to or greater than one-half of the tire width; if after several passes the soil is rutting excessively; or if at any time during rolling, weaving or undulating (as opposed to normal "springing" of the surface) of the material is taking place ahead of the roller, either the tire pressure is too high or, more likely, the water content of the material is wet of optimum water content (too high). However, if the roller tracks only vary slightly or not at all and leaves the surface hard and stiff after several passes, the soil is probably too dry of optimum water content. For most soils having proper water content, the roller will track nicely on the first pass, and the wheels will embed 3 to 4 inches. Some penetration into soil at its optimum water content is expected, though the penetration will decrease as the number of passes increases.

For sheepsfoot rollers, after several passes of the roller, the roller should start walking out if adequate and efficient compaction is being obtained (walking out means the roller begins bearing on the soil through its feet only; the drum is riding a few inches above the soil surface). If the roller walks out after only a few passes, the soil is probably too dry of optimum water content; if it does not walk out, but continues churning up the material after the desired number of passes, the soil is too wet of optimum water content or the roller foot contact pressure is too high. Note that soil type also plays a role in the action of the roller and has an influence on embedment depth of rubber tires or the walking out of a sheepsfoot roller. Figure 10.6.3.4-1 shows compaction by a roller that is similar to a sheepsfoot type because of the elongated feet. Sheepsfoot rollers may not walk out of low plasticity soils and, in those cases, use of a padfoot roller may be more effective. The cleanliness of the roller feet is also important. The soil is generally too wet of optimum water content when large amounts of material are being picked up by the feet and knocked off by the cleaning teeth. If the soil is near optimum water content, a minor amount of sticking on the roller feet is expected. If the feet are totally clean and dry, the soil may be too far below optimum water content. The inspector should be aware of these various signs that the soil moisture is adequate or inadequate and use this awareness to require testing to ascertain whether the proper moisture and density are being obtained by the roller and compaction effort being used. He should also be aware of equipment changes; for example, wear of tamping feet on the sheepsfoot roller or wear of disks on the disk plow diminish their ability to function effectively.

At a water content near optimum, there will always be a noticeable “springing” of the embankment surface as it reacts to the passage of any heavy construction equipment; the amount of “springing” will depend on the soil type. However, a sudden sinking or rising of the surface under the weight of the passing equipment is a good indication that a wet, 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 of optimum water content. If such a condition is noticed, it should be checked by laboratory testing of the material, and the condition should be corrected if the material is not within specifications.

There are some troublesome materials that deserve special attention. Silts, silty sands, and low plastic clayey silts will pump and rut badly at optimum moisture content and above. The water content of fat (CH) clays is particularly difficult to control. Specified density of fat clays may be difficult to obtain with generally used equipment, and the material will stick to and clog the equipment. The mobility of the rollers and other equipment will begin to be severely affected when fine grained soils are wet of optimum moisture content. It may be necessary to test the lift below the most recently compacted lift to measure density. Use of test fills to optimize equipment and develop the most effective placement, compaction, and control procedures may be prudent in silts, silty sands, clayey silts, and fat clays.

Figure 10.6.3.4-1 A Caterpillar, model 825C, roller compacting impervious fill (zone 1). The roller feet are elongated (chevron feet). Also, notice the filter upstream of zone 1 being compacted by a vibratory roller. The filter is placed over weathered and fractured zones in the foundation rock. USBR, July 1990

10.6.3.5 Field Control Testing and Sampling

10.6.3.5.1 General

Field control testing (field density tests) and record sampling of compacted fill are conducted for two reasons: (1) to ensure compliance with design requirements and (2) to furnish a permanent record of as-built conditions of the embankment. Field control testing consists largely of determining the water content, density, percent compaction, 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. Record samples are usually taken at a rate of one every

30,000 cubic yards. Block samples are taken, and in-place density tests are performed in the field. The blocks are usually submitted to Reclamation's laboratory in Denver for strength and consolidation testing. Index testing and construction control testing are also generally conducted for comparison with field results. Traditionally, Reclamation field laboratories would use winter slowdown periods to perform percolation and settlement testing on recompacted soils, along with the record test. This practice has been phased out with time, although it still might be helpful for marginal soils where permeability and settlement of the dam is a concern.

The designer must monitor this information to ensure that fill construction is compatible with design assumptions. The designer is responsible for conveying, in writing, a minimum field control testing and sampling program to the construction staff. It is also helpful if the designer's requirements are conveyed verbally through meetings with the construction staff so that questions can be answered and reasons for various requirements can be discussed.

10.6.3.5.2 Field Density Testing and Record Sample Programs

Control testing should be frequent at the start of fill placement; however, 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. The frequency depends on the type of material and how critical the fill being compacted is in relation to the overall function of the zone being tested (an impervious core will naturally require more control testing than will a random berm). Samples should be taken at locations that are representative of the area being checked. Reclamation relies heavily on trained field inspectors, and test locations are usually selected by the field inspector. Reclamation has construction control training manuals that are available to those involved in embankment construction.

As previously indicated, a systematic testing and sampling plan should be established at the beginning of the job. Control tests, which are routine tests used by inspection staff to ensure proper moisture/density on a daily basis, are laid out in a predetermined manner and are performed at the designated locations, no matter how smoothly the compaction operations are being accomplished. Chapter 3 of Reclamation's *Earth Manual,* Part 1 [6], gives a detailed description of testing philosophy and management of data. Reclamation computer programs such as "PC Earth" are used for large projects where statistical compilation of data are made to allow inspectors to look at the overall production and trends during construction. The program is set up to manage different zones and borrow areas. L-29 construction report summary tables and graphs can be generated. A routine control test should be performed for every 1,000 to 3,000 cubic yards of compacted material, and even more frequently in narrow embankment sections where only a small volume of material raises the section height considerably. There should be at least one control test for each lift of fill and one test per each shift. In the first lift above the foundation, tests should be made more frequently to ensure that proper compaction and foundation bond are attained in this important area.

A rough guide for taking record samples (which are tests taken to confirm engineering properties of the soil such as shear strength, consolidation parameters, and permeability) is 1 sample for every 30,000 cubic yards of core fill and 1 sample for every 30,000 to 50,000 cubic yards of compacted material outside the core. This would be a maximum number. The number of record samples taken should be adjusted according to the size of the embankment and the criticality of the area under consideration. For example, frequency may be greater on a small dam than a large dam, or in the beginning of a fill operation.

Figure 10.6.3.5.2-1 McPhee Dam, Colorado. Block sample from test pit in zone 1. Final saw cut is being made beneath the sample using a chain saw equipped with special tungsten carbide teeth. Also visible is an area where an in-place density test was taken 2 feet upstream of the block sample, 1983.

If record samples are taken primarily for determining shear strength of the fill, it may be more important, in many dams, to concentrate more testing in the material outside the core because this is where a major portion of the resistance to sliding is developed. Conversely, if the purpose of record samples is to confirm permeability or consolidation parameters, it may be more important to obtain them from the clay core of the dam. Figure 10.6.3.5.2-1 shows a record sample being taken from impervious fill at McPhee Dam.

Tests in addition to routine control tests should be taken in the following areas: (1) where there is reason to doubt the adequacy of compaction, (2) where the contractor is concentrating fill operations over relatively small areas, (3) where special compaction procedures are being used (power tampers in confined areas, etc.), (4) where instruments are located, and (5) adjacent to abutments and structures.

During the process of taking tests, the inspectors and testers should visually check the excavations to determine that laminations are not occurring at the lift lines. If laminations are suspected, special test pits to examine for laminations may be necessary.

10.6.3.5.3 Record Samples

Undisturbed record samples may be obtained by carefully carving out a block of approximately 1 cubic foot of material from the compacted fill (see figure 10.6.3.5.2-1). Chain saws have been successfully used to cut undisturbed samples and, if used properly, are time savers. The sample is then sealed in wax and cheesecloth encased in a wooden box or protected by other methods of packaging against disturbance or loss of water. Undisturbed record samples have also been taken by trimming around large steel or plastic cylinders as they are pushed into the fill by a dozer blade. Details for obtaining and preserving record samples are described in the *Earth Manual* [6]. Undisturbed record samples are subjected to shear and, perhaps, consolidation testing, and 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 tests. Undisturbed record samples and bag samples must be tested promptly if the results are to be useful in construction control.

10.6.3.5.4 Field Density Tests

Field density determinations are made by obtaining the weight, volume, and moisture content of a sample taken from the fill. Volume and weight measurements can be determined by direct or indirect methods. For direct methods, the weight of the material removed from a hole in the fill and the volume of the hole are used to determine the wet density; direct water content determination involves drying the soil by heating and then weighing the dried soil to determine the amount of water lost. Indirect methods of determining the density and water content involve measurement of a characteristic of the material that has been previously correlated to the density and/or water content. Generally, field density tests should be taken one or two lift thicknesses below the surface of the fill.

a. Direct Methods. Direct methods of measuring volume include the sand cone test, push cylinder, and large test pits with sand or water replacement. Apparatus, procedures, and guidance in obtaining satisfactory results for the sand displacement, water balloon, push cylinder, and piston sampler are given in the *Earth Manual* [6]. The sand displacement and water balloon methods are the most widely used methods of measuring in-place density because of their applicability to a wide range of material types and good past performance records. The sand cone method is the most reliable and most frequently used; it should be the referee test for all other control methods. Reclamation's standard practice for zone 1 impervious core material is to use sand cones in holes that are 8 inches in diameter and dug 10 to 12 inches deep. The test hole yields approximately 35 pounds of soil and is tested by the three point rapid compaction test. The push cylinder and piston sampler are good for obtaining samples from which the density can be ascertained, but they are limited to moist, fine-grained, cohesive soils containing little or no gravel and moist, fine sands that exhibit apparent cohesion. Test pits with either sand or water replacements are used on coarser soils. The water replacement method is generally used for testing gravelly soils (rockfill) where holes as large as 1 cubic yard are needed to obtain accurate results. The hole is lined with a thin plastic sheet to prevent leakage, and special equipment is often required for handling and weighing the large volume of excavated material and for measuring the large volume of water. A 3- to 6-foot-diameter steel ring with a height about equal to a compacted lift thickness is often used where the fill surface is rough and uneven. The volume of water required to fill the ring with plastic liner in place is determined, the water and liner are 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 in the *Earth Manual*, volume 2, USBR Procedure 7221 [6] and ASTM D 5030.

Water content measurements are required to control placement water content and to determine dry densities for field density tests, except when the rapid compaction test is performed. Methods for direct water content determinations include oven, microwave, hot plate or open flame drying, and drying by forced hot air. Procedures for oven drying are described in the *Earth Manual* [6]. In the hot plate method, a small tin pan and a hot plate, oil burner, or gas burner (something to furnish heat for fast drying) are used. A specimen of wet soil is weighed, dried by one of the previously mentioned methods, and weighed again to determine how much water was in the specimen. This method is fast; however, the laboratory technician must be careful to ensure that the material is thoroughly dry. Also, both organic matter and crystalline water may be removed, sometimes resulting in higher moisture content determinations than those obtained by oven drying. In all cases, the hot plate or burner method must be compared to oven drying to validate that accurate results are being obtained.

b. Indirect Methods. Indirect methods of measuring in-place density and water content are sometimes used to supplement the direct methods. This use of indirect methods gives the construction staff a better ability to ensure that adequate moisture and density are being obtained throughout the embankment fill than can be accomplished by the use of direct methods alone. However, no indirect method should ever be used without first calibrating it with results obtained from direct methods, and periodic checks using direct methods should be made during construction. If reliable calibrations can be obtained, then the results from indirect methods can supplement the results from direct methods. Indirect methods should never be used in lieu of direct methods. Indirect methods include use of the nuclear moisture-density meter and the Proctor penetrometer (often referred to as the "Proctor needle").

(1) Proctor Penetrometer. The Proctor penetrometer is generally accurate only under ideal conditions; it requires careful calibration using soils of known density and water content, as well as considerable operating experience. At optimum moisture conditions and with standard effort, needle pressures typically range from 300 to 500 lb/in^2. Therefore, the needle can be used to evaluate moisture conditions on the fill. Readings of 1,000 lb/in^2 and higher indicate that the soil is dry of optimum moisture content. The needle results may be questionable due to the great influence a nonuniformity of water content or a small piece of gravel can have on penetration resistance. It is, therefore, not recommended for general use in compaction control; however, it can supplement visual observations and provide a general guide for detecting areas of doubtful compaction. The procedure (needle-moisture test) for determining the relation between wet unit weight, penetration resistance, and water content is described in the *Earth Manual* [6].

(2) Nuclear Density Gage. The nuclear density gage is an expedient means by which both water content and density determinations can be made more rapidly than by conventional direct methods. However, there are questions within the profession regarding its accuracy, especially to determine moisture content. Therefore, the nuclear gage is not permitted as a primary control; it is used to supplement direct methods. Reclamation uses nuclear density gages under certain conditions. The gage may be useful on processed soils such as filter, drain, and soil-cement materials. The gage overestimates water content in silty and clayey soil, sometimes by as much as 2 to 4 percent; therefore, it is not used on zone 1 impervious core materials. To be used, a constant running calibration of gauge moisture to oven dried moisture is required. For impervious core materials, the sand cone and rapid compaction test are used. Misuse of the gage by failure to use moisture correction procedures has been a longtime problem. The procedure for performing nuclear moisture density tests is given in the *Earth Manual*, USBR Procedure 7230-89 [6]. Recently, the ASTM committee has revised the nuclear gage testing standard to D 6938, and it requires that moisture corrections be checked.

10.6.3.5.5 Test Pits

It is sometimes desirable to excavate deep test pits into the embankment to determine the overall condition of the compacted material. The Occupational Safety and Health Administration standards should always be followed during such excavations as well as the *Reclamation Safety and Health Standards* Manual [21]. Field density tests can be made and undisturbed record samples can be obtained at various elevations as the test pit is being dug. The degree of uniformity of water content with depth can be obtained by testing specimens from frequently spaced depths. An important advantage of the test pit is that it allows visual inspection of the compacted fill; soft spots and laminations can be detected, and a determination can be made whether bonding of fill lifts has been accomplished. Near the foundation, test pits are used to evaluate the bond of the impervious zone to the foundation. Large-diameter bucket auger holes (30 to 36 inches) can also be used to evaluate the bond at the embankment/foundation contact. All tests and visual observations should be documented, including numerous photographs. Test pits must be backfilled with appropriate, properly compacted soil.

10.6.3.5.6 Methods of Relating Fill Density and Water Content to Maximum Density and Optimum Water Content

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 [15].

Performance of the standard five-point compaction (Proctor) test on field density test material is the ideal method because it produces values of maximum dry density and optimum water content for that particular silty or clayey soil. However, performance of this test is time consuming, and it is generally not possible to perform the five-point test on material from each field density test.

There are other less time-consuming methods for comparing the field density material with soils on which standard laboratory compaction tests have been performed. Some of these means of identification for comparison are:

- USBR rapid compaction control (preferred method)
- Atterberg limits correlations
- Grain-size distribution correlation (sometimes used for coarse-grained soils)
- Visual comparison

The USBR rapid compaction control method is the most accurate and preferred method [15]. It is the method used by Reclamation in lieu of the other “quick” methods. Reclamation developed the rapid compaction test in the late 1950s and has been using the test for over 50 years. The three-point rapid compaction test (USBR 7240, ASTM D 5080) works on an adjusted wet density basis, and the water content of the material does not need to be determined. This allows test results to be conveyed to field inspectors in about 1 hour. Another advantage of the rapid compaction test is that the soil comes from the sand cone test hole, and having a three-point curve allows variations of materials properties to be measured. During large dam projects, the properties of borrow soils might change from day to day. Reclamation’s use of large sand cone test holes and the three-point compaction test of the soil from the test hole provide reliable compaction analysis. The test provides the same result as the Proctor compaction test using standard effort (USBR 5500, ASTM D 698).

Each test in the above list is discussed in detail in the *Earth Manual* [6]. Atterberg limits correlations are based on correlations of liquid limit, plastic limit, or plasticity index with optimum water content and maximum dry density. The visual method consists of establishing, by visual examination, that the field density material is the same as one of the materials for which laboratory compaction curves were developed. It is a frequently used method, but it is the least desirable because materials that look very much alike and have the same soil classification can have widely varying compaction curves.

Embankment dams are water retaining structures that impose a hazard to the public; therefore, the highest level of construction quality control must be maintained. Due to the limitations of the Proctor compaction test, and the fact that results cannot be obtained rapidly enough, some agencies use typical curves, single-point compactions, and a family of curve techniques for earthwork control. Reclamation does not allow these methods to be used on dams; it uses the Reclamation rapid compaction test described above.

10.6.3.5.7 Procedures for Gravelly Soils

Results of the five-point compaction test on gravelly soils and visual methods are usually correlated directly with field density test results if all the material is minus No. 4 sieve size. However, Atterberg limits correlations and USBR rapid methods are based on the minus No. 4 sieve size fraction; consequently, field density test results must be corrected to obtain the water content and density of the minus No. 4 fraction called the “control fraction.” When the amount of oversize (material retained on the No. 4 sieve) exceeds 30 percent of the total material, the density that can be obtained using standard compactive effort on the control fraction is reduced. Therefore, the required density of the control fraction can be reduced as shown in table 10.6.3.3-1. When the amount of oversize (material retained on the No. 4 sieve) reaches 60 percent, the correlation may not be useable, and the inspection staff must rely on method specifications to control compaction of those soils. Note 1 in table 10.6.3.3-1 says that soils containing more than 50 percent gravel sizes should be tested for hydraulic conductivity of the total material if it is used as the water barrier. In the impervious zone, a typical requirement for impervious fines content (material passing the No. 200 sieve) of coarse-grained soils is a minimum of 25 percent fines. The equations necessary to make these corrections and procedures for applying them are given in the Reclamation report, “Guidelines for Earthwork Construction Control - Testing of Gravelly Soils” [17].

10.6.3.5.8 Evaluation of Test Results and Subsequent Actions to be Taken

As soon as field test results have been obtained, they are related to appropriate values of laboratory maximum dry density and optimum water content to determine if specification requirements have been met. If test results equal or exceed specification requirements, the next lift can be placed. If test results definitely do not meet specification requirements, corrective measures must be taken immediately. A lift must be rejected if the material is too wet or too dry of optimum moisture content. If the density is too low, but the water content is acceptable, additional rolling is generally all that is required. If, however, the water content is outside the specifications, the entire lift must usually be reworked and recompacted. A lift that is too wet of optimum water content should be scarified using a disk until the water content is lowered to an acceptable value and then recompacted. A lift that is too dry of optimum water content should be disked, sprinkled, and disked until the additional water is uniformly distributed and then recompacted. When reworking a rejected lift, it is important that the full depth of the lift is reworked, not just the upper portion. Whether the lift is retested for density and water content is up to the discretion of the inspector. The contractor should be discouraged from placing additional lifts over a lift that is being evaluated for acceptance, so that excessive removal and disruption of the placement and compaction operation are avoided in cases of nonacceptance. It is desirable to determine the reason for the unsatisfactory condition of a rejected lift, whether in borrow operations or operations on the fill, so that conditions may be corrected on future lifts.

Specifications for moisture density are not necessarily based solely on a minimum density or a specific moisture range for pass/fail. Statistical evaluations of results are sometimes used where a percentage of material tests is allowed to be outside a specified moisture range or below a specified density; then, an average moisture or density of all accepted embankment material must be within a specific moisture range and equal to or above a certain density. Hilf's report, "Compacted Fill," presents this concept in section 8.4, under a subsection labeled "Statistical Control of Compaction" [15]. This kind of specification allows a bit of leeway for the inspectors to accept a few low values.

10.6.3.6 Operations in Adverse Weather

10.6.3.6.1 Cold Weather

Good compaction is not obtained if the soil is frozen, even at temperatures above freezing. Research [5] has shown that cold weather may make it more difficult to obtain good compaction, and the PCE may be faced with a difficult problem in deciding just 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 is dependent on the size of the construction surface and the rate of fill placement. To reduce the potential for poor compaction during freezing temperatures, it is important that the contractor maintain an "active" construction surface (i.e., to continue fill placement without extensive interruptions). At some dams, work has been continued in 20 to 30 degrees Fahrenheit (°F) weather, 24 hours per day, 7 days per week, in order to keep the construction surface active. Work must be terminated whenever water in the soil freezes quickly and equipment operation becomes difficult.

Protecting the construction surface during the winter when operations are shut down is another problem. The degree of protection depends on the severity of the winter. In many parts of the United States, it is not necessary to use any protection if the embankment surface was properly seal rolled (rolled with a smooth-wheeled roller to smooth and densify the surface so that water does not easily penetrate and runs off easily). The worst damage results from heaving and loosening of the upper several inches to, in extreme cases, a few feet of the embankment fill by frost action. Before construction resumes in the spring, the surface material should be excavated to a depth below the line of frost action. The depth of excavation of frost damaged embankment is best determined by the use of frost tubes or thermocouples supplemented by visual examination of the embankment in shallow test pits. In colder climates, where the embankment freezes to a depth of several feet, it may be desirable to protect the construction surface during the winter with several feet of loose fill material. Other methods of protection have been used in extremely cold areas, such as ponding water on the construction surface or using some type of heating coils on foundations for structures (spillway, outlet works tower, etc.).

10.6.3.6.2 Wet Weather

Fill placement during periods of high precipitation causes problems due to the necessity of maintaining specified water contents. Impervious materials should never be placed on the embankment during heavy rains, although construction operations can often be continued successfully between rain events. The water content of material spread on the embankment can be reduced somewhat during periods of no rain by plowing or disking before rolling.

It is desirable to compact fill material as soon as possible after spreading to minimize the time that the loose fill is exposed to precipitation. Rubber-tired rollers are superior to sheepsfoot rollers when rains are frequent. Rubber-tired rollers leave a relatively smooth, compacted surface that promotes runoff, while the sheepsfoot roller leaves a loose, rough surface that readily soaks up rainwater. If a sheepsfoot roller is used for general compaction, smooth-wheeled rollers (steel or rubber) can be used to seal the surface of the fill when rain is imminent. Since pneumatic-tired equipment has higher operating speeds than a smooth drum roller, it is often the preferred piece of equipment used for sealing the fill surface. In addition, the construction surface should be sloped to allow water to run off instead of standing in puddles and soaking in. After a rain, if some ponding does occur, it is usually beneficial for the contractor to put in a few small ditches to drain these areas. Smooth surfaces in the impervious zones should be scarified before continuing the placement and compaction operation.

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 satisfactory water content, or to remove and waste all affected material. If the described procedures for facilitating surface runoff are followed, the depth of moisture penetration will be kept to a minimum.

10.6.3.6.3 Dry Weather

As discussed in paragraph 10.5.1.3.3.a, the moisture content should be within specified limits during placing, and addition of water should be avoided. This is not always possible in dry weather. If the material is drying during hauling and placing, or drying on the fill to a condition where it is too dry of optimum water content for proper compaction, water must be added by sprinkling the soil after it is spread and before it is rolled. Precautions stated in paragraph 10.5.1.3.3.a. should be observed. The amount of water to be added and the amount of blending required to obtain uniform moisture distribution depend on the fines content and the plasticity of the soil. The soil must be scarified using disks to thoroughly blend the added water into the soil. The importance of uniform moisture distribution cannot be overemphasized because, if water is retained in pockets of wet soil, inadequate compaction will result. Sprinkling of the soil can be accomplished by attaching hoses to a pipeline that is located either along the embankment toe or crest, or by the use of water trucks. The latter method is the most effective and is most commonly used. Pressure sprinkling systems on trucks are superior to gravity systems. Water sprays must not be directed on the soil with such force as to cause fines to be washed out. Until inspectors and contractor personnel have gained experience with the amount of water that should be added on the fill, rough computations of the number of gallons to be added for a given area should be made and water applied accordingly. After a few trials, experimentation should lead to accurate judgment of the proper amount of water to be added. 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 moisture distribution in plastic clays containing lumps of dry clods without a "curing" period of a few days; this is, of course, not practical on the embankment surface. Consequently, disking followed by the addition of water, and then thorough mixing with a heavy rotary pulverizer, may be required to obtain uniform distribution of water in such soils.

10.6.3.7 Compaction in Confined Areas

Confined areas are those where typical compaction operations with heavy equipment are restricted or where heavy equipment cannot be used and hand compactors are more suitable. It is stressed that compaction with hand compactors should be avoided, and heavy equipment should be 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), spillway walls, conduit barrels, control towers, etc. Confined areas, where hand compactors are often used, 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 close enough to the surface to squeeze the fill into all the irregularities and openings in the rock; and around alignment collars or plugs where it is difficult to maneuver. It is almost always possible to avoid using hand compaction methods by shaping of the abutments or structure surfaces. Abutments can usually be shaped to remove irregular surfaces using proper excavation techniques or with the use of dental concrete to fill depressions or overhangs to eliminate the need for hand compaction. Structures can be shaped by battering the structure walls to facilitate heavy equipment compaction. Wheel rolling adjacent to structures or on rock surfaces is the generally accepted method of compacting materials if the specified roller cannot be used. The rubber-tired wheels of fully loaded front-end loaders work well against abutments or heavy structures, and the front wheel of a motorized grader works well against lighter structures. Concrete age, strength, bracing, and earth pressure must be considered, and the method of compaction needs to be coordinated with the structure designer. Equipment attachments for backhoes and smaller rollers usually provide better results than hand-operated whackers, rammers, and tampers.

Where impervious material is to be placed adjacent to abutments or concrete structures, the soil should be the most plastic material available. The soil must be plastic enough to penetrate all irregularities in the abutments and to form a well-bonded seal with the foundation. The moisture content is often increased to slightly above optimum moisture content (optimum to optimum + 2 percent) to provide a more plastic material for placement in these areas. The plasticity of the soil is sometimes increased by mixing bentonite with the available impervious soil, such as was done at Reclamation's Sugar Pine Dam in California.

Additional compaction control testing is required in these areas as compared to the main embankment because they are generally more critical with respect to seepage and settlements, which can cause cracking and piping. A special sampling program should be developed, and an inspector must observe the operation at all times.

Specifications should clearly define areas to receive special compaction, and provide measurements and payments for it.

10.6.3.7.1 Heavy Equipment

When conditions are such that heavy compaction equipment can be used to compact soil against rock abutments or walls of concrete structures, the construction surface of the embankment should be sloped away from the rock or concrete at about 6H:1V for a distance of 8 to 12 feet (2.4 to 3.6 m). This will allow the roller to act more directly to compact the soil against the abutment or structure. The area can then be rolled in a direction parallel to the face of the abutment or structure. On flatter abutment slopes, the area can be rolled perpendicular to the abutment. Caution is required to prevent damage to the foundation when placing the first lift of fill in the impervious zone. On rock, pneumatic tired rollers or loaded pneumatic tired earth moving equipment should be used for the first lift, and then tamping rollers. Refer to Design Standard No. 13, Chapter 3, “Foundation Surface Treatment,” for a more detailed discussion of compacting near foundations.

10.6.3.7.2 Hand Compactors

If heavy rollers cannot be used, as described previously, the roller should be allowed to work as close to the structure or foundation surface as possible, and the portion of the embankment directly against the rock or concrete should then be compacted with smaller equipment in thinner lifts. Smaller equipment refers to hand-operated power tampers, as shown in figure 10.6.1.2-1, or power tampers mounted on small tractors. These tampers are usually gasoline powered, or they operate using compressed air. The hand-operated power tampers (sometimes called rammer compactors or whackers) are probably the most widely used equipment for compacting fine-grained soils in confined areas. A compacted lift thickness of not more than 4 inches should be placed in conjunction with the use of power tampers. The compactors should have a minimum static weight of 100 pounds, and the inspector should carefully check to ensure that the manufacturer's recommended air pressure is being obtained. Experience has shown that 2- by 4-inch 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 the zones of hand compaction and compaction by heavy equipment overlap, so that no uncompacted material exists.

10.6.4 Pervious Fill

10.6.4.1 Definition

Pervious fill material is defined herein as free-draining cohesionless sand and/or gravel containing less than approximately 5 percent of material passing the U.S. standard No. 200 sieve.[3] Standard impact compaction tests on such materials do not yield well-defined values of optimum water content and maximum dry density. For clean, cohesionless soils such as those used in shells, drains, and filters, where water content is not important to achieving compaction, a traditional method of specifying a degree of compaction is by relative density. Relative density is a measure of the in-place density of the soil that is compared to a minimum and maximum void ratio or dry density. The relative density test has been replaced by the vibratory hammer test for the reasons presented in section 10.6.4.7.3. Recently, the vibratory hammer test (ASTM D 7382) has been used to control compaction of pervious soils, and Reclamation is switching to this test to overcome the problems with the relative density test. The new test is applicable to granular soils with up to 30 percent nonplastic fines and 15 percent plastic fines and can be used to evaluate the optimum water content for

[3] Outer embankment zones of some dams composed of coarse-grained soils which contain appreciable amounts of fines (i.e., > 5 percent) are sometimes designated as "pervious zones." Compaction equipment, procedures, and control for such materials can be as presented in this section or in section 10.6.3 for impervious and semipervious fill. The decision as to which method to use depends on whether the soil behaves like a pervious material or like an impervious material. Experience and/or laboratory tests will usually determine which material type is applicable; however, test fills may be necessary to establish the most efficient placement and compaction procedures.

compaction in soils with significant fines. When using a percentage of the maximum dry density, the required percent compaction in table 10.6.3.3-1 is the same as the standard effort requirement.

10.6.4.2 Compaction Equipment

Vibratory steel-wheeled rollers in the weight range of 5 to 12 tons are the best equipment for compacting pervious sands and/or gravels. Smooth drum, self-propelled, vibratory rollers have been found effective on fine uniform sands when other vibratory rollers were not. Figure 10.6.4.2-1 shows a vibratory roller compacting filter material at New Waddell Dam, and figure 10.6.4.2-2 shows a vibratory roller compacting a filter zone at Horsetooth Dam.

Figure 10.6.4.2-1 New Waddell Dam, Arizona. Bottom dump and 10-ton vibratory roller placing and compacting filter material in the downstream blanket drain. The filter material has been saturated by sprinkling with water.

Rubber-tired rollers are sometimes specified, and crawler tractors are sometimes used if they can produce the specified densities. Crawler tractors are sometimes effectively used in rough or hilly areas where a vibratory roller cannot operate efficiently; for example, when compacting a horizontal drainage layer on an undulating foundation. The contact pressure of the tractor should be at least 9 pounds per square inch, and the tractor should operate at the speed that imparts the greatest vibration to the fill. The track shoes may cause near surface, particle breakdown. The amount of particle breakdown should be investigated to ensure that it remains within acceptable limits.

Figure 10.6.4.2-2 Horsetooth Dam Modification, Colorado. Filter compaction by a Cat CS563 smooth drum, vibratory roller, and spreading of drain by a crawler-type tractor. Front-end loaders are being used to haul and dump the filter and drain material.

For a vibratory roller, the static weight, imparted dynamic force, operating frequency of vibration, and the drum diameter and length should be checked. Virtually all heavy, smooth drum, vibratory rollers in manufacture today have advanced instrumentation systems termed “Intelligent Compaction Technology.” The instrumentation consists of accelerometers mounted in the drum. From the frequency and acceleration data, the stiffness of the soil can be estimated. This technology has been used in Europe for over 20 years, and various State Departments of Transportation have been using this technology for 10 years. Reclamation is undertaking demonstration programs to use this technology on filters and drains in dams. These advanced instrumentation systems have displays onboard so that the operator can monitor the progress of the compaction. The color display relates directly to soil compaction conditions going from soft to compact to overcompacted to damaging the soil. These computer units are equipped with GPS technology, and a complete record of the compaction process is obtained. This allows 100-percent control of roller coverage on the fill. The use of these rollers should be considered because the operator has the benefit of seeing the soils being compacted, and the progress of the compaction is displayed.

Where free-draining pervious material is placed 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 small vibratory compactors are a small steel-wheeled vibratory roller or a "vibrating plate" compactor. Air-operated concrete vibrators have also been used successfully to densify narrow, relatively deep zones of pervious backfill in pipeline construction; however, this method is not advisable for dams. Figure 10.6.4.2-3 shows a sand filter being compacted with a vibratory plate attachment for an excavator and a hand operated vibratory compactor. Vibratory-type units should be checked frequently to ensure that they are operating at an appropriate frequency that will obtain adequate density. For cohesionless materials, the frequency of vibration should generally range between 1,000 and 2,000 vibrations per minute.

Figure 10.6.4.2-3 Folsom Left Wing Dam, California. View of a sand filter being compacted by a Cat 330L excavator with a vibratory plate compactor attachment. Also notice the hand operated vibratory compactor in the right side of the picture that is used for compacting against the concrete face. This is the interface of the embankment and concrete dam. 2008.

10.6.4.3 Material Gradations

Gradations of materials to be placed in the large pervious embankment zones (shells) are generally not specified, except to restrict the maximum size and/or the percentage, by weight, of particles smaller than the No. 200 sieve. However, a particle-size distribution within limits defined by roughly parallel gradation curves on the standard grain-size plot is specified for select pervious materials to be used in horizontal and inclined filter or drainage layers. See Design Standard No. 13, Chapter 5, “Protective Filters.”

10.6.4.4 Water Content Control

If the pervious material is gravel, no water content control is necessary, and the material is compacted in its as-received condition. If the material is sand or contains a significant quantity of sand sizes, the material is maintained in a condition as saturated as possible during rolling by using water trucks with pressure spray bars, hoses connected to header pipes laid along the embankment, or other approved methods. The effect of insufficient water in a pervious sand is to cause the sand to "bulk" (i.e., exhibit apparent cohesion), which will result in low strength and density when it dries out. It is, therefore, essential that the sand be saturated as the roller passes over it, which is sometimes difficult due to the perviousness of the sand. Figure 10.6.4.2-1 shows a sand filter at New Waddell Dam that was wetted by a water truck with a pressure spray bar system. If a pervious material contains an appreciable quantity of fines (more than 5 to 10 percent passing the No. 200 sieve), it may be necessary to use water content control to ensure that the water content is within a range that will permit desired compacted densities to be obtained.

Research has shown detrimental effects of allowing previously compacted lifts to dry out on the construction site. If the filter dries and develops some slight cohesion, the filter may be able to sustain a crack. Filter lifts should never be allowed to dry in the sun. If a lift has dried, it must be rewetted and rolled again.

10.6.4.5 Lift Thicknesses and Numbers of Passes or Coverage

Lift thickness and number of passes or coverage of the compaction equipment are provided in the specifications. Designers need to be very specific regarding the number of passes for the weight of the roller. If specifications say 2 to 6, the contractor will bid 2, and the inspector will expect 6. In general, depending on the roller size and weight, pervious fill is commonly placed in 12- to 15-inch loose lifts when it will be compacted by two to four passes of a smooth drum, steel-wheeled, vibratory roller (preferred) or a 50-ton, rubber-tired roller. Six- to 8-inch loose lifts are used when it will be compacted by three to six coverages of a crawler tractor.[4] The number of compaction passes over these zones may be limited, and the vibrator may be turned off for some of the passes to prevent overcompaction of these layers. In confined areas where small vibratory rollers or hand-operated vibrating compactors are required, material is typically placed in 3- to 4-inch-thick layers with vibratory compaction applied until densities comparable to those required for areas compacted with heavy equipment are achieved. In all cases, the contractor must demonstrate that the required density is being obtained with the roller/compactor and lift thickness that are being used.

[4] Guide specifications generally call for a specific number of "complete passes" of a rubber-tired roller or vibratory steel-wheeled roller and define a "complete pass" as the coverage of the entire lift to be compacted with the roller specified. It is apparent that this concept does not apply to compaction with a crawler tractor as a unit because of the wide separation of its tracks. Therefore, when compaction by a crawler tractor is specified, the specifications should require complete coverage of the area being compacted by the required number of passes of a single track of the tractor.

10.6.4.6 Density Requirements

Compaction equipment and procedures, and desired density, are typically specified. The expectation is that the specified field compaction methods and equipment will produce the desired densities. If these densities are not achieved in the field, then the specified procedures or equipment such as lift thickness, number of roller passes, moisture application, or roller weight must be adjusted, and the contractor must be fairly compensated for additional effort or different equipment.

Generally, the in-place relative density of pervious fill should be in accordance with table 10.6.3.3-1. However, fill in filter and drainage zones should have a relative density of no less than 65 percent and no greater than 80 percent. The maximum density in filter drainage zones is limited to prevent the formation of sustained cracks and the reduction of permeability. The minimum density in filter drainage zones is specified to reduce the potential for liquefaction during earthquake loading.

Reclamation currently uses density control (vibratory hammer test) as the compaction criteria for these materials. Using density control with the addition of intelligent compaction technology can ensure that density is being achieved continuously throughout the construction process (i.e., 100-percent monitoring).

10.6.4.7 Construction Control

10.6.4.7.1 Simple Control Procedures

Checking lift thicknesses of pervious fill materials can be accomplished using the same procedures described for impervious and semipervious materials (section 10.6.3.4), except that when 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 test pit in the loose material to the top of the underlying layer, which is identified by a relatively higher resistance to digging. Use of equipment with GPS leveling technology simplifies the task of checking lift thicknesses and is recommended.

The embankment surface should be sloped so that surface waters will not wash fines from impervious or semipervious fill materials into the pervious fill (filters and drains). During construction of earth dams, placement of filter or drainage materials should always be kept higher than adjacent fill containing fines to prevent spillage of fine-grained soil onto the pervious material and to reduce the possibility of washing fine-grained soils into the material by surface runoff. Designers and construction staff should recognize the appearance of pervious material that meets specification requirements, so that they can detect, without the delay of testing, the presence of excess fines content (material passing the No. 200 sieve). A good indicator of excessive fines content is when the hauling and compacting equipment sink into the fill and cause ruts in the fill surface. This usually indicates that water applied during compaction is not draining through the material due to reduced permeability caused by excess fines content. Another test for excessive fines content is called the “cloud test,” in which the sand is placed in a dish or bucket. The sand is swirled around to allow the fines to float. If you can see the soil grains through the cloud, the soil likely has low fines contents. Thick clouds, which obscure the soil grains, indicate excessive fines content.

In general, a vibratory roller should push only a small amount of material ahead of it and leave a smooth surface behind it 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.

It is more difficult to judge the compacted density of pervious material than fine-grained material. Resistance to penetration of a shovel or a reinforcing steel rod is not a suitable way of checking density, and it is necessary for the inspector to rely on field control tests and intelligent compaction technology. Some inspectors can judge the compaction obtained in pervious fill by walking on it and feeling the reaction of the material. The uniformity of particle-size gradations in the lift should be observed. If soil particles are being crushed during compaction, a layer of fines will develop in the upper few inches of the lift, which can greatly reduce the vertical permeability.

Loading, dumping, and spreading operations should be observed, particularly if the pervious fill is well-graded material, to ensure that undesirable segregation of particles is not occurring.

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

10.6.4.7.2 Gradation

Gradation tests should be performed to ensure that the material being placed is within specification limits. The number of gradation tests needed depends on the variability of natural pervious material obtained from the borrow areas. Complete gradation tests should be performed on material for which the entire range of particle sizes is specified. For materials that have only the percent finer than the No. 200 sieve (or some other sieve) specified, the material should be soaked and then washed over the No. 4 sieve and the designated sieve in accordance with procedures given in the *Earth Manual*, USBR Procedure 5335 [6]. Gradation tests should also be performed on compacted material, especially when contamination with fines from surface water runoff is suspected, or when the fill material may have been degraded by breakage of particles during compaction. Wash tests are routinely performed for every density test to ensure that the fines contents are within specified limits (usually less than 5 percent passing the No. 200 sieve in filters). Filter and drainage material gradation testing should be conducted on samples taken from the fill after it has been compacted.

10.6.4.7.3 Field Density Testing, Relative Density, and the Vibrating Hammer Test

The sand volume density test method described in the *Earth Manual*, USBR Procedures 7205 and 7220 [6], can be used to determine the in-place density of pervious fill classifying as sands and finer gravels. It is more difficult to dig test pits in pervious materials. When the fill material contains large quantities of coarse particles, it may be necessary to increase the volume of the test pits substantially and to line the test pits with plastic film, so that the volume can be determined by the quantity of fluid needed to fill it. The nuclear density meter can be used for supplementary density determinations under the conditions stated in 10.6.3.5.4.b.

Field density determinations using the sand volume procedures should be made for every 1,000 cubic yards of pervious fill placed at the beginning of the project and one test for every 3,000 cubic yards of material placed thereafter, with more frequent test determinations desirable for filter and drainage layers. These tests should generally be taken one- or two-lift-thickness deep, especially in sands.

The density of free-draining pervious fills and filter material cannot be related to standard impact compaction test results because water content-density relations are not as valid for such materials as they are for materials having varying degrees of plasticity. For clean, cohesionless soils such as those used in shells, drains, and filters, where water content is not as important to achieving compaction, a traditional method of specifying a degree of compaction uses relative density. Relative density is a measure of the in-place density of the soil as compared to a minimum and maximum void ratio or dry density. Two tests are run (USBR 5525 and 5530, ASTM D 4253 and D 4254). Table 10.6.3.3-1 shows typical relative density requirements for embankments. The relative density test has received much criticism because the maximum density of the large vibratory table used to conduct this test is difficult to calibrate. Also, because there are two tests, there is a greater likelihood for errors [16]. Over the years, some engineers have just specified the percentage of the vibrated maximum dry density.

A vibratory hammer test (ASTM D 7382) is now in use to provide compaction control of these soils. The large mold on this test handles a minus 2-inch control fraction. This test would be applicable to shell materials on dams with little fines. Reclamation is switching to this test to overcome the problems with calibrating vibratory tables. The test is applicable to granular soils with up to 30-percent nonplastic fines and 15-percent plastic fines and can be used to evaluate the optimum water content for compaction in the soils with significant fines. When using a percentage of the maximum dry density, the required percent compaction in table 10.6.3.3-1 is the same as the standard effort requirement.

Field densities must be expressed as a percentage of maximum densities, as determined from the vibrating hammer test (ASTM D 7382), or in terms of maximum-minimum densities, as determined by laboratory tests described in the

Earth Manual, USBR Procedures 5525, 5530, and 7250 [6]. The vibrating hammer test is the preferred comparison test used by Reclamation.

However, when using relative density, field densities are expressed in terms of their relation to maximum and minimum laboratory densities (i.e., in terms of relative density).

The relative density D_d of in-place material can be computed by this equation:

$$D_d\% = \frac{\gamma_{dmax} (\gamma_d - \gamma_{dmin})}{\gamma_d (\gamma_{dmax} - \gamma_{dmin})} \times 100$$

Where:

γ_d = dry unit weight of the pervious fill in place (in-place density), pounds per cubic feet [lb/ft^3]
γ_{dmin} = minimum density, lb/ft^3, from laboratory tests
γ_{dmax} = maximum density, lb/ft^3, from laboratory tests

The performance of maximum and minimum density determinations on material from each field density test provides the most accurate determination of the relative density of the in-place material; however, performing relative density tests is frequently not feasible due to time and manpower restrictions involved with performing these tests.

As discussed earlier, the specification may be based on a percentage of the maximum density (as determined by the vibrating hammer) instead of relative density. The relationship between percent compaction and relative density is as follows [11]:

$$RC = 80 + 0.2 \cdot D_d$$

Where:

RC = relative compaction which is the same as percent compaction.

The vibrating hammer test is easier and faster to perform than testing associated with relative density determinations and is the recommended compaction test for pervious soils.

Density control testing may not be possible for certain coarse-grained soils. Clean cohesionless pea gravels and uniform fine gravels used for drain materials cannot be reliably tested by any means. In such cases, method specifications can be used. Since these soils are easily compacted, specifications paragraphs can specify a minimum number of passes of a smooth plate vibrator or smooth drum vibratory roller as approved by the contracting officer. For these same materials, use of test fills and intelligent compaction equipment technology may be beneficial.

10.6.4.8 Test Results and Actions to be Taken

What should be done once it has been established that a lift has in-place relative densities ranging between 80 and 85 percent, and the minimum average specified is 85 percent? A review must be made of all results of previous lifts to ensure that a minimum average of 85-percent relative density will be maintained if the questionable lift is accepted. The intent of the relative density criteria is that the relative densities of the material measured immediately after compaction must conform to the requirements stated in the specifications without any increase of density caused by the placement and compaction of subsequent lifts. It should be recognized that the top 2 to 3 inches of the surface lift may be loosened by the roller. Therefore, density testing should be performed on a layer one or two lifts below the compacted surface. This same reasoning would also apply to results that are checked by the vibratory hammer test when a percent of maximum density is being specified as the requirement.

10.6.5 Rockfill [12, 13]

10.6.5.1 General

Embankments with large rockfill zones are becoming more common. This is primarily due to: (1) the necessity for using sites where rock foundation conditions are unsuitable for concrete dams, (2) the suitability of modern construction equipment to handle rock, (3) the increasingly higher dams being constructed, and (4) the economic benefit that is obtained by maximum use of rock from required excavation.

Rock, which does not readily break down during handling, transportation, and compaction, results in a pervious to very pervious fill, depending on the amount of fines present. Such sound rock is desirable for rockfill dams, especially if the source is from required excavations, such as for a spillway or foundation.

Less desirable rocks break down in varying degrees during excavation, handling, compaction, and even *in situ*. These unsound rocks may break down because of their lack of induration; their primary structure, such as thin bedding; their degree of fracturing; their weathering; and other physical and chemical properties. Some examples of generally unsound rocks, as related to large rockfill zones in dams, are shales, mudstones, siltstones, claystones, chalk, earthy limestones, decomposed granitics, and other sedimentary rocks which may be poorly cemented. Ordinarily, rocks which are very weathered and very fractured may not be acceptable for rockfill zones because of their susceptibility to break down. However, there are basically two types of rockfill dams: (1) dams with an upstream impervious facing element, such as Portland cement concrete or asphaltic concrete; and (2) dams with an impervious core and rockfill shells. Less sound rock can sometimes be used in impervious core dams, especially downstream of the impervious core, where the rock is less likely to be exposed to water. Also, zones that could possibly be upstream of the core, and that are not critical to the stability of the dam or that do not require high permeability, are sometimes designated for the use of less sound rock.

In general, because of the visual unpredictability of the breakdown of most types of rocks, the use of test quarries and test fills for designing and constructing rockfill dams is common.

10.6.5.2 Sound Rock in Rockfill Dams

10.6.5.2.1 Specifications

The specifications for pervious rockfill sections generally require that the rock be sound, well graded, and free draining. Gradation is dependent on rock quality, and quarrying and handling procedures. Limitations on the amount of fines or smaller-sized particles for the "as loaded" rock are sometimes specified. Other than the maximum permissible size, in-place gradation is not usually specified. Lift thickness is typically specified and is based on the maximum permissible size of the material. Rockfill is usually placed by dumping from trucks, with bulldozers spreading the material to the desired lift thickness. The required placement and spreading operations should avoid segregation of rock sizes. This is discussed in more detail in the following paragraphs. The type roller, lift thickness, and number of passes will be specified, preferably based on results of test fills.

10.6.5.2.2 Placement Operations

Fines usually accumulate at the lift contacts; consequently, Kh (horizontal permeability) is always greater than Kv (vertical permeability). This condition should be considered during design. 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 is produced that is thick enough to choke the upper part of the lift and prevent distribution of the fines throughout the lift, it may be necessary to specify that the rock be dumped directly in place.

Prior to compaction, all oversized rock must be removed. 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 removed and placed elsewhere, or they are broken down with a drop weight or explosives and used in the rockfill or riprap zone. Another common method of breaking oversized rock is with hydraulic chisels. Oversized rocks should not be placed along the contact slope of a closure section.

Close inspection is required to ensure that the material does not contain an excessive quantity of fines. An excessive quantity of fines will not produce free draining rockfill where it is desired and can cause excessive postconstruction settlements when the reservoir is filled. It is difficult to specify a limiting amount of fines in the specifications; consequently, this is rarely done. The designers should provide guidance to construction staff, based on results of rock test fill studies, which will aid in determining when excessive fines are present. The design and construction staff must be alert for material variations that could result in undesirable changes in gradation of the material being hauled to the embankment. If this occurs, the contractor should be notified, so that a change can be made in quarrying techniques.

10.6.5.3 Compaction

Current practice is to use smooth, steel-wheeled, vibratory rollers to compact all sound rockfill in comparatively thin lifts with minimal application of water. Vibratory rollers having static weights of 10 to 20 tons have been used to construct rockfill dams.

The lift thickness specified is dependent on the size and type of rock and the type of compaction equipment to be used, and it is usually determined from results obtained during construction of a test fill. The lift thickness specified will be 2 to 4 feet, unless test fills show that adequate compaction can be obtained using thicker lifts. Maximum-sized rock should not exceed 75 percent of the lift thickness. Scarification of compacted lift surfaces is not necessary and should not be allowed because it disturbs the compacted mass.

10.6.5.4 Unsound Rock in Rockfill

In the past, use of soft or unsound rocks has been dictated by its availability in large quantities from required excavations. The tendency of these materials to weather and soften with time when exposed to air and water within the embankment is the primary concern with their use. However, for dams in which large portions of embankments were composed of unsound rocks, it has been shown that when used in random and semipervious zones, they attained adequate shear strength and experienced no further appreciable breakdown after placement. Where unsound 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 design studies.

Some rockfills, composed of unsound rocks, have been compacted by first rolling the loose lift with a heavy tamping roller equipped with long spike or chisel-type teeth ("shale breaker"), and then compacting of the lift with conventional tamping or rubber-tired rollers. A summary of this technique is given in *Earth and Earth-Rock Dams* [5]. A shale breaker type roller is shown in figure 11.5:7 of that publication.

10.6.6 Semicompacted Earthfill

10.6.6.1 Uses

Stability berms, spoil berms, channel fillings, and low levees to protect farmlands are often constructed of semicompacted fills. However, semicompacted fill should not be used to construct levees that protect people.

10.6.6.2 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 a range of placement water content is either not specified, or a very wide range is permitted.

10.6.6.3 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, that suitable materials are being used, and that hauling and spreading equipment cover the fill uniformly.

10.6.7 Sequence of Placement, River Diversion, and Measurement of Quantities

10.6.7.1 Schedule of Construction

The schedule for construction of an earth or rockfill dam may require stage (or phase) construction. In a wide, flat valley, the embankment on one side of the river may be constructed to full or partial height under one contract or contract phase, with subsequent portions constructed during following years. Staged construction is sometimes employed to allow for the dissipation of embankment pore water pressures during construction, especially if the material is placed on the wet side of optimum moisture content. Where foundations are soft, the embankment may be constructed to a specified elevation and further fill placement deferred for as much as 1 year or more to permit dissipation of foundation pore pressures or to achieve an adequate degree of consolidation and settlement. In a narrow, steep sided valley with rock foundations, the entire embankment may be completed to a stipulated elevation by a certain date to prevent overtopping during 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 designer is responsible for specifying required phasing, staging, and scheduling to allow for optimum use of available materials and to safely and logically divert the river or contain flooding for protection of the public. Use of upstream borrow areas must be scheduled and planned so that materials needed for closure and future use are available in the higher elevations of borrow areas when lower areas are temporarily or permanently flooded. The contractor is responsible for constructing the particular stage or section of embankment within the time limits specified and for protecting the work accomplished during the contract. The inspection staff is responsible for determining that each stage or section is constructed using proper placement sequence. The designer must be aware of any changes in sequence or timing of stages so that each can be analyzed for approval or appropriately adjusted. Designers, construction staff, and the contractor are all responsible for scheduling and staging so that public safety and protection of property are ensured. The designers and construction staff should jointly prepare a construction logic diagram for inclusion in the specifications.

10.6.7.2 Placement Sequence

It is usually required that the embankment be constructed 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. Although the preferred procedure is given in section 10.6.4.7, during periods of dry weather, fill heights of central impervious zones are sometimes allowed to exceed heights of adjacent pervious zones by as much as 5 feet to permit continuous placement of impervious material. However, special precautions, such as sloping the impervious fill material away from the pervious zone and covering the pervious fill, are required to keep impervious material out of inclined filter zones. This practice should not be allowed in climates or seasons when fast developing storms, such as thunderstorms, are common. The provisions in section 10.6.4.7 should be strictly followed.

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 maintain the specified width of the filter zone and prevent filter contamination from other zones. The filter zone material should be maintained equal in height or higher than the other zones. A downstream horizontal filter and/or drainage zone should be completely placed and covered by two lifts of the overlying zone as soon as possible to prevent contamination of the blanket caused by surface waters carrying fines into the filter.

Designers should identify critical zones, such as filters/drains/slope protection that should be fully placed to the minimum dimensions, and the inspectors should be aware of these zones. One such zone is near the top of the dam, where all zones become narrow and placement and compaction become more difficult. It may be necessary to use smaller equipment in these congested zones. Another consideration is foundation surfaces that deteriorate, such as slaking shale, and that need to be quickly covered.

10.6.7.3 Diversion of and Care of Water During Construction

During construction, diversion and care of the river (stream, or surface runoff) is an important factor in the design of an embankment dam. The construction is sequenced to allow the river or stream to flow through the project during both normal flow and runoff from storms. Risks of damage to completed construction are high during this phase of construction because the partially constructed embankment will not handle extremely large floods, such as a probable maximum flood or floods approaching that magnitude, which the completed dam and appurtenant structures are designed to withstand without failure. Usually the outlet works is constructed prior to, or during, the early stages of embankment construction. During that time, the river or stream is contained in a channel, possibly in the existing river channel, through the embankment until a time when the river/stream can be diverted through the outlet works, and the embankment can then be constructed within the diversion channel. Side slopes of the diversion channel should be no steeper than 4H:1V (horizontal:vertical) as measured along lines parallel to the centerline of the dam. Figure 10.6.7.3-1 shows a temporary diversion channel through Bonny Dam, Colorado. Figure 10.6.7.3-2 shows construction and diversion at Olympus Dam, Colorado. Specifications should require that the contractor's plan for diversion be approved by the contracting officer, or the diversion plan should be provided in the specifications (preferable).

Figure 10.6.7.3-1 Bonny Dam, Colorado. Temporary diversion channel. USBR 1948

A decision must be made by the designer(s) about the size of flood that the diversion channel will pass through the construction site, without damage to the completed construction, and the size of flood that will be retained by the closure section for the safety of downstream residents and property, once closure is made. This requires the participation of both hydrologists and hydraulic engineers. Floods with return periods of 20, 50 and 100 years are usually developed by the hydrologist and then routed through the project by the hydraulic engineer. The floods may be larger or smaller depending on the potential for loss of life and property damage. The size of the diversion channel and the height of the closure section are selected from this process. These selections are based on the desired degree of minimum protection for both the downstream life and property and the construction project.

Figure 10.6.7.3-2 Olympus Dam, Colorado. General view looking north at Olympus Dam, which was under construction on the Big Thompson River, showing the river diversion around the south end of the dam. USBR 1947

The location and timing of the closure section is dependent on the shape and size of the valley. In steep sided narrow canyons the outlet works may be completed first and then the river diverted through it by means of an upstream cofferdam. The height of coffer dam would be based on the retention of floods that provides the desired degree of protection against loss of life and property damage. Once the river is diverted, foundation cleanup and treatment can be accomplished in the valley and then embankment construction can begin. It is usually desirable and economical if the cofferdam can be incorporated into the dam embankment.

In wide valleys, foundation cleanup and treatment, and then embankment construction, can usually begin on one or both sides of the river to form a diversion channel to pass the river through the project. Outlet works construction can also usually occur in the early construction phases. The size of the diversion channel will depend on the desired degree of protection against loss of life and property damage as well as the desired degree of protection against damage to the completed dam construction. Once the outlet works is completed and the embankment is constructed to the desired height for adequate protection, the river can be diverted through the outlet works by construction of a cofferdam or partial closure section in the upstream portion of the diversion channel. It is usually desirable and economical if the cofferdam or partial closure section is part of the dam embankment. Once diversion is made, foundation excavation, preparation, and cleanup can be accomplished in the diversion channel, and the remainder of the embankment closure section/cofferdam can be constructed to an elevation equal to the previously constructed dam embankment. At this time, the embankment would be at about an equal height for its total length and width, and embankment construction could continue for the full length and height of the dam embankment.

It should be noted that any side slopes of the diversion channel, which will become part of the finished dam embankment, will require special attention. The slopes have likely been subject to erosion, vegetative growth, equipment traffic, etc., and may be damaged to a significant depth. They will likely need to be excavated to acceptable embankment. This can usually be accomplished as the embankment fill lifts in the closure section are placed. The previous embankment can be excavated in a horizontal direction into the acceptable embankment just prior to placement of a new lift in the closure section. This may require oversteepening of the existing slopes of the diversion channel, and there may be concern for localized instability that requires the attention of the designer and inspection staff. However, the rather flat diversion channel slope, which should be no steeper than 4H on 1V, will probably allow this construction process to occur without incident, which is a major reason for specifying the rather flat diversion channel slopes. Also, this critical construction interface is a major reason for the inclusion of filter and drains (chimney drain) on the downstream face of the impervious core. Any seepage along the interface is intercepted by the chimney drain, and, thus, internal erosion is prevented.

10.6.7.4 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 to compute quantities. Quantities can also be calculated using software packages that model the fill and excavation surfaces (digital computer models). For separate zones within an embankment, theoretical quantities are computed from the lines and grades shown on construction drawings. Lines and grades to be used for computing quantities should be clearly specified and shown on construction drawings, so that instances of overexcavation or fill placement outside contract lines are easily discernable by the construction staff. This will help prevent possible errors in measurement and certification of payment for quantities in excess of contract provisions.

There is usually no separate measurement of quantities for diversion and care of water during construction. This cost is usually paid by including a lump sum bid item in the bid schedule for diversion and care of water during construction, or the contractor is directed to include the cost in the price for other bid items.

10.6.8 Slope Protection

10.6.8.1 Areas to be Protected

Slope protection is required to protect upstream slopes against damage from wave erosion, weathering, ice, floating debris, and surface erosion. Upstream slope protection of earth dams usually consists of riprap, although soil-cement, concrete paving, and asphalt paving have occasionally been used when riprap was not economically available. Dams with outer shells of sound, durable, large rock may not require further slope protection. Downstream slope protection is required to protect against damage from surface erosion by wind and rain. Downstream slope protection includes rock or gravel for dry climates, turf in humid climates, riprap where tail water may create wave action, or waste rock. Slope protection can be a substantial portion of the cost of the structure and is vulnerable to intensive maintenance if it is not designed and constructed properly. Proper design, as well as field construction procedures and enforcement of specifications, is particularly important in obtaining slope protection that will remain in place and require minimum maintenance during the life of the dam.

10.6.8.2 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 elevation limits of slope protection, the schedule for impounding reservoir water, and the type of slope protection. The best procedure is to require that slope protection construction not lag behind earthfill construction more than 10 to 15 feet in elevation.

10.6.8.2.1 Riprap

Riprap is the most commonly specified type of upstream slope protection. High quality, durable, 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. Design Standard No. 13, Chapter 7, "Riprap Slope Protection," presents detailed requirements for the design and construction of riprap slope protection. Some primary factors that govern successful construction are:

- Loading from the quarry to provide a good mixture of different sizes that are within the required gradation in each load. Proper loading from the quarry requires that blasting operations produce proper rock sizes and that loading operations are inspected.

- Loads should not be dumped down the slope, but should be placed on the slope. Riprap within each load should have a uniform distribution of different sizes without segregation. Individual rocks should be rearranged to provide a rock mass without large voids. A gradation test (performed by weighing a sufficient quantity) should be made for each 10,000 cubic yards of placed riprap during the early stages of riprap placement. If the inspector suspects a problem during the remainder of the project, additional tests can be performed at the discretion of the inspection staff. ASTM D 5519 also provides methods of determining riprap gradation. 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. A good method of placement to avoid segregation is to use a skip as shown in figure 10.6.8.2.1-1. Dumping rock at the top of the slope into a chute should never be allowed because this will result in segregation. Spreading riprap with a dozer almost always causes segregation and should be avoided. 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-foot-diameter) rock is specified, a crane with an orange peel attachment operating from a platform built on the slope can be used to place the material. In recent years, backhoes with 1.5- to 2.5-cubic yard capacity have become the most common equipment for placing riprap.

Figure 10.6.8.2.1-1 Dragline with skip placing riprap [1].

Backhoes can be used to grade the embankment slope and place the bedding as well as the riprap. Figure 10.6.8.2.1-2 [a. and b.] shows a Hitachi backhoe that was used to place upstream riprap and cobble-boulder slope protection on the downstream slope at Jordanelle Dam. Due to the reach of the backhoe, the riprap must be placed as the embankment is placed because the riprap can only lag about 15 feet below the top of the fill. Other equipment, such as Gradalls (figure 10.6.8.2.1-3), cranes with clamshell buckets, and rubber-tired front-end loaders, can be used to place riprap. These types of equipment are preferable to dumping from hauling equipment.

a. Shaping of embankment surface in preparation for placing riprap.

b. Example of excellent results that can be achieved when placing slope protection with a backhoe on the downstream slope of the dam.

Figure 10.6.8.2.1-2 Jordanelle Dam, Utah. Placement of slope protection using a Hitachi backhoe. USBR 1991

Figure 10.6.8.2.1-3 New Waddell Dam, Arizona. Gradall used to place slope protection. USBR 1992

- Close visual inspection is required after dumping and spreading to determine the degree of uniform distribution of different sizes and close-knit arrangement of individual rock 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). Sometimes, riprap can be "tightened up" by tamping with a heavy plate or walking over it with a small bulldozer. Checking gradation and agreeing on adequate placement are difficult. Sometimes, it helps to put together a load of properly graded rock and leave it for reference to provide visual reference calibration. Another technique, when placement starts, is having the contractor place a test strip that both the inspection staff and contractor agree is satisfactory for future reference. Supplemental gradation checks might be made by the photogrid method in which a 10- by 10-foot aluminum pipe form containing a 1- by 1-foot grid of 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 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, to ensure a well-graded mass having no large voids.

- Riprap should be placed at low void ratio on the order of 0.35 or smaller. If weight tickets are available, the void ratio over a placement area can be estimated by using the mass tickets from each truck and the area of placement if the volume is considered a solid volume; the void ratio is determined by proportion of the solid volume and the actual mass volume. For example, assume an area 100 by 100 by 3 feet thick. Assume that the density of riprap is 160 lb/ft3 (or use the specific gravity of the rock). The solid volume is then 100 feet x 100 feet x 3 feet = 30,000 ft3. If the mass tickets equal 1,600 tons, then the in-place volume of the rock mass is 1,600 x 2,000 pounds/160 lb/ft3 = 20,000 ft.3. The void ratio is then 30,000 - 20,000/30,000 = 0.33. This method of computing the void ratio ensures a tight structure, but does not ensure good distribution of rock sizes.

- A bedding layer or layers that are designed as a filter must be provided between the embankment and the riprap to protect the embankment material from eroding by wave action and to provide a stable base for the riprap unless the underlying embankment meets filter criteria for the riprap.

Many riprap failures have occurred because the gradation of the bedding material did not have enough large particle sizes to preclude being sucked out through riprap interstices by wave action. Removal of the bedding causes settling and dislodgment of overlying riprap, further exposing bedding and embankment material to direct wave action. It is, therefore, necessary that bedding material meets specification requirements for gradation and layer thickness. It is good practice to place rock spalls[5] or crushed stone of like size between the bedding and the riprap if they are available from the quarry or required excavation. Use of rock spalls or equivalent crushed stone should be evaluated during design and should be specified if appropriate. In some cases, rock spall material may replace graded bedding material.

10.6.8.2.2 Soil-Cement

Soil-cement slope protection has been used on several Reclamation dams. Design Standard No. 13, Chapter 17, “Soil-Cement Slope Protection,” presents detailed requirements for design and construction of soil-cement slope protection. Plant-mixed soil-cement is usually spread using the stair step method of placement in 6 to 9-inch thick horizontal lifts along the slope in a strip that is 7 to 10 feet wide (depending on the slope angle and specified thickness perpendicular to the slope) and then compacted. The stairstep method of placement (figures 10.6.8.2.2-1 and 10.6.8.2.2-2) provides for placement of soil-cement in successive horizontal layers adjacent to the slope in a step-like profile. Sheepsfoot rollers, followed by rubber-tired rollers, have been used successfully to achieve adequate compaction.

[5] The term “spalls,” as used herein, refers to the finer materials resulting from rock excavation for materials such as riprap. Spalls must be durable fragments of rock that are free of clay, silt, sand, or other debris. The gradation of spalls will vary and must be specified for each particular job.

Figure 10.6.8.2.2-1 Warren H. Brock Reservoir, California. Placement of soil-cement on the interior embankment slopes using the plating method (top photo) and stair step method (bottom photo) of placement. USBR 2009

Figure 10.6.8.2.2-2 Warren H. Brock Reservoir, California. Final results of stair stepped soil-cement (top) and final results of plating soil-cement (bottom). Construction is on the interior slopes of the embankment . USBR 2009

More recently, smooth drum vibratory rollers have been used successfully and more efficiently. Design Standard 13, Chapter 17, "Soil-Cement Slope Protection," covers compaction in more detail. Control of cement content, water content, and uniformity of mixture are required, as well as density tests and measurement of both lift thickness and lift width. A rapid test for determining the cement content at the batch plant is the Heat of Neutralization test, ASTM D 5982. In the step method, each lift of soil-cement is cleaned to remove loose material and scarified using a power broom prior to placement of the next lift. In the past, a bonding agent consisting of dry cement or cement slurry has sometimes been required between successive lifts of soil-cement, but not by Reclamation. Design Standard 13, Chapter 17, "Soil-Cement Slope Protection," discusses this. Curing is important, and in dry climates, special measures may be needed to prevent drying of compacted layer surfaces.

On the Warren H. Brock Reservoir project, soil-cement slope protection was placed using both the step and plating method. The plating method provides for placement of soil-cement in one or more layers parallel to the slope face. Figures 10.6.8.2.2-1 and 10.6.8.2.2-2 show photographs of the plating operations and final results. Tracked smooth drum vibratory compactors were used on the 3H:1V slope to compact the soil-cement. Case histories indicate that plating soil-cement has been placed on 3H:1V slopes or flatter. It is unlikely that the compaction equipment can travel steeper slopes. Since the reservoir embankment and foundation consist of dune sand, the reservoir was lined with a geomembrane liner, which provides the water barrier. The 9-inch-thick soil-cement was placed on a geomembrane to protect the geomembrane from deterioration caused by sunlight and the actions of man. To prevent failure during rapid drawdown, a drainage layer was placed between the geomembrane and soil-cement. It was found that the top 2 inches of the soil-cement were "feathered" by the compactors. The second roller shown in figure 10.6.8.2.2-1 had a line of rubber-tired wheels in front, which were used to seal the surface of the soil-cement. Note that the dozer used to spread the soil-cement has a GPS system on the blade to ensure consistent lift thickness. Since sand cones were not available, nuclear gauges were used for density control.

10.6.8.2.3 Other Upstream Protection

Monolithic concrete, hand-placed riprap paving (grouted and ungrouted), and asphalt paving are other methods of protection for upstream slopes. These methods have been used infrequently by Reclamation.

10.6.8.3 Downstream Slope Protection

10.6.8.3.1 Grass Turf

Grass turf is usually specified for protection of downstream slopes of earth embankments in humid climates. The slope should be flat enough to enable reasonably easy mowing and maintenance. 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 inches, fertilizing, seeding or sprigging, compacting, watering, and maintaining as required to establish the turf. Temporary or permanent slope 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. The final surface should allow mowing to be reasonably accomplished.

10.6.8.3.2 Riprap

Riprap placed on the lower downstream slope to protect against wave action caused by tailwater should be controlled in the same manner as that discussed above for the upstream riprap.

10.6.8.3.3 Gravel, Cobbles, or Spalls

Gravel, cobbles, 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 raked to the outer edge of the embankment and used in the slope protection. In this case, it is desirable that placement of the downstream slope protection be kept 5 to 10 feet below the embankment placement. The gravel, cobbles, or spalls are usually dumped and spread in horizontal lifts along the outer slope to thicknesses of at least 1 foot measured normal to the embankment surface. If the downstream embankment is erodible (e.g., cohesionless sands), bedding may be required to prevent erosion. The bedding should be designed as a filter between the embankment and the spalls. An aesthetically pleasing surface can be obtained by placing and/or fine grading the material with a backhoe.

10.6.8.4   Surface Drainage

Surface drainage, both during construction and for future operations, can be important and should be considered during design of slope protection. Lateral drains across the embankment face are sometimes useful to break up sheet flow caused by runoff on the slope and collect the flow in a more controlled manner. Because surface runoff concentrates in the groins of the embankment, special slope protection may be necessary in these areas.

10.6.8.5   Access Roads and Benches

Access roads are often cut into the faces of embankment dams to provide access between the crest and the toe of the dam. This often makes access to the outlet works control features or other special areas more convenient. The width of the dam and the slopes are adapted to accommodate such roads. Type of surfacing (e.g., gravel or paving) must be considered for such roads. Benches are included in embankment slopes for a number of reasons including instrumentation access, interruption of surface flow, to increase embankment stability, etc.

10.6.9 Construction Stability

During construction, the stability of certain slopes, temporary or permanent, may be at risk. Excavations in clay can actually become less stable with time, which needs to be accounted for if they are left open for a significant period. Construction pore water pressures in impervious or semi-impervious zones of the embankment may be at a higher pressure than they will be at any other time during the life of the dam. Surface erosion and raveling may occur on slopes that will remain for a significant period, which may cause a decrease in slope stability. These conditions must be anticipated and analyzed by the designer(s) to ensure that all temporary slopes remain stable during construction and that the permanent dam slopes are stable at the end of construction of the embankment. During construction, the creation by the contractor of unforeseen slopes or other conditions, such as large stockpiles on the embankment or above cut slopes, should not be allowed until the embankment in the vicinity is analyzed for stability and creation of the unforeseen condition is approved by the designer. The necessity of these types of analyses should be conveyed to the PCE and PCE's staff before construction begins. Procedures presented in Design Standard No. 13, Chapter 4, "Static Stability Analysis," should be used to analyze the dam embankment during and at the end of construction.

Excavations in areas where there is limited room may require shoring or a combination of slopes and shoring, such as:

- Sheet pile walls
- Soldier piles and lagging
- Secant pile walls
- Timber sheet piling
- Other support systems

The designers should be aware of these areas and, for more critical support systems, design and specify the shoring. If the contractor designs them, he should be required to submit the design, drawings, and construction procedure for approval. Reclamation should review and approve the contractor-designed shoring systems, and the installation of the system should be closely inspected by both design and construction staff.

Instrumentation to monitor pore water pressures and for embankment movement (e.g., piezometers and inclinometers) should be included in the design, as appropriate, but should be held to the minimum necessary because its installation impacts construction and slows progress. Need for instrumentation within the impervious core of a dam is an especially critical consideration because installation construction techniques/requirements can be a danger to the integrity of the impervious zone, and the installation is especially detrimental to construction progress. These instruments can be installed by the contractor or by Reclamation staff. In either case, provisions should be included in the specifications for their installation and monitoring because they will impact the contractor’s operation. If drilling into the embankment is required for instrument installation, Reclamation drilling guidelines should be consulted. During construction, these instruments should be monitored on a regular basis to ensure that pore pressures are not exceeding safe values and that movement along any potential failure plane(s) has not initiated and, if so, is not excessive.

The instruments should be protected from damage caused by construction equipment. The construction of barriers to protect the instruments throughout construction will be necessary and should be specified. These barriers will have to be continually reconstructed as the surfaces of the embankment rise to higher elevations. Because heavy construction equipment cannot be used near the instruments, provisions for special compaction procedures around the instruments will need to be specified.

The installation, protection, and monitoring of the construction instrumentation will require cooperation among the designer, instrumentation specialist and construction staff, and the contractor’s staff, to ensure that the instrumentation is not damaged. Procedures presented in Design Standard No. 13, Chapter 11, “Instrumentation,” should be used to design, install, protect, and monitor the instrumentation system. The results from monitoring the instrumentation should be compared to the values that were anticipated during design to ensure that the embankment remains safe during and after construction.

10.6.10 Modification to Existing Dams

Recent history suggests that Reclamation dam design and construction are more likely to be related to the modification of an existing dam than to construction of a new dam. The information discussed above is applicable to modifications of an existing dam, as long as good judgment is applied in its use and proper care is taken not to cause damage to the existing dam by an improper understanding of the existing conditions at the site. For example, inadequate knowledge of existing seepage conditions at an existing dam might lead to an improper dewatering design and unnecessary damage to the structure during excavation into the embankment or its foundation. Reservoirs should be drawn down or otherwise managed during construction to provide more storage for floods and reduce seepage gradients to minimize construction risk. The designer should ensure that adequate investigation takes place and that geologic and engineering conditions at the site are adequately understood. A proper design can then be created, and the construction techniques discussed in this design standard can be confidently implemented.

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Appendix A

Reclamation Instructions, Chapter 4, Documentation of Foundation Acceptance for Dams

.1 General. Design Team acceptance of foundations for dams is required. Design Team representatives involved in foundation approval include the Principal Geologist, Branch Coordinator from D-3620, the Principal Designer, and the appropriate design division(s) Branch Coordinator.

After a significant portion of the foundation is exposed and geologically mapped, appropriate Design Team representatives are to thoroughly examine the foundation for conformance with design intent and determine any treatment necessary to prepare the foundation for fill or concrete placement. The Design Team representatives will prepare a Decision Memorandum on foundation acceptance referencing available maps, photographs, and/or video tapes. If required, the Decision Memorandum should contain stipulations concerning additional work that must be completed prior to fill or concrete placement.

The foundation acceptance process shall incorporate areas as large as practicable in order to reduce travel and paperwork, but shall be repeated as often as necessary to ensure that the design intent is accomplished for the entire foundation. Foundation acceptance by Design Team representatives should be based on first-hand knowledge, and therefore, cannot be delegated. However, during the process, the Principal Designer and Construction Engineer should develop a method whereby the Design Team representatives do not have to visually examine the foundation in its entirety, but can, where conditions are similar, base their approval on communication with the construction staff by means of telephone, photographs, video tapes, or geologic maps. The Design Team representatives must, however, physically visit the site frequently enough to fulfill their responsibility of ensuring that the conditions revealed by foundation excavation do not differ substantially from what was expected during design and that construction procedures will accomplish the design intent. Likewise, the Project Construction Engineer (COR) and staff must remain alert to site conditions and construction techniques that are different than anticipated during design and notify the Design Team.

.2 Documentation. Each foundation acceptance will be documented by a Decision Memorandum. The Memorandum will be signed by the Design Team members who are accepting the foundation. The Construction Engineer or a designated representative will sign the Decision Memorandum concurring that the foundation has been prepared and treated in accordance with the specifications and additional work identified in writing by the Design Team will be performed. If the acceptance of a foundation area is by telephone, the Foundation Acceptance Decision Memorandum will be the same except Construction Engineer concurrence will be obtained by telephone and so noted.

The Decision Memorandum shall be prepared before the Design Team members leave the project or immediately after foundation acceptance by telephone, and distributed to all interested parties within 2 working days. Copies will be sent to all involved Design Team members, the Construction Engineer, the Regional Director, ACER, and involved ACER Division and Branch Chiefs. Those who receive copies of the acceptance reports should immediately bring concerns, if any, to the attention of the Design Team.

After acceptance of the entire foundation for a new dam or existing dam modification, the Principal Designer should prepare a Foundation Acceptance Summary Memorandum. The Memorandum should summarize data from all Foundation Acceptance Decision Memorandums and verify completion of the foundation acceptance process. The Memorandum is addressed to ACER and routed through the line organization. Following ACER's approval, distribution of this Memorandum is the same as the other Decision Memorandums. Reservoir filling should not begin until ACER has approved the Foundation Acceptance Summary Memorandum.