

PART 5 – LARGE SCALE DENSITY AND GRADATION TESTS IN COMPACTED ROCKFILLS

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Part 1 summarized rockfill placement and compaction guidelines for mine structures, including dams and structure foundations. Part 2 provided an historical perspective to rockfill dam construction. Part 3 defined the difference between rockfill rock fragments versus earthfill soil particles. Part 4 described large scale test fill procedures for determining compacted rockfill lift thickness and compactive effort. Part 5 for this article is a follow up to Part 4 and presents suggested guidelines for verifying the test fill performance of compacted rockfills with large scale density and gradation tests.

INTRODUCTION

Modern day rockfill dam construction must rely heavily on past experiences for guidance pertaining to the placement and compaction of large rock fragments in a compacted fill structure. Special rock equipment and procedures are required for rock borrow development, hauling, placing, and compacting to produce a stable and acceptable engineered fill structure. The conventional earthfill test methods for controlling lift thickness, gradation, moisture content, and compaction are not applicable to rockfills and must be modified to a site specific compactive effort specification using test fills and large vibratory roller compactors.

This article includes guidelines for conducting large scale in-place field density and gradation record tests in the compacted rockfill to verify the test fill performance. Photos 1 and 2 show a borrow stockpile of sandstone and siltstone rockfill materials that can be selectively excavated for coarse to fine rock fragment sizes, moisture conditioned, hauled and placed with conventional earthmoving equipment. Photos 3 and 4 show a more rugged limestone rock borrow source that required drill and blast techniques for borrow development and separation of oversized rock fragments to the exterior highway fill slope. Photos 5 and 6 show dozer ripping and loading of fractured granite rock materials for stockpiling and reuse as compacted structural rockfill. Photos 7 to 12 show rockfill placement, roller compaction and typical large scale density and gradation record testing in the upstream shell of an earthfill and rockfill dam embankment.

Transitional rockfills approaching less than 30 percent rock materials retained on the 0.75 inch (19 mm) square mesh or more than 15 percent fines passing the No. 200 ASTM sieve size in the bulk gradation sample will have less rockfill and more earthfill

soil characteristics. Placement and compaction guidelines for these type of transition fill materials, that are similar to earthfill requirements, are excluded from this rockfill discussion.

ROCKFILL DENSITY AND GRADATION TESTS

General

Construction quality assurance (CQA) record tests are routinely conducted in compacted earthfill structures to verify that the soil particle material type, lift thickness, moisture conditioning and compaction meet the minimum required fill placement specifications. Large scale field density and gradation tests can also be conducted in compacted rockfill structures, but generally on a less frequent basis due the larger rock fragment sizes and the higher volume of rockfill sample materials required for accurate testing.

The most common methods to conduct in-place field density testing for soil particles are by the Sand Cone Method (ASTM D-1556) and by the Nuclear Method (ASTM D-2922 for shallow depth and ASTM D-5195 for nuclear probe depths below the fill surface). These field density test methods for earthfill soil particles become less effective or accurate as the amount and size of rock fragments increase from earthfill to rockfill materials.

This section includes a discussion on the limitations in the Nuclear Method density testing in rockfills, followed by the historic development of the more accurate rockfill testing techniques that have become the standard in current practice. The Nuclear Method density testing can be a fast and convenient tool in indicating the construction quality control (CQC) rockfill density, however techniques similar to the large scale density testing first developed by the Corps of Engineers in 1963 are the preferred method for more accurate construction quality assurance (CQA) density testing of rockfills.

Nuclear Method Rockfill Density Tests

General

The Nuclear Method density testing in rockfills is generally used as an indicator of CQC compactive effort and is not representative of the actual CQA rockfill density. Nuclear density testing can accelerate the time for conducting density tests in rockfills, however the machine readings overestimate the rockfill moist unit weight density due to several physical limitations in this type of density test method.

The physical limitations include the following: 1) preparation of the machine base and probe for testing within rockfills containing large rock fragments, 2) the relatively shallow effective depth of the machine measurements, 3) the orientation of the machine on the rockfill surface, and 4) the variation in recorded moist unit weight values due to the

distribution of rock fragment sizes and void spaces, as measured between the nuclear probe and the base of the machine.

Probe Surface Preparation

The base of the nuclear method machine with the nuclear probe retracted generally requires some surface preparation to firmly seat the machine bottom on a smoothed and leveled fill surface. Rockfill surfaces generally require placement of a thin layer of fine grained sand material to level any irregular rockfill surfaces and fill in rock fragment surface voids.

A steel rod is hammered into the rockfill to beyond the nuclear probe depth, then removed to create a vertical annular space for inserting the probe shaft into the test hole. Several attempts may be required to establish an open vertical test hole in rockfills comprised of large or hard rock fragments. This limits Nuclear Method testing to areas where smaller rock fragments have been placed or where the in-place rock fragments can be crushed and penetrated by the steel rod to create the open vertical probe hole.

Shallow Test Readings

The typical depth of the nuclear test probe is about 8 to 12 inches (200 to 300 mm) for taking readings that represent fill materials close to the base of the machine at about 6 to 8 inches (150 to 200 mm) in depth by direct transmission mode. Taking a nuclear test reading without extending the test probe into the fill lift will indicate surface density conditions at 4 inches (100 mm) or less by backscatter mode. In either case the surface materials have the most influence on the Nuclear Method moist unit weight readings due to the shorter distance for gamma rays to penetrate the fill between the probe source and the base of the machine. Compacted rockfill materials deeper than 12 inches (0.3 m) below the fill test surface would have minimal affect on the Nuclear Method test readings.

The Nuclear Method moist unit weight readings on the rockfill lift surface represent the compacted surficial materials, which are not representative of the overall moist unit weight rockfill lift density. Rockfill fragments on the surface of the compacted lift are generally crushed to finer sizes by dozer tracks and vibratory roller passes, which result in less void spaces compared to rockfill fragments in the lower portion of the same lift. Most rockfill loose lifts are placed in thicknesses greater than 18 inches (0.5 m), in which the lower rockfill materials in each lift are beyond the effective depth for the Nuclear Method density test readings.

Orientation of the Machine

The Nuclear Method testing in rockfills will generally show variable density readings in the same test hole, depending on the orientation of the machine on the compacted lift surface. The surface density variations are affected by the distribution of the larger rock fragment sizes in the surficial rockfill lift, as well as the amount of fine grained sand used to level and fill voids beneath the base of the nuclear machine for level readings on the rockfill surface. The amount of in-place rockfill disturbance from hammering and

penetration of the steel rod to displace and create the open probe test hole may also affect the density reading to a lesser extent.

A minimum of 3 readings are generally taken in the same probe test hole location on the rockfill surface with the machine rotated at 120 degrees between each test to determine an average moist unit weight density test reading. The average of 3 density readings in the same probe test hole provides a more representative value for the compacted rockfill fragments, however the readings only represent the surficial lift surface moist density conditions, as discussed earlier.

Moist Unit Weight Estimates

The technician takes an initial Nuclear Method moist unit weight reading, and then corrects the reading with an estimated moisture content for determining the in-place dry density of the rockfill. The moist unit weight can vary depending on the amount of drying or wetting on the rockfill surface prior to testing and the amount of material sampled and taken to the laboratory for determining the rockfill moisture content. The minimum required Nuclear Method reading time may extend from 1 to 4 minutes to reduce the machine error in measuring larger fragments and voids in the rockfill compared to earthfill materials.

The moisture content in a rockfill is generally estimated from the minus 0.75 inch (19 mm) fraction, as discussed later in this article. The accuracy of the moisture content correction is generally difficult to achieve without obtaining a significant sample amount of rockfill material from the field test location for representative moisture testing in the laboratory.

As a rule of thumb, the Nuclear Method density tests can be used as a quick CQC check or indicator of the rockfill compactive effort, however these CQC rockfill density tests should be confirmed with large scale density test methods described in this article for a more representative and accurate determination of the in-place rockfill dry density.

Historic Large Scale Rockfill Density Tests

The CQA rockfill density tests are typically required for each change in rock borrow source or each change in rockfill placement and compaction procedures or equipment. Each rockfill CQA record density test is also recommended to include a CQA record gradation test for comparison of changes in fill placement or materials during construction, as discussed in a separate section.

The earliest CQA rockfill density tests were first conducted by the Corps of Engineers (COE) on Cougar Dam in 1963. The rockfill tests involved the use of 4 to 6 ft (1.2 to 1.8 m) diameter metal rings placed on the rockfill surface and leveled for measurement of rockfill material weight excavated from the test hole. The test hole excavations were lined for measurement of the hole volume by water replacement techniques.

The large scale COE density and gradation tests typically involved excavating a minimum 0.75 cu yd (0.57 cu m) of rockfill material weighing about 1.5 tons (1.36 tonnes) or more. A backhoe was used to excavate rockfill material from the larger diameter steel rings, followed by hand excavation and removal of loosened materials from the excavation to expose the undisturbed compacted rockfill surface for water replacement testing.

Construction equipment and 4 to 6 technicians were required to place and level the steel ring, excavate the test hole, and weigh the rockfill materials taken from the test hole. The water replacement technique included lining and filling the steel ring to the top rim with a known weight of water before excavating the test hole. Then the ring lining and water were removed, followed by excavating and weighing removed rockfill fragments, and filling the lined test hole with a known weight of water to determine the combined ring and test hole volume.

Knowing the weight and density of water, the excavated test hole volume was calculated by subtracting the ring water volume from the total measured ring and test hole water volume. Knowing the weight of the excavated rockfill and the volume of the test hole, the moist unit weight density of the rockfill was determined. The excavated and weighed test hole rockfill materials were subsequently screened for determining the rockfill material gradation, as well as the moisture content of the finer rock materials for calculating the test hole rockfill dry density.

Modern Large Scale Rockfill Density Tests

General

The rockfill density tests should be of sufficient size to obtain reasonable test results without becoming so large that testing becomes prohibitive or causes delays in rockfill placement, awaiting completion the field and laboratory test results. The CQA rockfill record testing ideally should be completed within one day for engineering evaluation, as rockfill placement continues. An in-place field density and gradation quality assurance record test is recommended to verify established rockfill placement and compaction procedures and design assumptions.

Smaller diameter rings have been successfully used by this author on several rockfill tailings dams in California, Nevada, South Dakota and Washington in the 1980's and 1990's to give reasonable and consistent rockfill dry density test results under the following conditions: 1) the diameter of the ring is at least four times the maximum rock fragment square mesh size excavated from the test hole, 2) the rock borrow source does not significantly change (rock fragment strength, fracture pattern, rock size distribution when excavated, etc.), and 3) the fill placement procedures for moisture conditioning, lift thickness and compaction effort remain the same. The measured rockfill dry density under these conditions was found to vary by less than 5 percent over an 8 month construction period on a rockfill dam project in Southern California. The large scale density and gradation tests were conducted on a monthly basis in the active

rockfill lift. The majority of these rockfill dry density test results varied by less than 2 percent.

A 3 ft (910 mm) diameter ring was used to excavate 2.5 to 3 ft (760 to 910 mm) deep to remove up to 1.5 tons (1.36 tonnes) of minus 8 inch (200 mm) square mesh size material for bulk density and gradation testing. Note that this includes rock fragments placed at greater than the 8 inch (200 mm) square mesh screen size, provided the rock is crushed in-place to an 8 inch (200 mm) or smaller size during dozer seating and roller compaction.

The manpower typically consisted of 1 engineer and 1 field technician to conduct the density and gradation tests over a time period of about 8 to 12 hours. The plus 0.75 inch (19 mm) square mesh rock sizes were screened and weighed in the field on fabricated screens to the maximum rock size excavated from the hole. A representative sample of the minus 0.75 inch (19 mm) test hole material was taken to the field laboratory for completing the gradation, moisture content and dry density tests and calculations. The smaller allowable ring size and amount of materials required for accuracy in density testing significantly reduced the equipment, manpower and time for rapid evaluation of the rockfill placement and compaction procedures, as discussed in more detail below.

Selection of Test Hole Limit

The target excavation limits for the large scale density test should include both a minimum vertical depth of at least 1 complete rock fill lift thickness and a circular diameter of at least 4 times the maximum square mesh rock size excavated from the density test hole. The testing can be conducted in a test fill area within or outside of the active rockfill placement limits on a relatively level compacted surface area.

The large scale density tests are suggested to be conducted where at least 5 ft (1.5 m) of rockfill has been placed and compacted. This allows for excavation through a single or multiple lifts for an overall density that is representative of the entire rockfill lift thickness. The optimum compactive effort for each lift is determined from the test fill settlement versus roller pass curve discussed in Part 4 of this rockfill series.

Excavation of Test Hole

Prior to the bulk density test, the ring must be leveled to within the thickness of the ring and firmly secured to prevent movement during excavation. The ring is generally constructed from a hole cut out of a minimum 0.75 inch (19 mm) thick plywood sheet. Fine grained sand material is placed on the rockfill surface directly beneath the ring area to level, seat, and firmly support the ring. Nail spikes are driven through four corners of the plywood sheet to secure the ring to the fill material.

A water replacement test is then conducted with 6 to 10 mil (0.15 to 0.25 mm) flexible synthetic liner to determine the volume of the ring above the uneven rockfill surface (rockfill surfaces are generally like a cobblestone surface following compaction). Then the liner and water are removed beyond the test area for the start of careful hand

excavation and weighing of each rockfill fragment removed from the test hole. The weighing scale is generally placed inside of an enclosed vehicle and calibrated, as needed to minimize any field testing error in measuring due to wind disturbance.

The field engineer or senior technician generally excavates the density test hole by hand, while a second technician weighs and records each bucket of excavated material and subtracts the known bucket weight. The second technician screens the plus 0.75 inch (19 mm) rock on each selected screen mesh size to the maximum rock size. Rock materials retained on each screen are weighed and recorded for calculating the bulk gradation. Rock fragments larger than gravel sizes are generally screened through fabricated square rebar or heavy gauge wire screen square openings at 2 inch (50.8 mm) intervals starting with 4 inch, 6 inch, 8 inch, and so forth.

The hole is examined during excavation to observe the following: 1) general tightness of the fill, 2) in-place compacted lift thickness, 3) seating and crushing of rock from top to bottom of each lift, 4) rock to rock contact, 5) rock to soil matrix condition, 6) moisture uniformity and 7) other indicators of the effectiveness of roller compaction on the rock type and rock fragment sizes for the lift thickness placed.

Water Replacement Volume

After final excavation and examination of the test hole, the flexible liner is again placed in the hole to above the ring level for water replacement volume determination. The liner is kept in a slackened condition to prevent bridging across pockets on the excavated fill surface wall, as measured and weighed buckets of water are carefully poured into the lined test hole.

The 6 to 10 mil (0.15 to 0.25 mm) liner thickness allows enough flexibility and strength to seat against the undisturbed rockfill walls under 3 ft (0.91 m) of water head without puncturing. By carefully weighing the rockfill material removed and water added to the hole, and calculating the total volume of hole less the ring volume, the in-place moist weight rockfill density is determined.

Fine Rock Gradation

The rock fragments larger than 0.75 inch (19 mm) for bulk gradation testing are measured and weighed by hand in the field for discarding. The minus 0.75 inch (19 mm) material is generally screened on a tarp or liner and can be accurately split and quartered by ASTM procedures to about 30 to 40 lb (13.6 to 18.2 kg) of representative material for removal to the laboratory to complete the gradation. Reducing the gradation sample size for the finer rock and soil materials and discarding the larger rock fragments as soon as practical allows quicker completion of the testing within acceptable test standards and accuracy. As an example of test sample size, the excavated rockfill test holes for minus 8 inch (200 mm) maximum mesh screen rock sizes produce about 1,500 to 2,000 pounds (681 to 908 kilograms) of rockfill material for gradation testing.

A portion of the split and quartered minus 0.75 inch (19 mm) material is placed in moisture proof containers for determining moisture content in the laboratory. A representative split sample of about 2,000 grams is sufficient for the minus 0.75 mm (19 mm) moisture content and is split and quartered again in the laboratory for determining the gradation of the sand size and smaller soil fraction.

Rockfill Moisture Content and Dry Density Determination

The moisture content of the plus 0.75 inch (19 mm) rock material is generally negligible, so that a dry in-place rockfill density can be computed knowing the moisture content of the minus 0.75 inch (19 mm) material fraction. This can be computed as shown in Equation 1 below.

$$\text{Bulk Density Dry Weight} = W / (1 + (M/100 \times A/100)) \quad (\text{Eq. 1})$$

Where:

W = Total moist weight of rockfill material

M = Moisture content on minus 0.75 inch (19 mm) fill material in % by weight

A = Amount of minus 0.75 inch (19 mm) moist fill material in % of total moist weight.

For example: 1,500 lb (681 kg) of excavated fill material from the bulk density test at 40% minus 0.75 inch (19 mm) material and 15% moisture content has a bulk dry weight of 1,500 lb divided by $(1 + (0.15 \times 0.40)) = 1,395$ lb (633 kg) dry weight. This dry weight is divided by the measured volume of the hole for computing the in-place dry density of the rockfill.

For plus 0.75 inch (19 mm) rock fragments containing some moisture (as in the case of weathered rock, claystones, wetted porous rock, high absorption rock fragments, etc.), air or oven drying of a representative 50 lb (22.7 kg) minimum sample of plus 0.75 inch (19 mm) rock fragments is recommended for determining the overall moisture content and dry density. This can be computed as shown in Equation 2 below.

$$\text{Bulk Density Dry Weight} = W / (1 + (M1/100 \times A1/100) + (M2/100 \times A2/100)) \quad (\text{Eq. 2})$$

Where:

W = Total moist weight of rockfill material

M1 = Moisture content on minus 0.75 inch (19 mm) fill material in % by weight

A1 = Amount of minus 0.75 inch (19 mm) moist fill material in % of total moist weight

M2 = Moisture content on plus 0.75 inch (19 mm) fill material in % by weight

A2 = Amount of plus 0.75 inch (19 mm) moist fill material in % by weight.

For example: 1,500 lb (681 kg) of excavated fill material from the bulk density test with 40 percent minus 0.75 inch (19 mm) material at 15 percent moisture content and 60 percent plus 0.75 inch (19 mm) material at 5 percent moisture content has a bulk dry weight of 1,500 lb divided by $(1 + (0.15 \times 0.40 + 0.05 \times 0.60)) = 1,376$ lb (625 kg) dry weight for computing the in-place dry density of the rockfill.

Guidelines for Rockfill Placement and Compaction

General

The modern day large scale rockfill test procedures have been successfully used on several large rockfill tailing dam projects in California, Washington, Nevada, and South Dakota to establish a basis for determining the placement and compactive effort procedures, and verify assumed design densities for slope stability analyses. The rockfill embankment heights varied from 80 to 470 ft (24 to 143 m), averaging 250 ft (76 m) in height.

The rockfill roller pass versus settlement curves, bulk density, and gradation test results from test fills allow the engineer to correlate similar rock material types, roller compaction equipment, placement and compaction procedures for comparison purposes and for determining acceptable rockfill performance. Based on rockfill construction experience and test fill results, a general set of guidelines can be established for rockfill placement and compaction, as discussed below.

Lift Thickness:

Maximum loose lift thickness is governed by maximum rock size and type of compaction equipment. Rock segregation in the thicker lifts may also limit the practical lift thickness for the particular rockfill borrow materials available for construction. Optimum rockfill loose lift thicknesses are generally about 18 to 30 inch (0.5 to 0.8 m) with maximum rock sizes limited to two thirds of the lift thickness. Larger rock sizes can be incorporated into the fill provided the rock does not protrude above the fill surface to hinder compaction.

Lifts approaching or exceeding 3 ft (1 m) are generally beyond the effective rockfill compaction limit of conventional 10 to 20 ton vibratory steel drum rollers commonly used on modern day rockfill dams. Acceptable compaction can be achieved by the heavy vibratory rollers in combination with loaded rock haul trucks in the 3 to 5 ft (1 to 1.5 m) lift thickness range. The depth of compaction for large haul trucks loaded with more than 240 tons (218 tonnes) of mined rock material can approach 10 ft (3 m) in lift thickness, however large scale field density test experience indicates most of this compaction will be occurring in the upper half of these thicker rockfill lifts with limited compaction in the lower portion of the lift.

Haul truck compaction is limited to the interior of the dam fills (away from exterior slope edges) for safety reasons. The exterior edges of the rockfills are compacted by the smooth drum vibratory rollers with a typical 3 ft (1 m) setback or inward graded fill surfaces to maintain safe compaction conditions along the outer edge of the fill. Thicker rockfill lifts can be allowed in the interior of dam depending on stability strength and allowable post-construction settlement requirements by the engineer.

Roller Type:

Experience indicates the most efficient rockfill compactors are vibratory steel drum rollers with vibrations in the range of 1200 to 1500 vpm, roller speed of about 2 mph

(3.2 km/h), a minimum static drum weight of 8 tons on level ground, and a minimum operating dynamic force of 15 tons (13.6 tonnes). Self-propelled rollers are the most maneuverable, especially at abutment contacts, for better coverage and compaction compared to rollers pulled by tractors.

Vibratory rollers are effective in the forward direction; which produces the maximum downward force from eccentric rotating shafts in the drum. Modern self-propelled double-drum and single-drum rollers generally can reverse the rotating shaft for maximum compaction in the forward and reverse direction without having to turn around at the end of each pass.

Roller Passes:

Optimum roller passes are determined from surveyed settlement versus roller pass curves developed in test fills. The general limit is between four to six passes. More than six passes tends to crush and pulverize the rockfill surface without adding significant compaction to the lower part of the lift. Each roller pass should overlap the edge of the preceding passes by about 1 ft (0.3 m) for 100 percent roller pass coverage on the surface.

As a general "rule of thumb", the acceptable number of roller passes should be set at 80 percent of the total surveyed settlement in eight passes on a test section. The average settlement of at least five survey control points should be used to determine the acceptable number of passes.

Gradation:

Rockfills for compacted dam structures are generally placed in transitional zones with the most coarse and competent rock fragments placed in the outer shell and finer more weathered rock fragments placed laterally in the interior or adjacent to earthfill filter drain and low permeability core materials. A similar vertical rockfill transition zone is placed beneath structure foundations like highways and leach pad sites with the finer rock materials placed above the more coarse rockfill materials to minimize differential subgrade settlement.

Well-graded rockfills with small voids tend to increase the in-place density and provide a stable mass for minimizing post-construction settlement. Poorly graded rockfills with large voids are sometimes desirable on the upstream shell for drainage during reservoir rapid drawdown conditions and in spillway areas for erosion protection and energy dissipation.

Riprap on reservoir slopes is generally the most durable and clean rock available. The larger-sized riprap rock fragments are typically seated into a bedding of smaller-sized clean rock. Angular rock fragments are preferred over rounded rock fragments for interlocking and support of the riprap structure against wave action.

Oversized rock fragments are generally placed on the downstream slope or in downstream outlet/spillway plunge pools for erosion and energy dissipation purposes.

Occasional extremely large oversized rock fragments can be incorporated into rockfills provided no overhangs occur and the surrounding rockfill is compacted against the larger rock fragments, similar to compaction techniques against the rock abutments. Phased downstream raises to existing rockfill dams can incorporate the new rockfill into the oversized rock on the downstream slope of the existing dam, provided the large rock fragments are not clustered or require filter control near the core zone.

Moisture Conditioning:

In the past, rockfills were dumped in thick loose lifts of typically 35 to 165 ft (11 to 50 m) and flooded with water to consolidate the rockfill to about 85 percent of its total settlement. Modern rockfills are placed in thin controlled lifts and compacted with vibratory compactors so that moisture conditioning requirements are not as critical to minimize post-construction settlement (see Overbuild below).

Wetting is generally accomplished on the fill area, unless water trucks have access to the rock borrow area. As with earthfill materials, moisture conditioning is desirable in the rock borrow areas for better mixing of moisture and materials during excavation, loading, dumping, and spreading for compaction. However, development of rock borrow areas involves blasting or ripping operations that sometimes make the borrow surface too rugged for conventional water trucks with spray bars.

Ideally the rock borrow should be sufficiently wetted so that no dust occurs, when the haul truck or scraper equipment dumps a load on the fill surface for spreading and compacting. Wetting of the rockfill in the fill area should be accomplished prior to spreading the new lift or following compaction of the lift. Wetting immediately prior to compaction by vibratory rollers significantly dampens the dynamic force of the compactor for inefficiency in compaction. The exception to this rule is a clean rockfill, which can be flooded with water and rapidly drained before compaction begins. Another option for overly dry rockfills containing some finer fraction rock and soils (assuming water truck access is difficult or not practical in the borrow) is to thoroughly drench the loose lift, scarify with dozer rippers, and level with a dozer blade for compaction.

An ideal rockfill moisture content contains minus 0.75 inch (19 mm) materials that appear near optimum moisture, not overly wet or overly dry, for enhanced vibratory compaction. Wetting before placement of each new lift is encouraged to provide bonding between successive lifts without the need to scarify the compacted rockfill surface. There is no need to scarify compacted rockfill surfaces provided the surface consists of clean rock or is moist.

Overbuild:

Modern day compacted rockfills that are relatively well graded show minimal post-construction settlements of the order of 0.2 ft per 100 ft (0.2 m per 100 m) of height at the dam crest from this author's experience and literature review.

For compacted large earth-rockfill dam structures with a relatively thin central core or upstream earthfill core and impervious liner facing, about 0.5 ft (0.15 m) crest overbuild

per 100 ft (30 m) of dam height appears conservative. For large compacted earth-rockfill dams with relatively thick central earthfill cores, about 1 ft (0.3 m) minimum crest overbuild per 100 ft (30 m) of dam height is reasonable to counteract the long-term consolidation of core materials (post-construction dissipation of excess pore water pressures in fine-grained core materials).

SUMMARY

Large scale test fills are generally conducted at the startup of rockfill placement using fill construction equipment at the site for verifying rockfill dam construction quality assurance performance. The test fills confirm design guidelines for rock quality, moisture control, lift placement and compaction requirements using the available rock borrow materials at the site. Additional test fills are conducted during construction, depending on any changes in rock borrow materials or equipment and placement procedures for acceptable compaction.

The large scale rockfill density and gradation tests can generally be limited to about 1 day of testing time with 1 field engineer or senior technician assisted by 1 technician for measuring excavated material and water replacement buckets, and to complete the laboratory gradation testing. The typical diameter size for the test hole ring should be 4 times the excavated maximum square mesh rock size for acceptable test accuracy. The typical test hole depth should extend through the entire rock fill lift, or through multiple lifts if practical, to account for the overall change in effective roller compaction with depth.

Water replacement techniques are used to determine the volume of the lined test ring and excavated and lined test hole. The excavated test hole material is weighed and test hole volume calculated to determine the moist unit weight rockfill density. Moisture content is generally determined on the finer minus 0.75 inch (19 mm) square mesh rock fraction for calculating the rockfill dry density. Some rockfills may require moisture content measurements in the larger weathered or moisture absorbing rock fragments, as needed.

Bulk gradations include measuring the larger plus 0.75 inch (19 mm) rock fraction in 2 inch (50.8 mm) square mesh increments for discarding. The minus 0.75 inch (19 mm) rock fraction can be accurately quartered and split by ASTM procedures to reduce the amount of finer rock materials for ease in completing the gradation testing.

Background rockfill information related to the modern day rock fill placement and testing procedures are presented in Parts 1 to 3 of 5 rockfill articles by this author. The test fill settlement versus roller pass compaction curves presented in Part 4 of 5 supplement the large scale rockfill density and gradation tests discussed herein (Part 5 of 5) for recommended construction quality assurance (CQA) record testing.



PHOTO 1 – ROCKFILL BORROW STOCKPILE WITH SOME ROCK SEGREGATION SHOWN ON EXTERIOR SLOPES



PHOTO 2 – SMALLER ROCKFILL FRAGMENTS AT TOP OF BORROW STOCKPILE TRANSITIONING TO LARGER ROCKFILL FRAGMENTS AT BOTTOM



PHOTO 3 – ROCK BORROW DEVELOPMENT IN HIGHWAY CUT USED DRILL AND BLAST TECHNIQUES TO EXCAVATE AND REMOVE ROCKFILL MATERIALS



PHOTO 4 – HIGHWAY FILL SLOPE SHOWS AN UPWARD TRANSITION FROM ROCKFILL TO EARTHFILL MATERIALS FOR HIGHWAY SUBBASE



PHOTO 5 – ROCK EXCAVATION USING A DOZER WITH SINGLE RIPPER TOOTH



PHOTO 6 – RIPPED AND DOZED ROCK MATERIALS LOADED INTO HAUL TRUCK



PHOTO 7 – ROCKFILL PLACEMENT ON UPSTREAM FACE OF 470 FT (143 M) HIGH EARTH AND ROCKFILL TAILINGS DAM



PHOTO 8 – HAUL TRUCK DUMPING MINUS 1 FT (0.3 M) TYPICAL ROCKFILL FRAGMENTS FOR DOZER PLACEMENT AND VIBRATORY ROLLER

COMPACTION



PHOTO 9 – PREPARATION FOR ROCKFILL DENSITY AND GRADATION TEST USING A 3 FT (0.9 M) DIAMETER RING (NOTE OVERSIZED ROCK ON SLOPE)



PHOTO 10 – WATER REPLACEMENT TEST WITH FLEXIBLE GEOMEMBRANE

LINER IN DENSITY TEST HOLE TO DETERMINE EXCAVATED ROCKFILL VOLUME



PHOTO 11 – SEPARATION OF MINUS ¾ INCH (19 MM) SQUARE MESH SOIL PARTICLES FROM LARGER GRAVEL AND COBBLE SIZED ROCK FRAGMENTS



PHOTO 12 – ROCKFILL GRADATION TEST SHOWN IN FOREGROUND AND