INFOMINE E-BOOK

Rockfill For Mines

By

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INTRODUCTION

Modern day rockfill construction must rely heavily on past experiences for guidance in determining acceptable procedures for the placement and compaction of large rock fragments in a compacted fill structure. The conventional earthfill field and laboratory 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 large-scale test fills and heavy vibratory roller compactors.

Based on rockfill construction experience and engineering studies on several large-scale test fills (Breitenbach 1993), a general set of guidelines can be established for rockfill placement and compaction as discussed below. Typical rockfill placement and compaction operations, as well as large scale rockfill density and gradation testing are shown on photos 1 to 7 below.

Photo 1: Rockfill raise construction on 120 m (400 ft) high dam

Photo 2: Upstream rockfill facing to raise existing tailings dam

Photo 3: 0.5 m thick rockfill lift placement by haul truck and dozer

Photo 4: Fill lift compaction with steel smooth drum vibratory roller

Photo 5: 1 m diameter plate for large scale rockfill bulk density test

Photo 6: Water replacement test in hand excavated and lined hole

Photo 7: Bulk gradation test on excavated rockfill materials

HISTORY OF ROCKFILL DAM CONSTRUCTION

First Milestone

Rockfill materials have been used in dam construction since ancient times. However, modern day rockfill dam construction essentially originated in California about 160 years ago during the mining gold rush era. Drill and blast mining techniques by miners provided an abundant supply of rock materials for use in dam construction. Gold mining in the 1850's also required a large and steady supply of water for sluicing and extracting the heavier gold nuggets from alluvial placer deposits. The miners used the rock quarry materials to construct water storage dams in remote areas by hand or with available mine haul and dump equipment.

The early rockfill dams were small and generally consisted of a single lift of loosely dumped rockfill with an upstream timber facing to retard seepage. The downstream slope was typically at the natural angle of repose approaching 1.2 horizontal to 1.0 vertical (1.2H:1V). The upstream slope was sometimes hand shaped to as steep as 0.75 horizontal to 1.0 vertical (0.75H:1V) for the timber facing.

One of the highest dumped rockfill dams constructed in the California Sierras during this early gold mining era was the Meadow Lake dam at 75 feet (23 m) high. The upstream slope was constructed to 0.75H:1V with the crest freeboard area at 0.5H:1V using hand placed rocks to maintain the face slope during rock dumping. The downstream slope was constructed to 1H:1V in the lower section and hand shaped to 0.5H:1V in the upper section similar to the upstream facing.

Second Milestone

The second milestone covers the time period from the 1910's to 1940's in which rockfill dump water storage dams began to exceed 100 feet (30 m) in height. The "dry rock dump" technique in rockfill dam construction developed into the placement of thick single or multiple rockfill lifts in combination with relatively low permeability upstream facing materials (timber, steel, concrete, or asphaltic concrete). One of the highest dry rock dump dams in this time period was the Salt Springs Dam in California at 328 feet (100 m) in height.

The unprecedented water storage dam heights for rock dumps constructed in thick dry loose rock lifts at the angle-of-repose was possible because the rockfill dams remained stable with no slope failures. However, the larger dams were beginning to experience seepage problems on the upstream facing due to post-construction settlement movements.

The dry rock dump dams experienced undetermined self-weight settlements during construction loading and large observable post-construction settlements during initial reservoir filling. The post-construction settlements appeared to be directly caused by hydraulic loading on the upstream facing. This in turn caused some differential movement of the relatively rigid facing materials and leakage along separated facing panel joints.

Additional settlements may have occurred from subsequent wetting of the dry rockfill due to facing leakage or abutment foundation seepage. The post-construction wetting action increased the total moist unit weight of the dry and fully drained rock dump mass. Repair of facing leaks during reservoir operations was expensive and involved underwater repairs or reservoir drainage.

Third Milestone

The third milestone covers the time period from the 1940's to 1950's in which the dry rock dump placement continued, except the dry and loose rockfill lifts were wetted to promote self-weight settlement during construction of the larger rockfill dams. The 1940's also included the first use of earthfill core and filter materials in the interior section of the rockfill dams.

Rockfill dam heights began to exceed 300 feet (100 m) in the 1940's to more than 500 feet (152 m) in the 1950's. High-pressure jet wetting or irrigation flooding techniques were developed on the dry rock dump surfaces to consolidate and reduce large post-construction settlements to acceptable levels. Thorough wetting during construction reduced typical post-construction rockfill dam settlements from 5 to 7 percent without wetting to about 1 percent with wetting, thus reducing leakage and repair costs.

Prior to 1955, the loose rock dump lifts for in-place wetting or flooding typically ranged from 35 to 165 feet (11 to 50 m) in loose lift thickness with the maximum known rock dump lift placed at 200 feet (61 m). After 1955, the dry rock dump lift placement was modified on some dams to thinner lifts to incorporate the use of weaker rockfill materials in dam construction (weathered rock or poor quality rock materials that were locally available at the dam sites). The thinner rockfill lifts also reduced rock segregation, where larger sized rocks tend to roll to the bottom of the lift during dumping and dozing operations. Rock segregation in a dumped fill slope can be seen in photos 8 and 9 below, where boulder-sized rocks to 3 feet (0.9 m) in diameter rolled to the bottom of a 45 feet (15 m) thick dry rock dump lift composed primarily of sand, gravel and cobble sized fill material.

Photo 8: Rock dump loose lift placement in 45 ft (15 m) thickness

Photo 9: Rock segregation with boulders at bottom of rock dump lift

By the late 1950's, the rock dump lift thickness on several large dams was reduced to 10 to 12 feet (3 to 4 m) thick with the top surface leveled and tracked by dozer passes and loaded haul truck traffic. This type of lift construction thickness and equipment provided a limited amount of compaction effort in the upper half of the loose lift with the lower half remaining relatively loose and uncompacted.

No rockfill water storage dam failures occurred for both the earlier "dry" and subsequent "wet" rockfill dumps. However, there was growing concern for the stability of large rockfill dams in more populated areas with the limited amount of engineering knowledge about rockfill strengths and the lack of established rockfill placement and test control procedures. This concern led to a rapid change in rockfill dam construction by the late 1950's, after 110 years of relatively successful rock dump fill construction.

Fourth Milestone

The fourth milestone covers the time period from the 1960's to the present day in which rockfill construction changed from wet rock dump placement in relatively thick loose lifts to compacted rockfill placement in relatively thin controlled lifts for heavy roller compaction. The wet rock dump technique was essentially discontinued by 1965 on large rockfill dams around the world.

The current maximum compacted rockfill dam height is 800 feet (243 m) for the Alberto Lleras Dam constructed in 1989 in Columbia. Other compacted earth and rockfill dams are under construction to greater heights, including Tehri Dam in India at 853 feet (260 m) high and Rogun Dam in Tadjikistan at 1,100 feet (335 m) high. The highest compacted earth and rockfill dam in the USA is the New Melones Dam in California at 627 feet (191 m) high.

Compacted rockfills in the late 1950's into the early 1960's utilized dozer track passes, controlled routing of loaded haul truck equipment, or the use of heavy steel drum or pneumatic rubber tired roller passes for compaction. Rockfill loose lift thicknesses for compaction varied, but generally were in the range of 3 to 10 feet (1 to 3 m) in thickness. The movement away from rock dump techniques toward controlled thinner rockfill lifts

and compaction improved the rockfill density and strength, as well as further reducing the post-construction settlement movements.

Large scale engineering test fill studies by the US Army Corps of Engineers and US Bureau of Reclamation in the early 1960's confirmed better compaction by heavy steel drum vibratory rollers compared to non-vibrating heavy pneumatic rubber-tired or steel drum rollers. Large scale test fill lift thicknesses for the early studies varied from 1.5 to 3 feet (0.5 to 0.9 m). The vibratory roller static steel drum weight for the study was 10 tons and the pneumatic rubber-tired roller static weight was 50 tons.

The vibratory roller compactors are a relatively new concept in compacted rockfill construction, having been developed within the last 50 years. The tractor-pulled rollers began to change to self-propelled rollers in the 1970's for improved rockfill lift compaction, particularly at the dam abutments.

Single and double drum rollers with static drum weights of 8 to 20 tons are typical for use in modern day compacted rockfills. Rockfill materials are moistened in the borrow or fill area, if required, and compacted under fully drained conditions. Water storage dam rockfill loose lift thicknesses are generally less than 5 feet (1.5 m) for the 10 to 20 ton static smooth steel drum weight vibratory rollers with well compacted rockfill loose lift thicknesses placed in the 2 to 3 ft (0.6 to 0.9 m) range, particularly in the high earthquake seismicity areas of the world.

ROCKFILL VERSUS EARTHFILL MATERIAL

HISTORIC DEFINITION OF ROCKFILL MATERIAL

In 1952, the United States Bureau of Reclamation (USBR) and the Army Corps of Engineers (COE), with Professor Arthur Casagrande as consultant, developed the Unified Soil Classification System (USCS). This classification system is used extensively world-wide to the present day for soils, but excludes rock particles larger than the 3 inch (76.2 mm) square mesh screen size.

In a 1960 symposium on rockfill dams sponsored by the American Society of Civil Engineers (ASCE), a rockfill dam was defined as "one that relies on rock either dumped in the lifts or compacted in layers as a major structural element." Rockfills at that time were either placed in a single thick lift without compaction or placed in typical 3 to 5 feet (0.9 to 1.5 m) thick lifts and compacted by dozer tracks or large non-vibrating steel drum and pneumatic rubber-tired rollers. The single rock dump lifts, typically of the order of 35 to 165 feet (11 to 50 m) in height, were generally flooded with water at two to four times the rock pore volume to consolidate the fill to about 85 percent of its total self-weight settlement.

Limited information was available at that time on defining rock sizes for use in rockfill construction or establishing engineered procedures for placement and compaction. Large-scale in-place bulk gradations were not performed on the rock dump fills, and the gradation limit between rockfills and earthfills remained undefined.

In 1963, Sherard et al, published Earth and Earth-Rock Dams, which classified dams primarily constructed of rockfill with thin clay cores as "earth-rock" dams. The term "rockfill dam" described embankments constructed wholly of rockfill materials with an upstream impervious facing.

Visual Rock Gradation Estimates

Visual rock gradation estimates were conducted by the engineers in the field using measured grid patterns or other types of visual aids for determining maximum, average and minimum rock sizes. The rock fragment sizes were estimated either by volume or by weight.

The visual gradation estimates were generally not used in early rock dump dam construction, where the large rock fragments in the thick loose lifts were physically impractical to test. In addition to variations in the quarried large rock borrow material sizes, the rock dump fill material sizes varied from top to bottom on the advancing dump slopes due to material segregation. Rock segregation occurred along the front face of the advancing rock dump lifts with the larger rock fragments rolling to the bottom of the relatively high lifts. The segregation of fine rock material sizes at the top to coarse rock material sizes at the bottom of the thick lifts made it difficult to determine a representative gradation size for the overall rockfill lift thickness. An example of rock segregation on stockpile can be seen in Photo 10.

Photo 10: Rock segregation on stockpile

Large rock fragments were also used for dam embankment upstream slope protection and spillway channels. Selective borrow rock quality and sizing in combination with controlled placement of thinner fill lifts made visual gradation estimates for these type of less segregated rockfill structures more approximate.

The visual gradation estimates by volume were generally specified as the largest and smallest permissible rock fragment sizes in cubic yards or cubic feet (cubic meters). The visual gradation estimates by weight were generally specified as D_{85}, D_{50} and D_{15} sizes representing the rock size by dry weight passing 85, 50 and 15 percent of the total rock sample dry weight, respectively. As an example, the D_{50} size represents the estimated rock fragment size at which half of the total sample dry weight is larger or smaller than the rock size determined by visual gradation estimates or by large-scale bulk gradation testing as 50 percent.

The transition from rock dumps to compacted rockfills reduced the lift thickness and limited the maximum rock fragment size allowable for controlled lift placement and compaction. By the late 1950's the more controlled rockfill lifts made it possible to physically conduct large-scale gradation tests on the compacted rockfills.

Early Rockfill Gradation Tests:

By the late 1950's, rock dump construction in thick lifts was changing to thinner rockfill lifts leveled by dozers for tracking the surface or for loaded haul truck and heavy rubber-tired roller compaction. The earliest reported large-scale rockfill gradation tests were being conducted on these types of rockfills by 1959.

In 1963 and 1964, the Army Corps of Engineers first experimented with vibratory roller compactors on test fills at Cougar Dam, a 445 feet (136 m) high earth and rockfill dam near Eugene, Oregon. Large-scale bulk gradation tests were conducted along with other testing to evaluate the performance of the compactors. Prior to this time period, a limited mount of large-scale gradations had been performed on other rockfill dams.

The large-scale test fill gradations for the first time established a basis for defining rockfill materials according to measured rock fragment screen sizes, rather than by visual estimations. The large-scale screen mesh gradations are significant from the standpoint

that geotechnical engineers, from this author's experience, have a tendency to over estimate the visual size of rock fragments in a rockfill. As an example, an elongated rock fragment can be more than 12 inches (0.3 m) in length and yet pass through a 6 inch by 6 inch (0.15 m by 0.15 m) square mesh screen opening, therefore classifying the fragment as a minus 6 inch (0.15 m) rock fragment.

Another error that commonly occurs in visual rockfill gradation estimates is to under estimate the percentage of large rock fragment sizes to small earthfill particle sizes by dry weight passing a given screen size. A rockfill can appear visually to have a larger percentage of clay, silt, sand or fine to medium grained gravel earthfill materials versus larger coarse gravel, cobble and boulder rockfill sizes. However, if a large-scale gradation test is conducted on a bulk sample of the material, the test results by dry weight passing the various square mesh screen sizes will generally show a larger percentage of rockfill to earthfill materials, when compared to the visual estimate.

USBR Rock Definition:

In 1968, the USBR published the Earth Manual, which further defined cobble and boulder rock particles as follows: "Rounded particles are called cobbles, if they are between 3 and 12 inches (0.07 to 0.30 m) in size, and boulders, if they are greater than 12 inches (0.30 m) in size. Angular particles above 3 inches (0.07 m) in size are classified as rock fragments."

No further distinction was made about the rock fragment quality or gradation required for defining rockfill structures. From this author’s experience, the “cobble” definition is commonly used by engineers to the present day for defining both rounded and angular rock fragments falling within the 3 to 12 inch (0.07 to 0.30 m) square mesh size range.

The term “rock fragment” is defined for this article as any rock (rounded to angular in shape) retained on the ¾ inch (19 mm) square mesh screen size.

Suggested Rockfill Definition

Upper Rock Fragment Limit for Compacted Rockfills

From the original rockfill dams in the 1850’s to the present day, it appears that rockfills have been loosely defined by the engineering community as predominantly rock fragment materials larger than gravel sizes, containing some sand and gravel and minimal fines (silt and clay sizes).

Rock dump fills constructed by massive lift thickness placement generally had no limit on the maximum rock fragment size. The largest rock fragment in rock dumps was the largest rock size that the available construction equipment could move and dump in the fill by large loaders, haul trucks and draglines. The largest rock fragment sizes shown in Photo 11 at the downhill toe of the 400 feet (60 m) high dump were in the range of 8 to 12 feet (2.4 to 3.7 m) rock fragment sizes. The blasted rock fragment rubble shown in Photo 12 contained rock fragments larger than 20 feet (6 m) at the downhill toe of the dump slope.

Photo 11: Dump with rock fragments at downhill toe

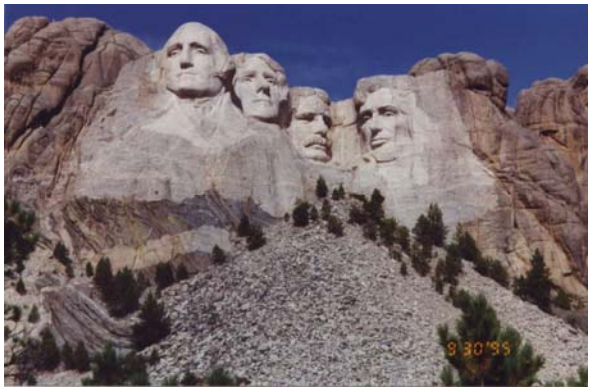


Photo 12: Blasted rock fragment rubble (Mount Rushmore, USA)

Rock dump fill construction for large dams essentially ended by 1965 in favor of compacted rockfills, where rock materials were placed in thinner controlled lifts for compaction by heavy rollers. This limited the maximum allowable rock fragment sizes within the compacted rockfills to where any over sized rocks greater than the lift thickness were raked or dozed to the downstream slope outside of the roller compacted rockfill limits.

With the development of vibratory steel drum compactors in the last 50 years, rockfill dams are now constructed in controlled lift thickness placement, typically less than 5 feet (1.5 m) in loose lift thickness, and compacted with a determined number of passes by conventional vibratory compactor rollers. With the development of large rock haul trucks in recent years capable of hauling more than 240 tons (218 tonnes) of mined rock material, the comparable lift thickness for loaded rubber-tired haul truck compaction can approach 10 feet (3 m) in depth, although effective compaction diminishes with depth. The greater depth of rockfill compaction requires more control of moisture conditioning and a followup large-scale density test in test fills to confirm the effective depth of compaction. Well compacted rockfills within high seismicity earthquake areas of the world are suggested to be in the 2 to 3 ft (0.6 to 0.9 m) range.

The maximum target rock fragment size in past practice from this author's experience has been 2/3 of the maximum loose lift thickness with some allowance for larger rocks that do not protrude from the rockfill lift. Therefore, the upper limit of rock fragment size for compacted rockfills is controlled by the lift thickness and available construction equipment at a general range of 2 to 5 feet (0.6 to 1.5 m) in rockfill loose lift thickness with the use of conventional vibratory steel drum compaction equipment. The upper limit of rock fragment size increases at a general range of 5 to 10 feet (1.5 to 3 m) in rockfill loose lift thickness with the use of large loaded rock haul trucks for rubber-tired compaction in combination with thinner lifts and vibratory roller compaction along inaccessible abutment areas and along the exterior rockfill slopes.

Applying the "2/3 lift height" rule of thumb for the upper rock fragment limit is recommended to minimize the potential for zones of less compaction around the flanks of oversized rock fragments.

Lower Rock Fragment Limit for Compacted Rockfills

The transition from earthfill to rockfill materials for geotechnical engineers is readily defined as the point at which standard field and laboratory soils testing methods are no longer applicable to earthfill soils that contain excessive rock fragments.

The American Standards for Testing Materials (ASTM) defines the upper rock limit for determining laboratory maximum dry density and optimum moisture content of earth soil materials as no more than 30 percent of the sample retained by dry weight on a 3/4 inch (19 mm) square mesh sieve size. Rock correction procedures and compaction methods are specified for determining the measured field and laboratory soil densities (ASTM D-698 and D-1557) for the oversized rock fragments up to the 30 percent rock limit.

Fills with rock fragment content above the 30 percent limit are generally controlled by large-scale rock test fills to establish placement and compactive effort procedures.

Based on established ASTM field and laboratory test standards, the lower rock fragment limit for defining rockfills versus earthfills is suggested by this author to be defined as the following:

- in-place granular fills with a minimum of 30 percent by dry weight of clean rock fragments retained on the 3/4 inch (19 mm) ASTM sieve screen size; and
- fine particle size to contain less than 15 percent silt and clay materials passing the No. 200 (0.074 mm) ASTM sieve size.

The maximum 15 percent fine particle limitation is required from past observations and experience for maintaining a high strength granular rock-to-rock skeleton structure conducive to drainage and vibratory roller compaction efficiency. The reduction in fines content also allows compaction by large loaded haul trucks without rutting of the wetted rockfill surface.

Rock fragments that break down to finer material sizes during excavation, placement, and compaction, and are below the defined lower rock fragment limits, are considered to be earthfills amenable to standard ASTM soil testing procedures and laboratory compaction methods.

Rockfill Gradation Limitations

Gradations for rockfill fragments are based on dry weight square mesh screen size openings, similar to gradation sieve sizes for earthfill particles (ASTM D-422). For example, an 8 inch (0.2 m) maximum rock size refers to all rock fragments passing through an 8 inch by 8 inch (0.2 m by 0.2 m) square mesh screen opening.

Clean rock materials retained on the 3/4 inch (19 mm) sieve can be oven or air-dried rock fragments. A clean rock fragment refers to rock retained on the sieve after hand rubbing or washing to remove clay balls and sand, silt, and clay-sized particles that adhere to the rock fragment surface.

In the borderline case of weathered rock materials susceptible to breakdown during screening, clean rock is suggested to be defined as intact dry rock fragments remaining on the square mesh screen after hand rubbing to remove finer soil particles that become attached during rock borrow and fill placement operations.

GUIDELINES FOR ROCKFILL PLACEMENT AND COMPACTION

Lift Thickness

Maximum loose lift thickness is governed by maximum rock size and type of compaction equipment. Optimum rockfill loose lift thicknesses are generally about 18 to 30 inches (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 (0.9 m) are generally beyond the effective compaction limit of conventional 10 to 20 ton vibratory steel drum rollers commonly used on modern day rockfills. Large haul trucks loaded with rockfill materials can assist the roller compactors for lifts exceeding 3 ft, however the time required for controlled truck traffic passes and the wear and tear to the truck tires to make end turns and to wheel-roll each lift surface generally is less efficient compared to lesser lift thicknesses with conventional heavy vibratory rollers.

Bulk density and gradation tests and settlement versus roller pass curves are recommended in test fills for large rockfill dams or other critical rockfill structures to determine the maximum lift thickness acceptable for the compaction roller used on site.

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.

Heavy rubber-tired rollers in the 50 to 100 ton range were found in the early 1960's to be less efficient in compacting rockfills compared to the vibratory rollers (Pope 1966). The modern day heavy loaded rubber-tired haul trucks (up to 240 tons) can provide some dynamic deep lift compaction, however the large haul trucks are limited to keeping a safe distance away from exterior fill slopes to prevent concentrated tire load bearing capacity failure near the edge of the fill slope or potential accidental truck roll over.

Self-propelled vibratory rollers are the most maneuverable, especially at abutment contacts, for better coverage and compaction compared to vibratory 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 large-scale 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 preceding passes 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, according to US Army Corps of Engineers test procedures (COE 1994).

The average settlement of at least five survey control points is recommended for each 2 passes of the roller compactor to determine the acceptable number of passes. The multiple control points typically will show some variance in settlement, depending on the direction of fill placement. The variance is related to the number of dozer passes to level the top surface of the test fill with less dozer passes required at the leading edge of the rockfill.

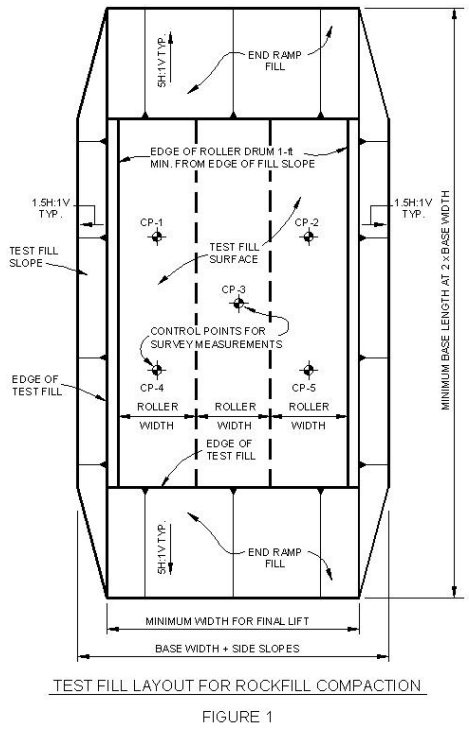
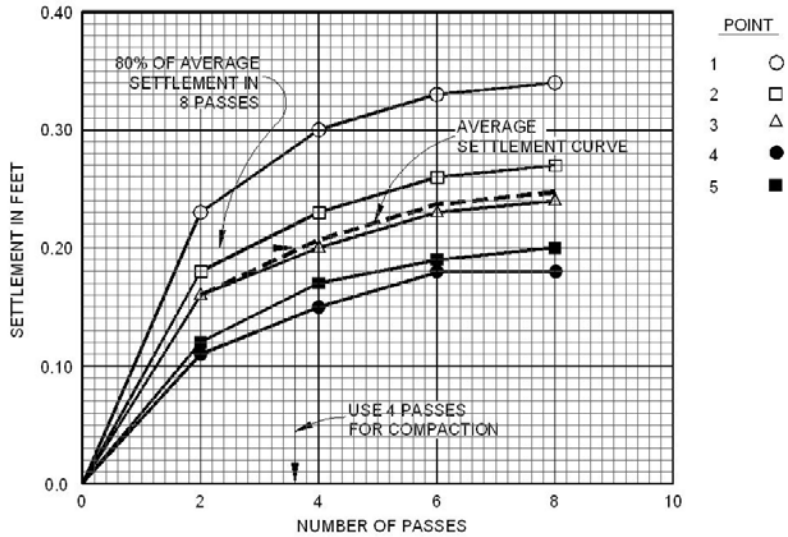


Figure 1: Test fill layout for rockfill compaction



EXAMPLE PLOT OF TEST FILL DATA

FIGURE 2

Figure 2: Example plot of test fill data, with number of passes versus settlement in feet.

Gradation

Rockfills for compacted dam structures are generally placed in transitional zones with the most coarse and competent rock placed in the outer shell and finer more weathered rock placed in the interior or adjacent to earthfill filter drain and core materials. A similar transition zone is developed for leach pad site grading fills with the finer rock materials placed beneath the pad subgrade soil and geomembrane liner system.

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 of a water storage reservoir for drainage during reservoir rapid drawdown conditions, and in spillway areas for rip rap or grouted rock erosion protection and energy dissipation.

Oversized rocks are generally placed on the downstream or exterior rockfill slopes and in downstream outlet and spillway plunge pools for erosion and energy dissipation purposes. Occasional extremely large oversized rock can be incorporated into rockfills provided no overhangs occur and the surrounding rockfill is compacted against the large rock pieces 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 an existing dam, provided the large rock fragments are not clustered.

Photos 13 – 16: Typical rockfill placement operations and test fill survey control locations

Moisture Conditioning

In the past, rockfills for water storage embankments 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 (Sherard, et. al. 1963, USBR 1974, Gloze 1977). Modern rockfills since the 1960's are placed in relatively thin controlled lifts and compacted with vibratory compactors, so that moisture conditioning requirements are not as critical to minimize post-construction settlement. Wetting is generally accomplished on the fill area unless water trucks have access to the rock borrow area.

Photo 17: Borrow stockpile of sandstone and siltstone rockfill materials.

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 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.

An ideal rockfill moisture content contains minus 3/4-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 for bonding like in earthfills, provided the rockfill 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 of height (0.2 m per 100 m). For compacted large earth-rockfill dam structures with a relatively thin central core or upstream earthfill impervious core 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 the low permeability core materials (post-construction dissipation of excess pore water pressures in the fine-grained core materials).

Additional overbuild may be required in high seismicity dam locations to accommodate potential dynamic deformation and related settlement of the dam crest. The engineering analyses of potential earthquake-related dam crest movements typically include the maximum design earthquake during operations and the long-term maximum credible earthquake at closure.

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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 US Army 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

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 US Army 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 quartered by ASTM methods and 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 subgrade 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.

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 surface material.

Photo 18: 1 m diameter plate for large scale rockfill bulk density test

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.

Photo 19: Water replacement test in hand excavated and lined hole

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 to 5 ft (0.9 to 1.5 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.

Photo 20: Bulk gradation test on excavated rockfill materials

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.

Bulk Density Dry Weight = W / (1 + (M/100 x A/100)) (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 x 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.

Bulk Density Dry Weight = W / (1 + (M1/100 x A1/100) + (M2/100 x A2/100)) (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 x 0.40 + 0.05 x 0.60)) = 1,376 lb (625 kg) dry weight for computing the in-place dry density of the rockfill.

REFERENCES

American Society for Testing and Materials (1978), Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures, ASTM.

Breitenbach, A. J. (1993), Rockfill Placement and Compaction Guidelines, Geotechnical Testing Journal, ASTM, Philadelphia, Pennsylvania, Vol. 16, No. 1, pp. 76 to 84.

Cooke, J.B. (October 1984), Progress in Rockfill Dams, ASCE, Journal of Geotechnical Engineering, Vol. 110, No. 10, pp. 1,383 to 1,414.

Gloze, Alfred R. et al (1977), Design of Rockfill Dams, Chapter 7 - Handbook of Dam Engineering.

Pope, R. J. (1966), Evaluation of Cougar Dam Embankment Performance, ASCE Soil Mechanics and Foundations Division Conference, Berkeley, California, ASCE, New York.

Swaisgood, J.R. (2003), Embankment Dam Deformations Caused by Earthquakes, Proceedings from Pacific Conference on Earthquake Engineering, Christchurch, New Zealand, Paper No. 014.

Sherard, J. L., Woodward, R. J., Gizienski, S. F., and Clevenger, W. A. (1963), Earth and Earth-Rock Dams, Wiley, London.

Soil Mechanics and Foundations Division Conference (1966), Stability and Performance of Slopes and Embankments, Proceedings of the ASCE, Berkeley, California, ASCE, New York.

United States Army Corps of Engineers (COE 1994), Engineering Manual EM 1110-2-2301, Washington, D.C.

United States Department of the Interior, Bureau of Reclamation (USBR 1974), Rockfill Dams, Chap. VII of Design of Small Dams, Water Resources Technical Publication, Denver, Colorado.

United States Department of the Interior, Bureau of Reclamation (1968), Earth Manual, Water Resources Technical Publication, Denver, Colorado.