PART 3 – DEFINITION OF ROCKFILL VERSUS EARTHFILL MATERIAL

Allan J. Breitenbach, P.E.
AB Engineering Inc.
Littleton, Colorado, USA
Telephone: 1/720-981-5244
Telefax: 1/720-981-5245
Email: ajbreitenbach@hotmail.com

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 for this article defines rockfill versus earthfill materials. The terms "rockfill" and "earthfill" are commonly used in the geotechnical engineering profession, but the transition between the two types of fill, to this author's knowledge, has not been accurately defined to the present day.

An earthfill material with various mixtures of clay, silt, sand or fine-grained gravel sizes is well defined by the Unified Soil Classification System (ASTM D-2487-00). As larger sized rock fragments are added to an earthfill, at some point the “earthfill” becomes a “rockfill” with predominantly coarse-grained gravel, cobble and boulder sized rock fragments. A review of past rockfill definitions and suggested upper and lower rock fragment size boundary limits are presented in this article for compacted rockfills.

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 presents a suggested definition of rockfill versus earthfill material. Typical rockfill and earthfill materials in stockpiles, waste dumps and fills are shown on Photos 1 to 4.

HISTORIC DEFINITION OF ROCKFILL MATERIAL

<u>Early Rockfill Classification</u>:

In 1952, the United States Bureau of Reclamation (USBR) and the 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 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. Examples of rock segregation on stockpile and fill slopes can be seen in Photos 1 and 2, respectively.

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 permissable 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%.

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 type of rockfills by 1959.

In 1963 and 1964, the 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 DEFINITION FOR ROCKFILL MATERIALS

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 3 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 4 contained rock fragments larger than 20 feet (6 m) at the downhill toe of the dump slope.

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 40 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. 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.

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.

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 the larger 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 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, discussed in Part 4 of this series of rockfill articles.

Based on established ASTM field and laboratory test standards, the lower rock fragment limit for defining rockfills versus earthfills is suggested to be defined as 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) sieve screen size. The definition of the rockfill lower limit is also suggested to limit the fine particle size to contain less than 15 percent silt and clay materials passing the No. 200 (0.074 mm) sieve size. This 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 compaction efficiency. The reduction in fines content also allows compaction by large loaded haul trucks without rutting of the wetted fill 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 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 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.

SUMMARY

The terms “rockfill” and “earthfill” are commonly used in the geotechical engineering profession, but the transition between the two types of fill, to this author’s knowledge, has not been accurately defined to the present day.

The historic definition of rockfill material was primarily limited to visual estimates by volume or weight. Early rockfill dam construction by rock dump techniques allowed rock segregation to occur on advancing thick rock dump lifts. No known gradation tests were performed for these type of fills due to the physical rock size limitations and the variation in thick fill lift gradations from the top to bottom of the advancing fill slope surface due to segregation.

The construction practice for rockfill dams changed in the late 1950’s to thinner controlled lift placement and compaction by conventional dozer and roller equipment. Vibratory roller compaction was adopted in the early 1960’s to the present day. The controlled rockfill lifts for compaction allowed the start of large-scale gradation testing in 1959 to confirm visual gradation estimates.

The suggested definition for rockfill materials includes an upper and lower rock fragment limit. The upper rock fragment limit is defined by the allowable loose lift thickness for adequate compaction using conventional vibratory rollers or large loaded haul truck rollers for rubber-tired compaction. The target maximum rock fragment size for rockfills is suggested to be 2/3 of the maximum loose lift thickness with some allowance for larger rock fragments, as long as the rock fragment does not protrude from the lift and hinder compaction.

The lower rock fragment limit is defined as the point at which standard field and laboratory soils testing methods are no longer applicable to earthfill materials that contain excessive rock fragments. This earthfill soil limit is defined by ASTM test methods as no more than 30 percent of the sample retained by dry weight on a ¾ inch (19 mm) square mesh sieve size. The definition of the rockfill lower limit is also suggested to limit the fine particle size to contain less than 15 percent silt and clay materials passing the No. 200 (0.074 mm) sieve size. This 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 compaction efficiency. The reduction in fines content also allows compaction by large loaded haul trucks without rutting of the wetted fill surface.

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List of Photos attached:

Photo 1 – Segregated Earthfill at Top and Rockfill at Bottom of Stockpile Slope

Photo 2 – Earthfill and Rockfill Placed in Rock Dump Fill Lift Thickness

Photo 3 – Predominantly Earthfill Waste Dump with Boulders at Downhill Toe

Photo 4 – Predominantly Rockfill Waste Dump from Top to Bottom of Slope


Photo 1 – Segregated Earthfill at Top and Rockfill at Bottom of Ore Stockpile


Photo 2 – Earthfill and Rockfill Placed in Controlled Fill Lift Thickness

Photo 3 – Predominantly Earthfill Waste Dump with Boulders at Downhill Toe

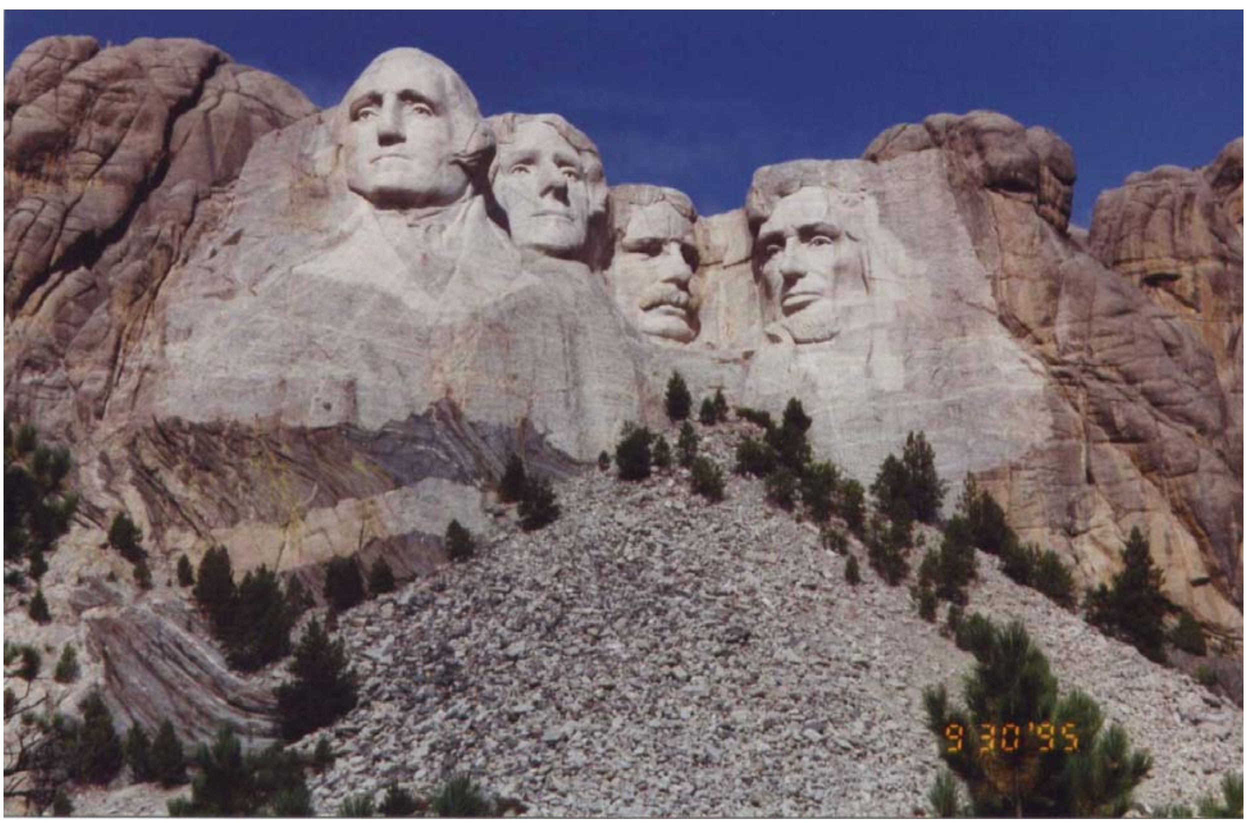

Photo 4 – Predominantly Rockfill Waste Dump from Top to Bottom of Slope