Modification Study and Practice of Impervious Soil of Ultra-High Core Rockfill Dams

LI Yong-Hong, YU Ting, WANG Guan-Qi, WU Xian-Wei

(PowerChina Chengdu Engineering Corporation, Chengdu, Sichuan, 610072)

Abstract: Ultra-high earth-rock dams over 200m high pose rigorous requirements for Impervious soils. The use of spreading gradation gravelly soil with good physical and mechanical properties promotes the development of ultra-high earth-rock dams; however, material sources in the project region are usually associated with such problems as uneven spatial distribution, insufficient content of coarse or fine grains, and excessive or insufficient water content, and it is therefore necessary to make corrections by taking some modification measures. This paper mainly describes the study and application of three types modification measures used in projects: introduction of coarse grains into soil; removal of grains larger than certain size by screening; blending gravelly soils extracted from different pits in the borrow.

Key Words: Earth-rock dam; soil Core (wall); Rockfill dam; Impervious soil; Spreading gradation; Gravelly soil; Gradation; Blending; Screening; Removal

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About the author: LI Yong-Hong (1970-), male, of Han nationality, a native of Daying, Sichuan; professor-level senior engineer, assistant chief engineer of PowerChina Chengdu Engineering Corporation, and project chief engineer of Shuangjiangkou Hydropower Station.

1. Introduction

Earth-rock dam is a common dam type in the world. So far, the design and construction of these dams have reached a high level. For instance, Nurek dam, a soil core rockfill dam built in Tajikistan, is up to 300m high.

High soil core rockfill dam has developed at a quick tempo in China since 1980s: 186m high Pubugou dam was built on a 78m-thick overburden by 2010, Nuozhadu dam (261.50m high) was completed in 2012, and three other dams (Changheba, Lianghekou, and Shuangjiangkou) standing 240m, 295m, and 314m high respectively are under construction.

The choice and design of impervious soil are critical considerations in the construction and design of earth-rock dams. Clay was commonly used as impervious material in earth-rock dams before 1960s; however, practices demonstrate that using pure clay as impervious material in high dams has its problems, which include large deformation, poor post-crack seepage deformation resistance, high soil moisture content, unavailability of acceptable soil source, and great
construction difficulty. With the evolution of engineering machinery and construction technology and, particularly, thanks to the development of practice and theory of the reversed filter of soils, spreading gradation gravelly soils represented by moraine soil, weathered rock, and gravelly soil have been extensively used as impervious material in high dams. These greatly expand the choice of impervious materials, overcome the aforementioned limitations associated with pure clay, and highlight the "local sourced material" benefit of earth-rock dam, thus promot further the development of high earth-rock dams.

Nevertheless, for high earth-rock dams the local natural soil is often unable to meet the general engineering requirements since the desired soil material is typically of large quantity and has a high requirement. It is usually necessary to take some modification measures before the soil is incorporated in the works.

2. Properties of Impervious Soil and Modification Requirements for Ultra-High Earth-Rock Dams

High earth-rock dams, particularly ultra-high ones with a height over 200m, have a rigorous requirement for Impervious soil, which is expected to have good compression, strength, deformation, and imperviousness properties. Spreading gradation gravel is used the most often in practice as Impervious material in high earth-rock dams. In addition to meeting Impervious requirement, this type of soil has the following characteristics: the compressed soil mass is of high strength and low compressibility, which helps reducing the deformation difference between the core and the rockfill and minimizes core cracking and hydrofracturing risks; in the event of core cracking, the coarse soil grains may mitigate seepage erosion, and improve the self-sealing capability of cracks due to reversed filter protection; the moisture content is easier to adjust and the filling thickness becomes less sensitive; a good bearing capacity is guaranteed, allowing for heavy construction machinery traffic and roller compaction.

Unluckily, in a project region the material reserve is typically not sufficient or the material is unevenly distributed in space, the coarse or fine grain content is deficient, and the moisture content is excessive or insufficient. Modification measures have to be taken in order to make the material useful. Soil moisture content is generally adjusted by scarifying, airing, and watering. Watered soil is left for digestion for some time for the purpose of moisture homogenization before being used. To improve imperviousness, anti-seepage, mechanical, and compression properties, it is necessary to modify soil gradation. This is a complicated process since technical requirement is high and quality control is difficult.

Engineering practice suggests that with spreading gradation gravelly soil suitable for high dam construction the grains larger than 5mm ($P_5$) should not exceed 50% and the grains smaller than 0.1mm should be around 20%. However, some natural soils are found to have excessive fine grain content and are of inadequate strength for high dam construction whereas other natural soils may have insufficient fine grain content and excessive coarse grain content (or the size of course grains are too large) such that the imperviousness and anti-seepage requirements are not satisfied. Also, with some naturally occurring soils the fine and coarse grains display an uneven spatial
distribution, making blending necessary if it is desirable to improve quality and increase utilization ratio.

Table 1 summarizes the Impervious material properties of earth core rockfill dams constructed or under construction with a height above 240m. It is surprising to find that Impervious material in these dams has most been modified in some way. In general, there are three modification methods: the first one is introducing coarse grains into finer soil, this practice is used in Nurek, Tehri, Nuozhadu, Lianghekou, and Shuangjiangkou dams; the second one is to remove coarse grains larger than a certain size by screening, which is used in Pubugou and Changheba dams; the third one is to blend gravelly soil from different borrow pits and this is the case with Changheba dam.

Table 1  List of Impervious Soil Properties of Core Rockfill Dams over 240m High in China and Other Regions

<table>
<thead>
<tr>
<th>Dam</th>
<th>Country</th>
<th>Dam type</th>
<th>Dam height (m)</th>
<th>Properties of core soil</th>
<th>Year of completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nurek</td>
<td>Tajikistan</td>
<td>Straight core rockfill dam</td>
<td>300</td>
<td>A mixture of loam, sandy loam, and -200mm aggregate; the content of -5mm grains is 60%-80%.</td>
<td>1980</td>
</tr>
<tr>
<td>Ckicoasen</td>
<td>Mexico</td>
<td>Straight core rockfill dam</td>
<td>261</td>
<td>Clayey sand with a high gravel content; coarse grains are well-graded, with slightly weathered argillaceous rock and alluvium; the content of +5mm grains is 18%-45%.</td>
<td>1980</td>
</tr>
<tr>
<td>Tehri</td>
<td>India</td>
<td>Sloping core rockfill dam</td>
<td>260.5</td>
<td>A mixture of clay and sandy gravel, maximum grain size 200m; the content of -5mm grains is 60%-80%.</td>
<td></td>
</tr>
<tr>
<td>Guavia</td>
<td>Colombia</td>
<td>Sloping core rockfill dam</td>
<td>247</td>
<td>Gravelly soil; overburden clay was blended with underlying coarse grains</td>
<td>1989</td>
</tr>
<tr>
<td>Mica</td>
<td>Canada</td>
<td>Sloping core rockfill dam</td>
<td>242</td>
<td>Moraine soil, maximum grain size 200m, content of +5mm grains 25%-47%</td>
<td>1973</td>
</tr>
<tr>
<td>Nuozhadu</td>
<td>China</td>
<td>Straight core rockfill dam</td>
<td>261.5</td>
<td>Soil blended with gravel (35% of gravel). Content of -5mm grains is about 60%-70%.</td>
<td>2012</td>
</tr>
<tr>
<td>Shuangjiangkou</td>
<td>China</td>
<td>Straight core rockfill dam</td>
<td>314</td>
<td>Soil blended with gravel (about 45% of gravel); content of -5mm grains is about 50%-60%.</td>
<td>Under construction</td>
</tr>
<tr>
<td>Lianghekou</td>
<td>China</td>
<td>Straight core rockfill dam</td>
<td>295</td>
<td>Soil blended with gravel (about 30%-45% of sandy gravel); content of -5mm grains is about 55%-65%.</td>
<td>Under construction</td>
</tr>
<tr>
<td>Changheba</td>
<td>China</td>
<td>Straight core rockfill dam</td>
<td>240</td>
<td>A portion is delivered directly to the dam after being removed of oversized rocks; a portion is obtained by blending fine soil with coarse soil (after removal of oversized rocks) before being delivered to the dam.</td>
<td>Under construction</td>
</tr>
</tbody>
</table>

Using three gravelly soil core rockfill dams in China (Shuangjiangkou, Pubugou, and Changheba) as examples, the following paragraphs describe Impervious material property
modification and its application.

3. **Introduction of Coarse Grains into Soil (Shuangjiangkou Dam)**

3.1 **Brief Description of Soil Blending Methods**

Research suggests there have been four major blending methods of earth-rock dam Impervious soil: ①horizontal spreading and vertical extraction in borrow pit or on blending ground; ②dumping and blending on filling surface; ③blending by belt conveyor; and ④blending by mixer. As a simple blending process, "horizontal spreading and vertical extraction" is widely used; rich experiences have been accumulated in this regard. This blending method was used in Nuozhadu dam construction. Experimental study of this method has been conducted in both Shuangjiangkou and Lianghekou projects. Given the limited workspace in Shuangjiangkou dam project, an automatic blending process has been proposed in the study.

3.2 **Shuangjiangkou Dam and Soil Source**

Situated on the upper reaches of Dadu River, Shuangjiangkou gravelly soil core rockfill dam rises to 314m high, its crest is 16m wide, the upstream slope is 1:2.0 and the downstream slope is 1:1.9. The gravelly soil core crest is at an elevation of 2508.00m and its width is 4m, with a ratio of 1:0.2 for both upstream and downstream slopes. Two reversed filter layers are provided on both upstream and downstream slopes, the two upstream layers being 4m thick each and the two downstream layers being 6m thick each. A transition layer is installed between the dam shell and the reversed filter layer. The dam foundation riverbed overburden is typically 48m~57m thick, with a maximum thickness of 67.8m. Gravelly soil core and reversed filter layers are constructed on bedrock, but the rockfill dam shells and the transition layers are rested on overburden, from which large-scale sandy lens have been eliminated. The design seismic dynamic acceleration of the dam is 205gal.

Dangka borrow pit, the main source of Impervious soil, is about 9km downstream of the dam site and varies between 2420m and 3040m in elevation. Its terrain slope is about 30°. This borrow pit is of a dual configuration. The usable layer, 1.0m~16.52m thick and containing a small amount of brecca, is the non-dispersive yellow silty clay stratum in the upper portion of the pit. Being a low liquid limit clay, the soil has a mean natural density of 1.74g/cm³, a dry density of 1.52g/cm³, and a natural moisture content of 15.1%. Regarding grain composition, the content of grains larger than 60mm is 2.1%, the content of grains smaller than 5mm is 94.0%, fine grains smaller than 0.075mm account for 82.6%, and clayey grains finer than 0.005mm account for 21.0%. For a 300m-class high dam, the soil is satisfactory in Impervious performance; the grain size is however on the fine side, the strength is on the weak side, and the compressibility is on the high side. Modification by introduction of coarse grains is thus necessary.

3.3 **Blending Strategy and Soil Property Study**

(1) Choice of material to be introduced

In light of the availability and condition of natural construction materials in areas close to the dam, three introduction materials have been studied: moraine soil aggregate in the lower portion
of Dangka borrow pit, naturally occurring sand and pebble, and crushed granite aggregate. Study suggests that blending of crushed granite rock into the soil at a specific proportion is more likely to ensure quality and strength, and is good to progress, and cost control for large-scale construction; this strategy was used accordingly.

(2) Crushed granite aggregate gradation study

The study of soil and crushed granite aggregate blending has considered three strategies and has included physical and mechanical property tests for different post-modification gradations. A number of tests have been conducted under the three strategies. Based on the test results, the following gradation was selected for crushed granite aggregate with due consideration given to the possibility of economic and reasonable flow process and to good quality control in large-scale construction: the control maximum grain size is 100mm, the -5mm grain content corresponding to the upper envelope curve is 15%, that corresponding to the average curve is 5%, and the minimum grain size corresponding to the lower envelope curve is 5mm.

(3) Blending proportion study

The study included a set of laboratory tests using five blending ratio: (clay: crushed granite aggregate proportions, namely, mass ratio, the same below) 70%: 30%, 65%: 35%, 60%: 40%, 55%: 45%, and 50%: 50%. Laboratory physical and mechanical property tests demonstrated that the soil aggregate produced using 55%: 45% and 50%: 50% proportion of clay: crushed granite aggregate generated better comprehensive physical and mechanical properties.

(4) Properties of mixture

When the clay was blended with crushed granite aggregate corresponding to the average curve of the proposed gradation at a proportion of 55%: 45%, the -5mm grain content corresponding to the average curve of the mixture was 54.3%, the -0.075mm grain content was 46.0%, the clayey grain content was 11.7%, the coefficient of uniformity was 2138.6, and the coefficient of curvature was 0.05. Based on the modified Proctor compaction(2685kJ/m³), the mixture produced a maximum dry density of 2.13g/cm³ and an optimum moisture content of 8.3%; when tested under 0.1MPa~0.2MPa in laboratory, the coefficient of compression was 0.025MPa⁻¹ and the modulus of compression was found to be 51.1MPa; the hydraulic fracture gradient was ≥ 10.1 and the permeability coefficient was 2.75×10⁻⁷cm/s; direct shear test suggested that the friction angle was 30.4° and the cohesion was 60kPa.

3.4 Blending and Construction Process Study

(1) Crushed granite aggregate production study

Crushed granite aggregate production study was carried out with specific consideration given to the raw material properties and mass production requirements. The study was conducted using the sand and aggregate production system installed for Shuangjiangkou diversion tunnel construction. The proposed general production process was: three-stage crushing, fine crushing & reshaping sand production, two-stage screening, dry production, and blending of coarse and fine sands.
The test material was sourced from tunnel debris with a grain size over 200mm, the feeding quantity was controlled by a power feeder, and the product of the system was -150mm mixture. The test showed that the final crushed granite aggregate was able to satisfy gradation requirement. If the feeding quantity is constant, the material source is consistent, the feeding rate remains unchanged, and the opening parameters of the machine is set properly, the random fluctuation of the mixture product quality would be small, thus making it suitable for continuous and large-scale production.

(2) Horizontal spreading and vertical extraction process study

"Horizontal spreading and vertical extraction" is a process widely used in soil blending in high earth-rock dam construction. The principal production process is: alternating spreading of sandy gravel and soil layers; vertical extraction; blending by repeated loading and unloading; loading and delivery to dam. This process involves the conversion of mass ratio into volume ratio, and the blending proportion is computed based on spreading thickness. In Shuangjiangkou and Lianghekou tests, the study included two blending methods: dry blending and wet blending (sandy gravel was soaked and surface-dry). Wet blending was used because the affinity between the sandy gravel and the clay was stronger and the soil moisture content could be adjusted to some extent.

(3) Automatic blending process study

"Horizontal spreading and vertical extraction" is a simple blending process and has accumulated a great deal of application experiences. As extra advantages, traditional construction equipment like dump trucks, bulldozers, and loaders may find their use in various work procedures. Unfortunately, because of the above characteristics, this process has its own problems: loose quality control, low production efficiency, and large blending ground. For Shuangjiangkou and other works in deep valley, a lot of work and investment would be involved in ground grading and in access road construction. For this reason and inspired by continuous belt feeding, metering, and mixer technology, another blending process was suggested for Shuangjiangkou: automatic transport and blending.

The principal production process of this system is: Soil extraction/sandy gravel production → Transport by belt conveyor (or reclaiming from self-regulating stockpile) → Batching bin and metering system → Blending by mixer → Transport of mixture by belt conveyor → Spreading by stacker, watering → Storage (digestion) → Loading and delivery to dam. The capacity of soil and aggregate supply systems was 770t/h and 550t/h respectively, while the production capacity of the blending, transport, and storage systems was 1400t/h. The capacity of the storage system as well as the watering and digestion time depend on material preparation and water content homogenization requirements of the system. Study suggested that compared against road transport and "horizontal spreading and vertical extraction" process, this method was expected to save about 20% in cost for Shuangjiangkou works. In addition, quality control could be more intensive and efficient.

4. Removal of Coarse Grains from Natural Soil (Pubugou Dam)
4.1 Pubugou Dam and Soil Source

Pubugou soil core rockfill dam is on the middle reaches of Dadu River. With a maximum height of 186m, the crest elevation is at 856.00m. The upstream slope is 1:2 or 1:2.5 whilst the downstream slope is 1:1.8. Being 4m wide, the core crest is at 854.00 m elevation. The slope of both the upstream and downstream surfaces of the crest is 1:0.25. The dam foundation overburden is up to 78m thick. Two concrete cut-off walls, being 1.2m thick each and at a center-to-center distance of 14m, are installed. The seismic design fortification intensity is Ⅷ.

Heima I borrow pit, the major source of Impervious soil, is situated upstream of the dam and is about 16km away from the dam site. The soil material is distributed from 1,345m to 1,510 m in elevation. With respect to grain composition, -5mm grains account for about 46%, -0.1mm grains and -0.005 mm grains account for 20% and 4.6% respectively. Being a little on the coarse side, the naturally occurring soil is not qualified for core Impervious material if no modification is made.

4.2 Impervious Soil Gradation Adjustment Study

After a lot of laboratory and outdoor tests and field roller compaction tests, a strategy was selected to improve the quality of Heima I deluvial subregion soil: grains larger than 80mm shall be removed by screening. After removal of +80mm grains, the -5mm grain content was around 51.06%, the -0.075 mm and -0.005 mm grains accounted for 21.89% and 5.46% respectively, and the permeability coefficient was up to the $10^{-5}$~$10^{-6}$ cm/s orders of magnitude. Practice suggested that removal of coarse grains produced good results because the gradation had been bettered, the soil category had changed from poor graded gravel (GP) to clayey gravel (GC), and the physical and mechanical properties had satisfied high dam Impervious soil requirements.

4.3 Removal Process of Coarse Grains

Coarse grains are removed from the soil by screening. Screening test was performed at the start period of construction and test items included screening mode, screen mesh structure, and screen mesh angle. After repeated study, two-stage screening was used: gravelly soil was firstly screened by bar screen in order to remove gravel larger than 120mm; then, the screened soil was transported by belt conveyor to a vibrating screen for secondary screening in order to remove gravel larger than 80mm. Two-stage sieving is advantageous because removal of large gravel by bar screening reduces vibrating screen wearing, and secondary vibrating screening shortens the retention time of gravel on the screen so that screen clogging probability is minimized, screening efficiency is improved, and gravel soil wearing is reduced.

With due consideration to construction material supply requirement, bin opening size, material feeding time, and other factors, four bar screens were installed for the screening system, with one as a standby. Each bar screen was 4.5 mx6 m large and was fabricated using light-duty steel rails. Bar screen slope is an important design parameter that helps ensure screening quality and efficiency. Tests suggested that in the case of Heima gravelly soil the optimum screening slope was 30°~ 35°.
Likewise, four vibrating screens were installed, each having a capacity of 350 t/h. Vibrating screens achieve their sieving effect by high-frequency and low-amplitude screen surface vibration generated by vibration exciter so as to prevent screen clogging and improve sieving rate & production efficiency.

5. Blending of Gravelly Soil from Different Pits in Borrow (Changheba Dam)

5.1 Changheba Dam and Soil Source

Changheba soil core rockfill dam is situated on the upper reaches of Dadu River. The crest elevation is 1697.00m and the maximum dam height is 240m. Both the upstream and downstream slopes are 1:2 and the crest is 16m wide. The core crest is 6m wide and the upstream and downstream slopes of the core are both 1:0.25. Both the upstream and downstream sides of the core are provided with reversed filter layer. The upstream reversed filter layer is 8.0m thick and the two downstream reversed filter layers are both 6.0m thick. A transition layer of 20m in horizontal thickness is provided between the dam shell rockfill and the upstream and also the downstream reversed filter layer. Two full-sealing concrete cut-off walls are installed for dam foundation overburden Impervious treatment. The walls, 1.4m and 1.2m thick respectively, are at a clear distance of 14m and are up to about 50m deep. The design seismic acceleration of the dam is 359gal.

The soil from Tangba borrow has a natural density of 2.06 g/cm³, a dry density of 1.86g/cm³, and an average natural moisture content of 10.7%. Regarding grain composition: +200mm boulder content is 0~10.0%, with a mean value of 1.05%; -5mm grain content is 35.0%~91.0%, with a mean value of 53.17%; and -0.005mm clayey grains account for 4.0%~30.0%, with a mean value of 9.86%. The soil falls into clayey gravel (GC) category.

The gravel content is unevenly distributed in Tangba borrow. Only a portion of Tangba borrow soil (around 2.90 million m³) is qualified for direct delivery to the dam after removal of coarse grains; the rest is either on the coarse side (P₅ content exceeding 50%, around 1.76 million m³) or on the fine side (P₅ content less than 30%, around 0.87 million m³), and therefore blending after removal of coarse grains becomes necessary.

5.2 Core Material Gradation Adjustment Study

Four tests were carried out in an effort to find out proper blending proportions. According to design requirements, the fourth test was performed for the purpose of improving Tangba borrow utilization ratio, with the emphasis laid on P₅=43% blending. The specific requirements are: coarse soil (P₅>50%) and fine soil (P₅<35%) are blended to get P₅=43% blended product, the P₅ fluctuation shall be within ±7% and shall meet the design criteria 30%≤P₅≤50%. The compaction and rolling test results of the fourth test products suggested that the blended mixture satisfied dam core construction requirements.

5.3 Blending Process

Horizontal spreading and vertical extraction process was used for blending. Dump trucks were employed to transport mixture ingredients and bulldozers were responsible for spreading.
After spreading, an excavator extracted the material vertically from bottom upward. The excavator raised its bucket and then let the material fall freely and this free falling was repeated for 3 to 6 times for each bucket of material. Soil moisture content dropped after blending. Blended mixture was therefore watered and then stored in the material preparation yard until the moisture content satisfied design requirements.

The spreading thickness of fine and coarse soils was determined after field testing based on the proposed blending proportion of the two soils in the test. The proposed spreading thickness of coarse soil was 0.5m and that of fine soil was determined by testing as appropriate to the blending proportion. Placing sequence: the first layer was coarse soil, and then fine and coarse soils were placed in alternating layers until the placement thickness satisfied the working condition of blending machinery.

6. Conclusion

(1) Earth-rock dam has gradually become one of the principle high dam types in the world. The application of spreading gradation gravelly soil promotes the development of high earth-rock dams, particularly ultra-high soil core rockfill dams over 200m high. However, natural soils are usually associated with some defects, so proper modification measures tailored to the actual conditions are necessary. A lot of experiences in this field have been obtained in practical construction.

(2) The study and experience of Shuangjiangkou and Nuozhadu projects suggest that inclusion of sandy gravel could be a successful modification technique when naturally occurring soil contains more than needed amount of fines and when its strength does not satisfy high dam construction requirement. "Horizontal spreading and vertical extraction" blending process employs traditional construction equipment, is simple in work process, and is supported by rich experiences. In recognition of space limitation and road condition of Shuangjiangkou works, an automatic transport and blending process was proposed, which not only saved construction cost but also enhanced quality control level.

(3) The study and experience of Pubugou and Changheba projects suggest that gradation adjustment and performance improvement by removal of coarse grains larger than certain size is effective and practical when naturally graded gravelly soil contains insufficient fines to such an extent that its Impervious and imperviousness performance is unacceptable.

(4) The study and experience of Changheba works suggest that blending of fine and coarse soils is effective in improving soil quality and maximizing natural soil utilization ratio in the case of uneven spatial distribution of coarse and fine grains.

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