TRAPEZOIDAL CSG DAMS

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1. INTRODUCTION

Many technologies have been developed to construct dams in Japan, but today, the aims of this technology development must include lower costs and improved protection of the environment. Conditions related to quarries needed to obtain dam body materials are particularly severe, as falling yields and expansion of the scale of slope excavation are causing severe problems: higher cost of quarrying and heavier load on the environment among them. So "rationalization of materials" is required to lower high costs and to reduce environmental load.

Dam rationalization technologies include those which achieve three goals, "rationalization of design", "rationalization of materials", and "rationalization of execution", but a trapezoidal CSG dam is a new form of dam intended to achieve "rationalization of materials" which is the most important of the three goals which must now be achieved. It will also contribute to "rationalization of design" and "rationalization of execution".

The trapezoidal CSG dam theory has been applied to design and execute two structures: the marsh control works at the Taiho Dam operated by the Okinawa General Bureau of the Cabinet Office (Photo 1.1) and the Kawai Dike at the Haizuka Dam operated by the Chugoku Regional Bureau of the Ministry of Land, Infrastructure and Transport. And work is about to begin on construction of two full-size trapezoidal CSG dams.

2. OVERVIEW OF A TRAPEZOIDAL CSG DAM

2.1 Shape and structure of a trapezoidal CSG dam

Figure 2.1 shows the standard section of a trapezoidal CSG dam. A trapezoidal CSG dam is built mainly using CSG as its dam body material. Protection concrete is placed on the surfaces to ensure that they are durable and waterproof. At the bottom of the upstream slope, a gallery is built, structural concrete is placed, and seepage control concrete is used to ensure creep length. The part of the CSG in contact with the foundation bedrock is rich mix CSG used to provide durability.

Photo 1.1 Execution of the Marsh Control Works at the Taiho Dam

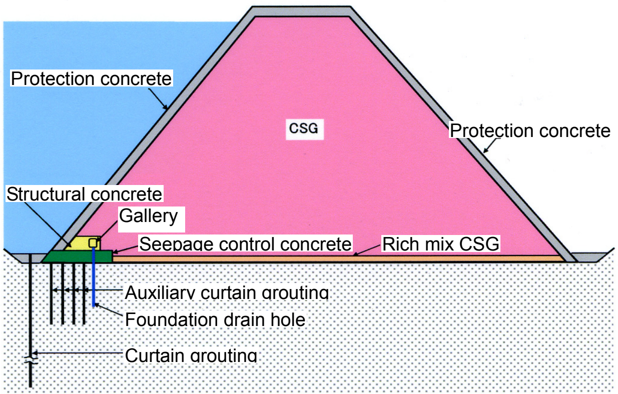
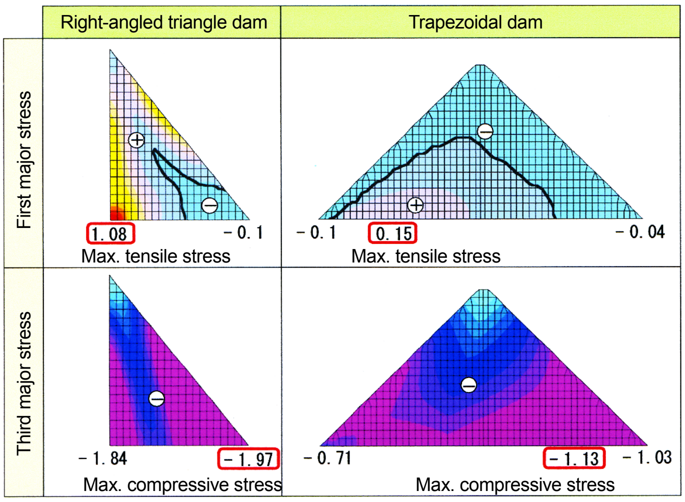


Figure 2.1 Standard Section of a Trapezoidal CSG Dam

2.2 Trapezoidal dam and triangular dam

1) Stress and required strength

Shapes of dams are right-angled triangle shaped dams such as concrete gravity dams and trapezoidal shaped dams such as the trapezoidal CSG dam introduced by this report. Materials used to make dams require sufficient strength to resist stresses produced, but in the model shown in Figure 2.2 for example, the maximum compressive stress produced inside the dam body



Calculation conditions
- Dam height 50m, reservoir depth 45m
- Elastic modulus of dam body (Ec)/elastic modulus of foundation bedrock (Er) = 2
- Self-weight + hydrostatic pressure + inertia and hydrodynamic pressure during earthquake
  (As earthquake load, acceleration wave forms in the upstream – downstream direction obtained at the Hitokura Dam during the Hyogo-ken Nanbu Earthquake adjusted to maximum acceleration of 250gal were used)

Figure 2.2 Distribution of Stress in the Dam Body According to Dam Body Shape

is, in the right-angled triangle dam, 1.97N/mm^2, and in the trapezoidal dam, it is 1.13N/mm^2. Accordingly, a trapezoidal dam need only provide about 60% of the necessary compressive strength of a right-angled triangular shaped dam.

On the other hand, the tensile stress of a right-angled triangle dam and a trapezoidal dam are 1.08N/mm^2 and 0.15N/mm^2 respectively. The concrete strength sufficient to build a concrete gravity dam is assumed to be tensile strength equal to about 10% of compressive strength. Applying this relationship, at a right-angled triangle dam, in order to ensure tensile strength of 1.08N/mm^2, compressive strength of 10.8N/mm^2 which is ten times this value is necessary, and at a trapezoidal dam, similarly, compressive strength of 1.5N/mm^2 is necessary.

Figure 2.3 shows these relationships. The compressive strength required by a trapezoidal dam can be strength from 10% to 20% of the compressive strength required by a right-angled triangle dam, permitting a broad selection of materials. And in the case of the trapezoidal shape, the gentler the gradient, the lower the required strength.

2) Overturning

A trapezoidal dam will, because of its shape, never overturn in the way assumed to occur when studying a retaining wall etc. Thus, a condition for a trapezoidal dam is that not only at normal times, but also during an earthquake (according to dynamic analysis), overturning is prevented by maintaining the vertical stress basically in compressive state throughout the surface of its base. This is a condition which must be satisfied by a trapezoidal dam.

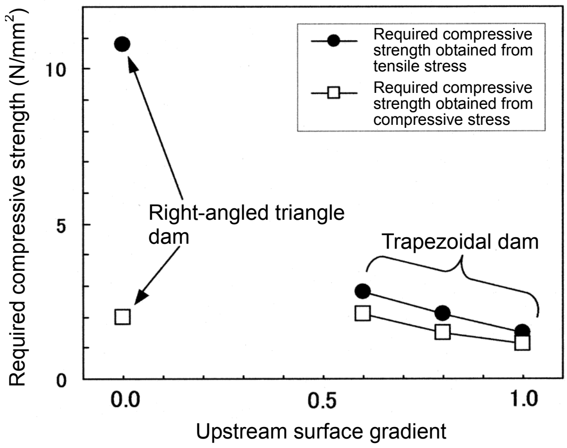


Figure 2.3 Comparison of Required Strength

In the case of a right-angled triangle dam on the other hand, vertical stress obtained by dynamic analysis is easily transformed into tension state near the upstream and downstream ends during an earthquake. So a right-angled triangle dam can be made to resist tensile stress by integrating its dam body with its foundation.

In the case of a trapezoidal dam on the other hand, it is not necessary to integrate the dam body with the bedrock, because basically, vertical stress being constantly on the compressive side throughout the surface of the base is a condition for prevention of overturning. This is a big difference between a right-angled triangle dam and a trapezoidal dam (Fig. 2.4).

3) Sliding

The length of the base of a trapezoidal dam is relatively long compared with that of a right-angled triangle dam and its shape is symmetrical to the left and right, so throughout the surface of dam base, its vertical stress (Fig. 2.4) is compressive and the shear stress (Fig. 2.5) changes little. Consequently, sliding can be adequately resisted by only the friction of the dam body and foundation bedrock, because frictional force can be counted on stably acting on the entire bottom surface. At a right-angled triangle dam on the other hand, tensile stress is produced on the upstream side (Fig. 2.4) and large shear stress is produced on the downstream side (Fig. 2.5). So on a right-angled triangle dam, the dam body and foundation bedrock must be integrated so the bedrock shear strength on the adhesion surface will be used to resist sliding.

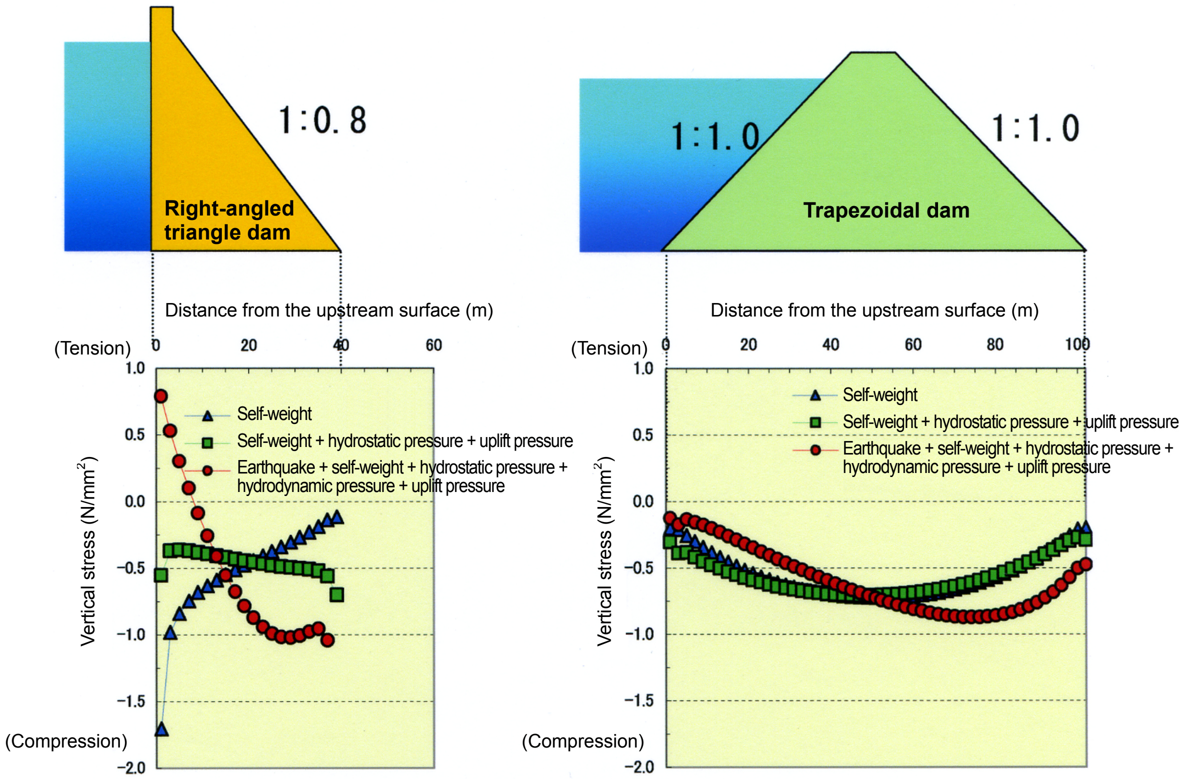


Figure 2.4 Vertical Stress Distribution Acting on Dam Base

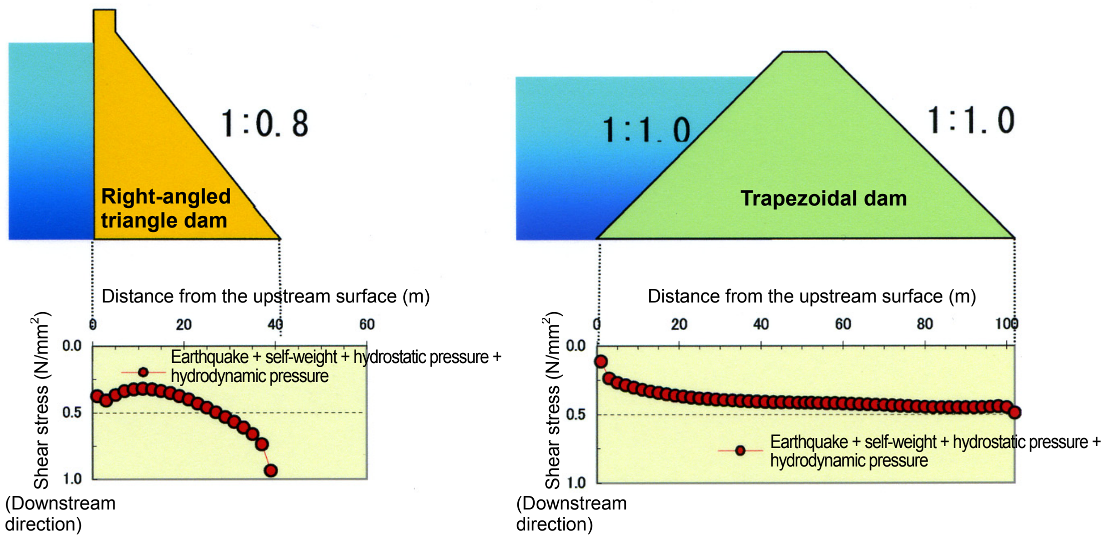


Figure 2.5 Shear Stress Distribution Acting on the Dam Base

2.3 CSG AND THE CSG CONSTRUCTION METHOD

CSG is "a mixture made by using simple equipment to mix cement and water with materials obtainable near the surroundings of a construction site, basically without sorting, grade adjustment, nor cleaning of the materials, but when necessary, removing or crushing oversize materials". The CSG construction method is, "Spreading CSG with a bulldozer and compacting it with a vibrating roller to form a structure."

Figure 2.6 shows the normal CSG production process. The "Matrixes" are made of rocky raw material relatively easily obtained: excavated muck and other materials produced on site, riverbed gravel, terrace deposits, and weathered rocks etc. "CSG material" is made by removing oversize pieces only from the base material which is the original raw material using an aggregate sorter called a Grizzly etc. or crushing the oversize pieces with a crusher, but basically without sorting, blending, other grading adjustment, and cleaning the material. Thus, equipment such as an aggregate production system or a turbid water treatment system necessary to construct a concrete dam, are unnecessary. CSG is material obtained by using simple equipment to continually mix cement and water with "CSG material". Figure 2.7 shows an example of CSG mixing facilities.

CSG which has been mixed is executed by the planar execution method in the same way as the RCD method, and the equipment used to place the material includes general purpose machinery such as dump trucks, bulldozers, vibrating rollers, and other equipment used for ordinary dam construction. CSG is made based on a low unit cement quantity (assumed to be less than 80kg/m^3) and low unit water content and bleeding of CSG is extremely rare. Therefore, green cut is unnecessary and transverse joints are not formed during placement, permitting the simplification and speeding up of execution. The CSG construction method effectively uses material obtainable near at hand and is executed using simple equipment and general purpose machinery without grade adjustment and cleaning in this way, permitting the simplification of execution, reduction of impacts on the environment, cutting costs, and speeding up execution.

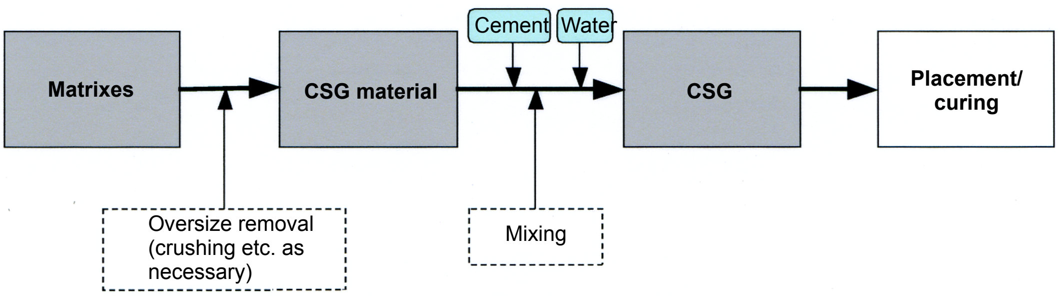


Figure 2.6 Normal CSG Production Process

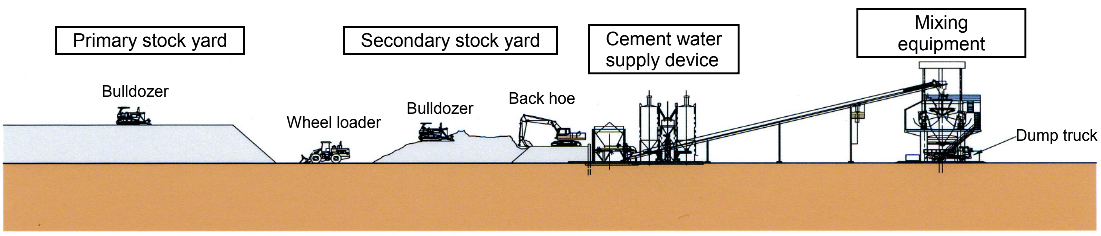


Figure 2.7 Example of CSG Mixing System

2.4. TRAPEZOIDAL CSG DAM

The CSG construction method uses materials obtainable near the construction site and builds the dam using simplified methods, cutting the unit cost, but on the other hand, it cannot be counted on to provide strength equal to that of concrete. However, the trapezoidal shape of the dam permits much lower required strength of the material than that of a right-angled triangle concrete dam. Thus, the CSG construction method can be used to build a trapezoidal dam, and the product of doing so is a new kind of dam called a trapezoidal CSG dam.

Figure 2.8 shows the properties of a trapezoidal CSG dam. The trapezoidal CSG dam which was developed primarily to "rationalize materials" in this way, will also contribute to the "rationalization of design" and the "rationalization of execution".

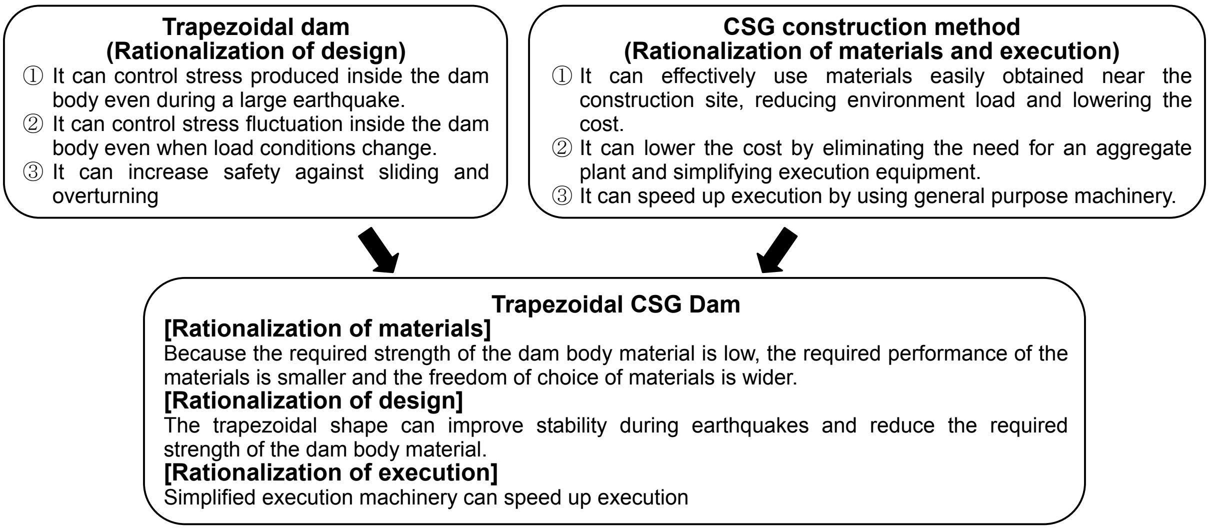


Figure 2.8 Special Features of a Trapezoidal CSG Dam

3. DESIGN AND EXECUTION OF A TRAPEZOIDAL CSG DAM

3.1 Strength of CSG (Diamond shape theory)

Materials are used for dam bodies which are permanent structures on the condition that for each material, there is a, "method of evaluating its strength" and "method of managing its quality". Therefore, this section begins with a discussion of the "method of evaluating the strength" of CSG.

"Matrixes" is basically neither classified nor grade adjusted. The only process applied is either removing or crushing oversize pieces so they can be used. As a result inevitable fluctuation of grading occurs, even in material obtained at the same location. And the fluctuation of the grading makes it difficult to ensure constant unit water content. If material with fluctuating grading and unit water content is used, even if the cement quantity is constant, the strength of the CSG naturally varies. Hence, "CSG strength" is set rationally by the following procedure.

First, the grading is done by performing many grading tests of the material obtained by collecting matrixes to clarify the coarsest and the finest grades of the "CSG material" which will presumably be actually produced from the "Matrixes". The grades selected for use for strength testing are the coarsest and the finest grades. And to clarify the strength – grading relationship, the mean grading is always added to the test grades.

Regarding the unit water content, if the water is gradually lowered, a shortage of water clearly occurs, preventing the development of strength, and if the quantity of water is increased, material will adhere to the mixing equipment blades and other phenomena which reduces the quality of the execution will appear during mixing. This shows that there is an allowed range of unit water content. Consequently, to determine the unit water content used for strength testing, broadening the specimen water range to perform the test using a number of unit water quantities within this range clarifies the impacts of unit water content.

The test results plot the strength of the coarsest and finest grades for each unit water content with the vertical axis representing strength of CSG and the horizontal axis representing the unit water content as shown by Figure 3.1. Linking the strengths for each grading

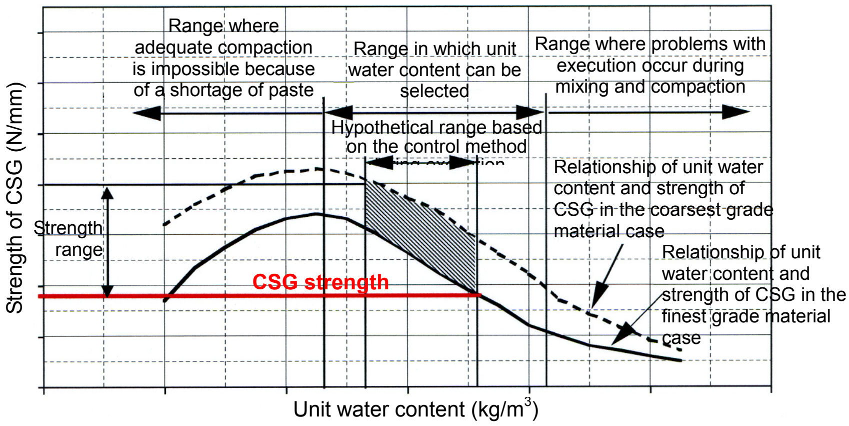


Figure 3.1 Range of Strength of CSG decided from the Grading Range and Unit water content Control Range "Diamond shape theory"

obtains the unit water content – strength of CSG line with grading as the variable. If the allowable range of unit water content is entered on this figure as the vertical axis, the strength of CSG is within the area enclosed by two grading – strength lines above and below, and is distributed within the range of the "diamond shape" which is demarcated by vertical lines showing the allowed unit water range of the two lines. Regarding the "CSG material" which is within the range set by the grade and unit water content, if the lowest strength within this "diamond shaped" range is treated as the strength of the CSG, a value at or higher than this strength is constantly ensured, this value is defined as "CSG strength", and is the strength used to design a trapezoidal CSG dam. This is called the "Diamond Shape Theory". The concrete strength is controlled by point-like control which controls one point which applies grading and unit water content that promise the greatest strength, while strength of CSG control is planar control.

3.2 Quality control

Quality which CSG must provide as dam body material for a trapezoidal CSG dam is strength. Therefore, CSG quality control is performed in order to control the strength of CSG which has been poured. CSG is made by applying the "Diamond Shape Theory" which is premised on fluctuation of the grading and unit water content of "CSG material" to control the strength of the CSG. CSG is executed by controlling strength of CSG based on compaction energy control (control of vibrating roller compaction frequency). To support this control, the suitability of the control system is confirmed based on the fluctuation trends of the specimen strength of CSG which has been manufactured and the on-site density of the CSG which has been poured.

Quality control of CSG consists of three control items: quality control of "Matrixes", quality control of "CSG material", and quality control of CSG.

① Quality control of "Matrixes"

To control the quality of the "Matrixes", a check is made to confirm whether or not its material properties vary to a significant degree, and its quality is clarified more than one month before execution to allow adequate time to remake the diamond shape when it is necessary to do so because of quality variations.

② Quality control of "CSG material"

The quality of "CSG material" is controlled in the primary stock yard (enough to be used for a 3 to 5 day period) and the secondary stock yard (enough to be used the following day). Items controlled are dry surface density, water absorption coefficient, grading, surface water (for that to be used the following day, only grading and surface water). Setting the quantity in the primary stock yard as that which will be used during the following 3 to 5 days is done

Photo 3.1. View of Execution of Cofferdam Upstream from the Tobetsu Dam

considering the execution, but is also a period set considering the time required to perform dry surface density and water absorption coefficient testing.

③ Quality control of CSG

The quality of CSG is controlled in the mixing equipment and at the placement location. In the mixing equipment, simple methods are used to control the unit water content and grading. The time interval between measurements is short when execution begins, then an appropriate frequency is set based on an analysis of the first results. In the mixing equipment, the weight is controlled. Because CSG is, in principle, supplied continuously, it is weighed in real time.

At the placement site, roller compaction frequency is controlled (energy control). It is supplemented by on-site density testing, but this is done to confirm whether or not the properties of the material have fluctuated, if the weighing, spreading, and rolling compaction, etc. are done suitably, and if the control system operates correctly.

And strength testing of specimens is done, but this is, like the on-site density tests, done to confirm that the control system is operating correctly, and in order to check on the strength as quickly as possible, strength testing should be done every 7 days.

3.3 Execution

The unit quantity of cement set to build a trapezoidal CSG dam is generally extremely low at about 80kg/m^3, transverse joints are not formed in the CSG part, bleeding almost never occurs, and tensile strength is not manifest vertically. Therefore, green cut which is performed to build concrete dams is not done. In the CSG construction joints, bedding mortar or cement paste are spread to ensure integration with the horizontal construction joints.

At the part of the CSG in contact with rock, the trapezoidal CSG dam need not be integrated with the bedrock, so bedding mortar is not placed. For these reasons, the execution of the CSG part can be performed more rapidly than at a concrete gravity dam.

Among the concrete parts, the seepage control concrete integrates the dam body with the foundation bedrock to ensure the creep length, so the part in contact with the rock must be treated in the same way as at a concrete dam. The protection concrete is placed with joints formed at intervals of 15m just like a concrete dam in order to prevent cracking, and the protection concrete on the upstream side is installed along with cut-off plates. And in the concrete parts, construction joints are processed similarly to those on concrete dams.

4. EXAMPLES OF REDUCTION OF IMPACTS ON THE ENVIRONMENT

4.1 Example of Dam A

Dam A was originally planned as a concrete gravity dam as shown in Figure 4.1. The geology distributed in the area around the dam site ranges from a Mesozoic Age Triassic Period geology consisting mainly of sandstone, mudstone, and chert to a Jurassic Tamba Zone.

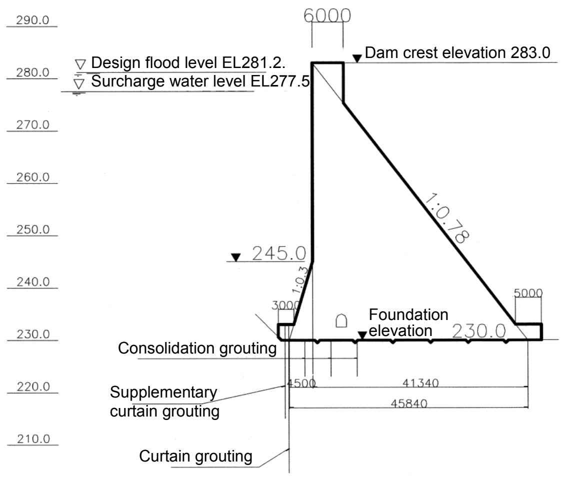


Figure 4.1 Proposed Concrete Gravity Dam (Dam A)

If the concrete gravity dam was built, the raw aggregate (approximately 110,000m^3 required) would be sandstone, but there are relatively few locations of clusters of blocks of angular sandstone distributed around the dam site, and the quarry would be constructed approximately 8.5km from the dam site. A second dam (concrete gravity dam requiring approximately 270,000m^3 of quarried rock) was planned for a drainage basin adjoining that of Dam A, and it was assumed that this quarry would be used to supply the two dams. But, as shown by Figure 4.2, at this

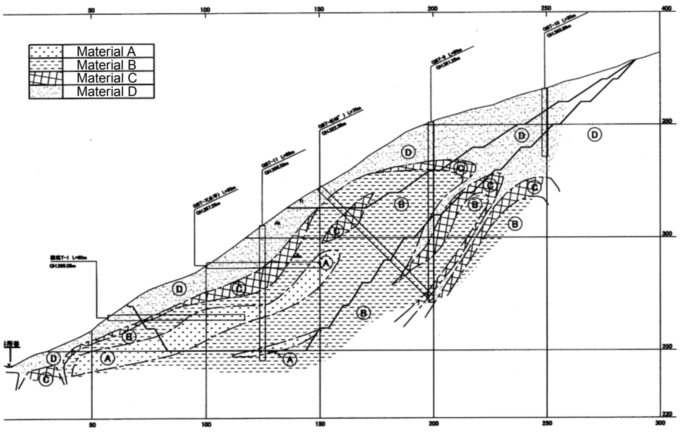


Figure 4.2. Quarry (Dam A)

Building the proposed trapezoidal CSG dam will allow the transport of the "Matrixes" only a short distance from the dam site, while building the proposed concrete dam would have required the long distance transport of quarried rock, sharply increasing the quantity of CO^2 emitted during transport. And acquiring the rock would have produced approximately 1 million m^3 of waste rock, requiring that a large muck disposal yard be obtained, but building a trapezoidal CSG dam will more than halve the quantity of waste rock produced.

quarry, deterioration extends from the surface to a deep level and bedrock of CM class or higher that can be used as concrete aggregate is distributed only deep under the quarry. Therefore, it is assumed that a large quantity of the rock would have been discarded, reducing the yield to between 20% and 30%.

It has been confirmed that if the planned dam is changed to a trapezoidal CSG dam, as the "Matrixes" of the CSG that would be used as the dam body material (approximately 170,000m^3 required), except for its weathered surface, the CL class slate which is the softest of the bedrock distributed inside the reservoir directly upstream from the dam site can be fully used. So based on the results of comparative design work, the originally proposed concrete gravity dam was replaced by a trapezoidal CSG dam as shown in Figure 4.3. And similarly the dam planned for the adjoining river basin was also replaced by a plan for a trapezoidal CSG dam.

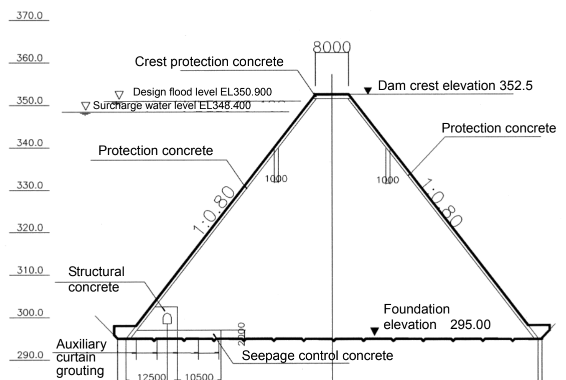


Figure 4.3 Proposed Trapezoidal CSG Dam (Dam A)

In this way, at Dam A, adopting the trapezoidal CSG dam type ensures that the impact on the environment of transporting materials from the location they are obtained to the dam site and transporting waste rock to the muck yard will be lower than the impact which would be imposed by building a concrete gravity dam.

4.2 Example of Dam B

The original study to plan Dam B was, as shown in Figure 4.4, intended to design a rockfill dam with central core standing approximately 70m in height. Low strength tuff breccia is widely distributed around the dam and reservoir sites, but the stratification is mainly volcanic ash containing almost no volcanic conglomerate, so it is unusable as rock material. So as the rock material (approx. 1.15 million m^3), the plan called for the use of andesite which is distributed in the upstream region around the reservoir. And it was decided that the core material would be obtained from the region downstream from the dam. If, on the other hand, the proposed trapezoidal CSG dam is built, as the "Matrixes" (approx. 700,00m^3), it will be possible to use tuff breccia distributed around the dam site and reservoir after removing the weathered surface part, permitting the provision of a matrixes quarry either in or around the reservoir near the dam site. This will shorten the distance the material is transported, sharply lowering the cost of obtaining materials.

The temporary equipment used to execute the work in the proposed rockfill dam case would, considering that the rock would be obtained upstream from the reservoir and the core material

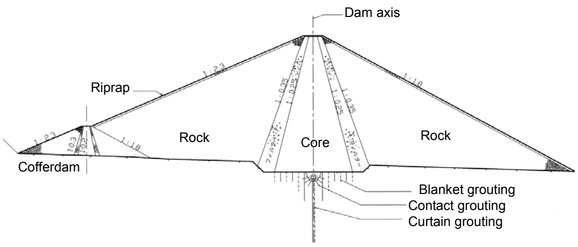


Figure 4.4 Proposed Rockfill Dam
(Dam B)

downstream from the reservoir as explained above, be installed over a wide work area. If, on the other hand, a trapezoidal CSG dam is constructed, it will be possible to obtain the materials in or around the reservoir, allowing the work area to be very small.

Concerning the muck yard, rock excavated at the dam foundation and waste rock from the quarry would have been disposed of together in a single muck yard, but if the proposed trapezoidal CSG dam is built, transporting waste rock from the location the materials are obtained can be done by transporting far less waste rock over a shorter transport distance than in the case of the original rock fill dam.

As shown above, building a trapezoidal CSG dam can cut costs at the same time as it can lower the scale of the transport of materials and waste soil and narrow the work area, reducing the impact of the dam on the surrounding environment.

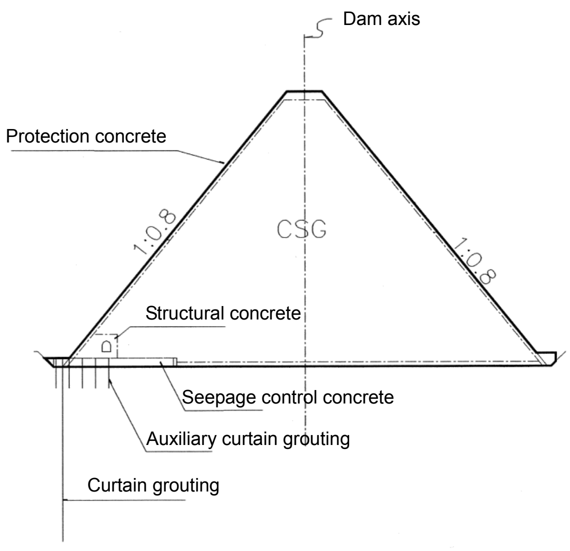


Figure 4.5 Proposed Trapezoidal CSG Dam
(Dam B)

5. CONCLUSION

A trapezoidal CSG dam can achieve "rationalization of materials", cutting costs, at the same time as it can lower environmental impact of the dam. In Japan, the construction of dam using the trapezoidal CSG dam method is about to begin. These dams are being studied in detail to establish execution methods, quality control methods, etc. And in order to reduce impacts on the environment, studies must also incorporate initiatives to restore natural environments on work land: dam site surroundings and matrixes quarrying locations, and so on.

In conclusion, the authors wish to express their deep gratitude to Councilor Fujisawa of the Japan Dam Engineering Center, for his generous guidance concerning the preparation of this report.

Sources

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