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MATERIAL PROPERTIES OF CSG FOR THE SEISMIC DESIGN OF TRAPEZOID-SHAPED CSG DAM

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SUMMARY

CSG (Cemented Sand and Gravel) is a new material for dam construction works and it is produced by adding cement and water to rock based material such as riverbed gravel or excavation muck that can be easily obtained near dam sites, and mixing them with simple device. The physical properties of CSG are affected by gradation curves of raw materials, unit water content, unit cement content and so on. In order to investigate dynamic properties of CSG during earthquake, cyclic loading tests have been carried out.
From the results of tests, it is confirmed that a stress-strain curve clearly showed non-linearity compared with concrete. The elasticity of stress-strain relationship was confirmed by cyclic loading tests under conditions that the maximum compressive stress did not exceed the linear range of CSG. In addition, the elasto-plasticity is observed when cyclic loads exceeds the linear range of CSG.
For the basic design of a trapezoid-shaped CSG dam, strength and modulus of elasticity in linear range are used as material properties of CSG. However, taking account of plasticity of CSG, the trapezoid-shaped CSG dam is considered to have enough safety margin against stress generated during earthquakes.

INTRODUCTION

Japan is known as a prominent earthquake country in the world. Therefore, important civil engineering structures must have sufficient aseismic performance against severe earthquakes. Especially, because a dam is very important structure, it must be designed to ensure the safety against seismic loads. Due to careful designing, no dams have suffered serious damages by previous earthquakes in Japan.
Recently, “Trapezoid-shaped CSG Dam” has been developed in Japan. The trapezoid-shaped CSG dam is a new type of a dam that different from a conventional concrete dam or an embankment dam[1]. The cross section shape of the trapezoid-shaped CSG dam is a trapezoid and its body is made of CSG. CSG is a new material made by adding cement and water to raw material; rock based material such as riverbed gravel or excavation muck that can be easily obtained near dam sites, and mixing it with simple device[2]. The strength of CSG is relatively not strong and the fluctuation of its physical property is large. On the other

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hands, the stress occurred in a trapezoid-shaped dam with gentle slope is small even under the strong earthquake, the required strength of its material can be lowered. It is, therefore, possible to use CSG as a dam body material for the trapezoid-shaped dam. The trapezoid-shaped CSG dam has been proposed as a new type of dam that combines both merit of CSG and a trapezoid-shaped dam. The features of the Trapezoid-shaped CSG Dams lies in a design process; a shape of a dam is designed to be a suitable for the property of CSG that can be easily produced at the site.
In this paper, introduction of a trapezoid-shaped CSG dam, result of stress analyses and dynamic properties of CSG confirmed by cyclic loading tests are described. From the test results, it is confirmed that a stress-strain curve clearly showed non-linearity compared with concrete. The elasticity of stress-strain relationship was confirmed by cyclic loading tests under conditions that the maximum compressive stress did not exceed the linear range of CSG.

TRAPEZOID-SHAPED CSG DAM

Introduction of CSG

In the face of strong demands for lower cost of public work projects and the protection and conservation of the natural environment, future dams must be constructed at lower cost and with less impact on the environment than in the past. From such social backgrounds, constructing dams using CSG, Cemented Sand and Gravel, that can effectively utilize riverbed gravel, excavated muck, and other materials produced on the sites has been proposed. CSG is a material prepared by adding cement and water to raw material such as riverbed gravel or excavation rock that can be easily obtained near dam sites, and mixing it by simple devices. Because a quarry, aggregate plants and turbid water treatment facility can be diminished largely by using CSG, lower cost of dam construction works, protection and conservation of the environment can be achieved.
Fig.1 shows a typical production process of CSG. The production method of CSG is determined in proportion of the characteristics of its raw material obtainable at the site, considering the rationality of execution and required strength of the structure. After large stones have been removed from raw material, water and cement are mixed with CSG material in order to make CSG. Basically, raw material is used without washing and classifying grain sizes.

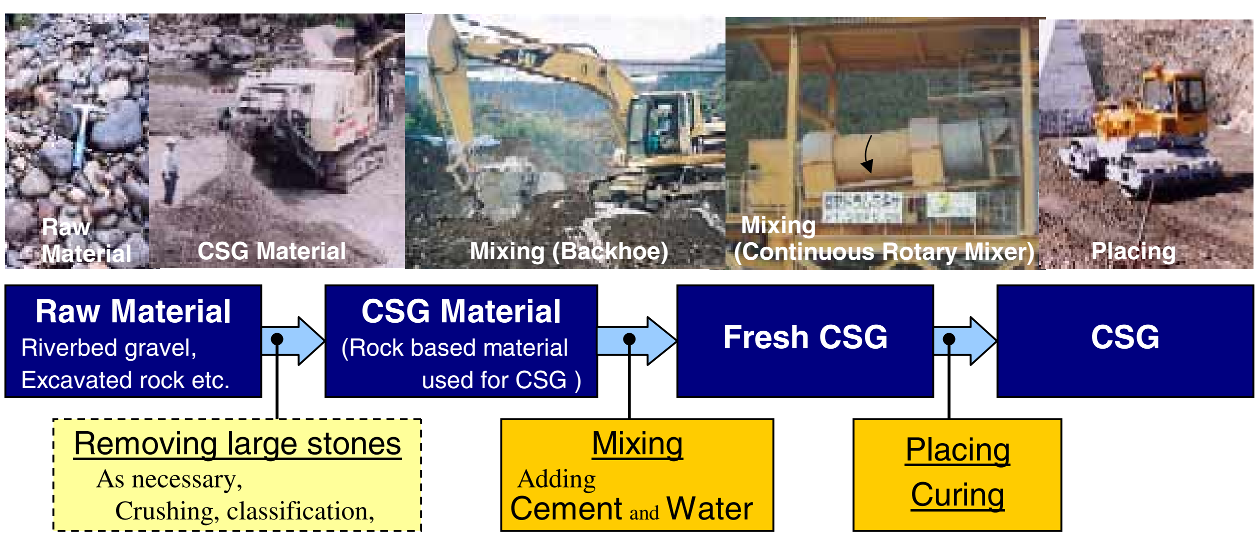


Fig.1 CSG production process

Physical properties of CSG are effected by the grain size distribution curve of raw material, unit water content, unit cement content and so on. Basic properties of CSG, such as compressive strength, modulus of elasticity, tensile strength, stress-strain curve and so on, are obtained by laboratory tests. Fig.2 shows a typical stress-strain curve of CSG obtained by a uniaxial compression test. As the shape of stress-strain curve is non-linear, it is considered that CSG is an elasto-plasticity material. In Fig.2, the range that the stress-strain relationship can be approximated to be linear is defined as "linear range", and the maximum stress in the linear range is also defined as "linear limit strength (σ_L)".

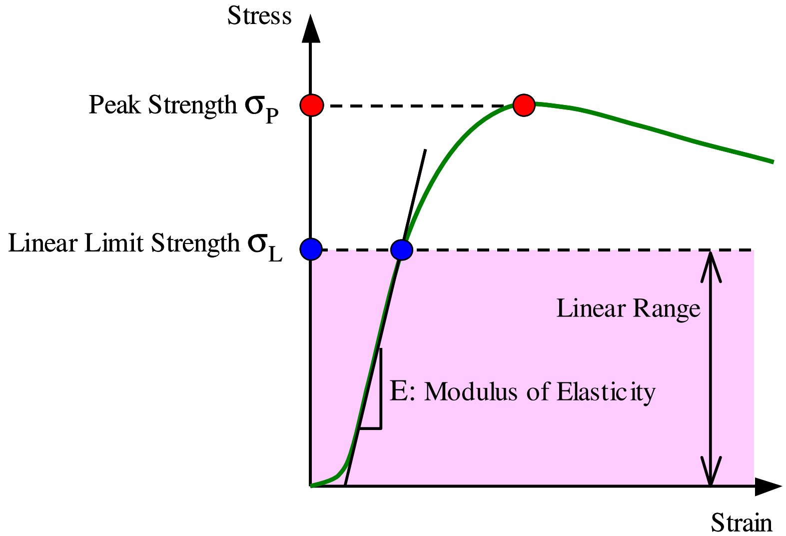


Fig. 2 Typical stress-strain curve of CSG

Introduction of a trapezoid-shaped CSG dam

As shown in Fig.3, a trapezoid-shaped CSG dam is a new type of the dam that combines both merit of a trapezoid-shaped dam and CSG, achieves three rationalizations at the same time: the rationalization of design, of execution, and of materials.

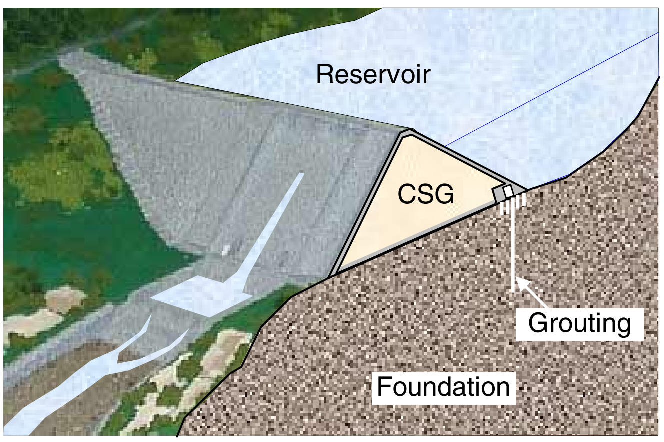


Fig.3 Prefigurement of a trapezoid-shaped CSG dam

Rationalization of design

A trapezoid-shaped dam is proposed as the dam that enables to minimize the tensile stress in the dam during severe earthquakes. Furthermore, there are little changes of stress distributions along the dam bottom in the various loading conditions.

Because a trapezoid-shaped dam has much bigger weight and longer length of its bottom for shear resistance than a conventional gravity dam, high shear strength of dam foundation is not required in order to satisfy the safety against sliding. As the results, a trapezoid-shaped dam can be constructed even on poor foundation.

Rationalization of execution

It is possible to shorten the construction processes; aggregate production, mechanical stabilization, mixing, and placing by adopting the CSG. It is also possible to shorten the construction term and lower the construction cost by rapid execution using machinery; dump truck, bulldozer, vibrating roller and so on, that usually used in dam construction works.

Rationalization of materials

Because a trapezoid-shaped dam can reduce the required strength of dam body materials, the quality of the material is not necessary as good as that of usual dam concrete. It is possible to choose raw material from wide range of rock based materials such as riverbed gravel or excavation muck obtainable at the dam site can be used. Because the raw material is basically used without an orthodox aggregate production process, little of the material is wasted and it does not need a quarry or a large aggregate plant.

Characteristics of a trapezoid-shaped dam

In designing these dams, weight of the dam body is the important factor to satisfy the safety against overturning and sliding. And the strength of the dam body material (concrete) is also important. Especially, tensile strength during severe earthquake is the most important factor in a seismic design. Therefore, if such tensile stress would be minimized, low quality material could be used in the dam body and a construction cost could be reduced. A trapezoid-shaped dam is proposed as the shape of the dams that enable to minimize the tensile stress in the dam during the severe earthquake loading condition.

A trapezoid-shaped dam has much bigger weight than a conventional gravity dam, and therefore do not require the high shear strength of bedrock in order to satisfy the safety against sliding. As the results, a trapezoid-shaped dam can be construct even on the poor foundation. It is another advantage of the dam. Furthermore, a trapezoid-shaped dam can install the outlet works in their bodies, since design of the dam based on the mechanics of elastic materials, and it is the other advantage of the dams compare to an embankment dam.

STRESS CHARACTARISTICS OF TRAPEZOID-SHAPED CSG DAM

Stress analysis

Two-dimensional FEM analysis in plane strain condition was conducted for both the static and the dynamic analyses. The loads considered in static analysis were dead weight of dam body and the hydrostatic pressure due to the reservoir water. Deposit sediment pressure was not accounted in the analysis because it has little effect on a dam body with a gentle upstream surface slope.

The dynamic loads considered in the dynamic analysis were the dam body inertial force and the hydrodynamic pressure acting on the upstream face. The hydrodynamic pressure was calculated assuming that the reservoir is incompressible for convenience.

Fig.4 shows the shapes of dam models used for the analyses. In case of model A, the upstream surface is vertical and the downstream surface slope is 1:0.8, and it is modeled as a conventional concrete gravity dam. The upstream slope and downstream slope are symmetrical for models B, C, and D and these slopes are 1:0.6, 1:0.8 and 1:1.0 respectively. The dam height is 50 m and the reservoir depth is 90% of the dam height. The deformability of foundation was considered only in the case of static analysis.

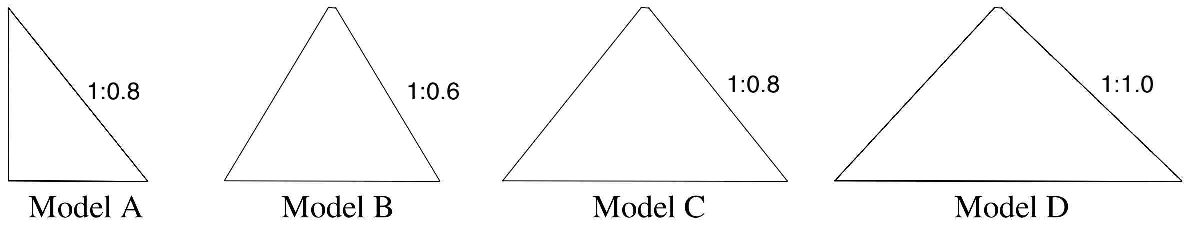


Fig.4 Shape of dam models used for analyses

Material properties of CSG may vary widely according to properties of raw materials obtained near the sites. However, in this study, material properties were assumed as the constant value shown in Table 1. The input earthquake wave used for dynamic analyses is the acceleration recorded at the lowest inspection gallery of Hitokura Dam during Hyogo-ken Nambu Earthquake in 1995. The maximum value of acceleration in stream direction component was adjusted to 250 gal and the wave was inputted from the bottom of dam models as the horizontal vibration. Fig.5 shows the time history of the acceleration wave, and Fig.6 shows the acceleration response spectrum of the input earthquake wave. The damping ratio used for analyses was 10%.

Table 1 Material properties for FEM analysis

Item	Dam body	Foundation
Modulus of Elasticity (MPa)	2,000	1,000
Poisson's ratio	0.25	0.30
Unit mass (kg/m^3)	2,200	-

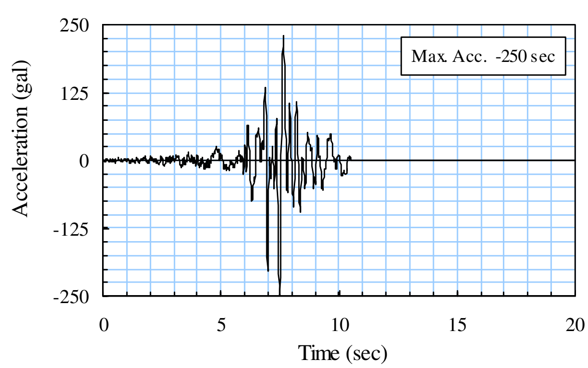


Fig.5 Time history of input earthquake wave

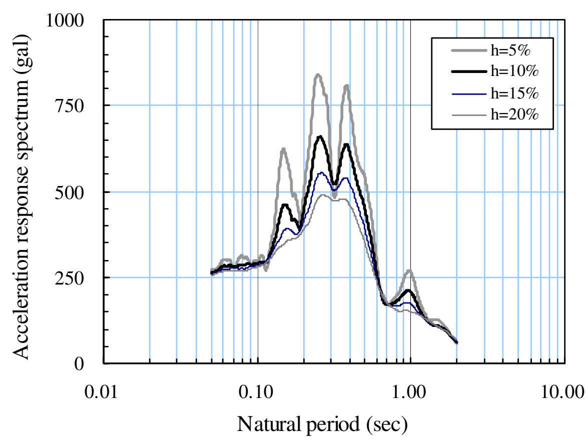


Fig.6 Response acceleration spectrum of input earthquake wave

Results of FEM analyses

Stress distribution along dam bottom

Fig.7 shows the distribution of normal stress at the bottom of dams at the time when the maxim acceleration affected. In this paper, the positive value means the tensile stress, and the negative value means the compressive stress.

It reveals that while the value of the stress in models A and B varies widely according to location, there is little variation in the stress according to the location in models C and D.

Fig.8 shows the distribution of normal stress at the bottom of dam body under various load conditions in models A and C. Stress in dynamic condition is the value at the time when the maxim acceleration affected. Compared with model A, fluctuation of normal stress distribution of model C is small. These are one of the advantages of a trapezoid-shaped dam.

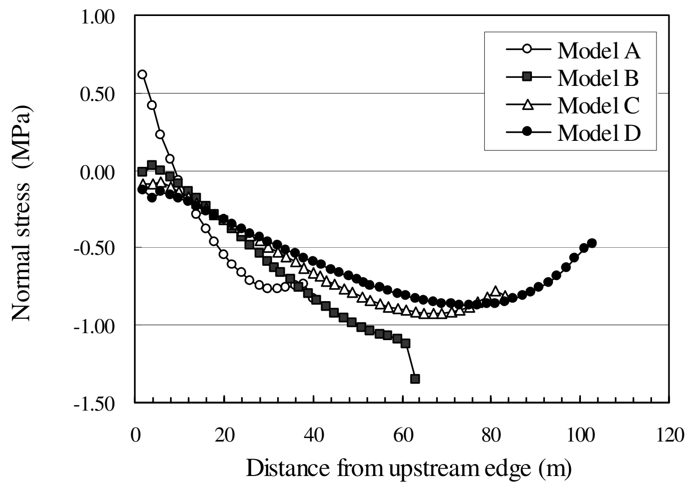
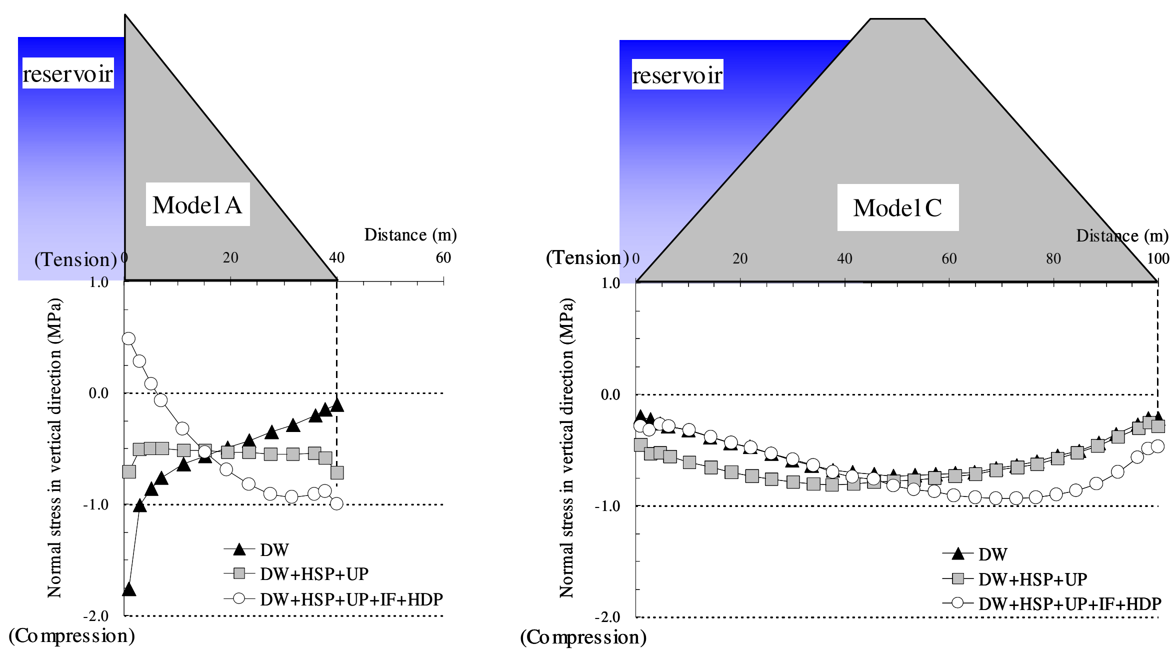


Fig.7 Distribution of normal stress at the basement of dams



DW: Dead Weight HSP: Hydrostatic Pressure UP: Uplift Pressure

IF: Inertial Force HDP: Hydrodynamic Pressure

Fig.8 Distribution of normal stress at the basement of dams under the different load conditions

Stress distribution in dam body

Fig.9 shows the maximum and minimum principal stress distribution in dam bodies. These stresses are the maximum and minimum values calculated over the duration of the earthquake, and are not at the specified time. 'σ_1' signifies the principal stress on the tensile side, 'σ_3' is the compressive side.

In the σ_1 case, the dominant stress in model A is 1.08 MPa, but in models B, C and D, it is 0.28, 0.21, and 0.15 MPa respectively, revealing that much small tensile stress is generated in contrast to model A. In the σ_3 case, the dominant stress in models A, B, C and D were -1.97, -2.12, -1.49, and -1.13 MPa respectively, and in model D that is the widest dam body, the stress was about half that of model A, a conventional concrete gravity dam shape.

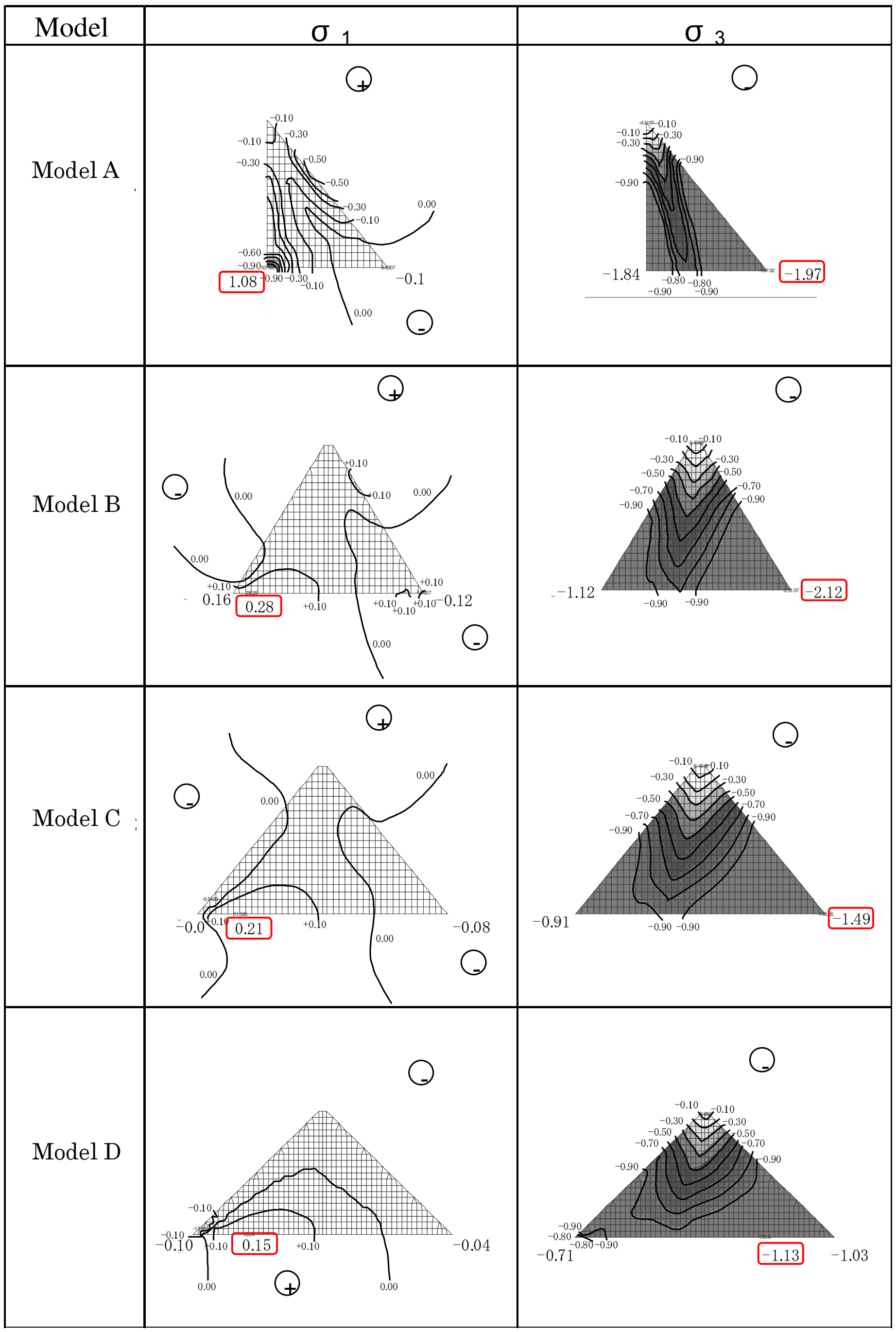


Fig. 9 Distribution of maximum principal stress (Unit: MPa, ⊕Tensile/ ⊖Compressive)

Relation of maximum stress and surface slope of trapezoid-shaped dam

Fig. 10 shows relationship between the maximum and minimum values of principal stresses and the upstream slope models A, B, C and D. It shows that the gentler the slopes of upstream surfaces are, the smaller the stress is.

The maximum tensile stress of model A is 1.08 MPa. Assuming that 10 times of tensile strength are equal to the compressive strength of the material of dam body, the material with 10.8 MPa in the compressive strength is necessary for model A. However, the maximum compressive stress of model A is –1.84 MPa, and it shows that the required strength in compressive side and tensile side is much different. On the other hands, the maximum tensile stress of model C is 0.21 MPa, it means that the material with 2.1 MPa in the compressive strength is necessary. Considering that the maximum compressive stress of model C is 1.49 MPa, the required strength in the compressive side and the tensile side is close and the values are quite smaller than model A, the material strength of dam body is efficiently utilized in case of a trapezoid-shaped dam.

Fig. 11 shows the maximum deformation of dam bodies. In case of Model A, the bending deformation is predominant. On the other hand, in case of trapezoid-shapes, especially models C and D, the shearing deformation is predominant.

From above results, the stress generated in a dam body of a trapezoid-shaped dam is small, high-strength material is not necessary for the trapezoid-shaped dam.

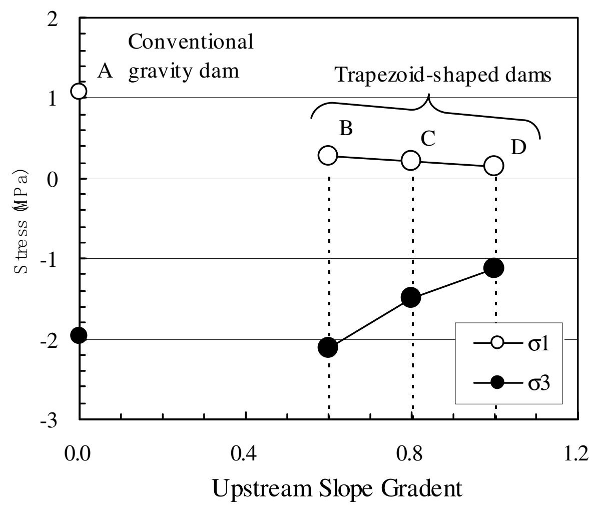


Fig.10 Relationship between maximum and minimum principal stress and upstream gradient

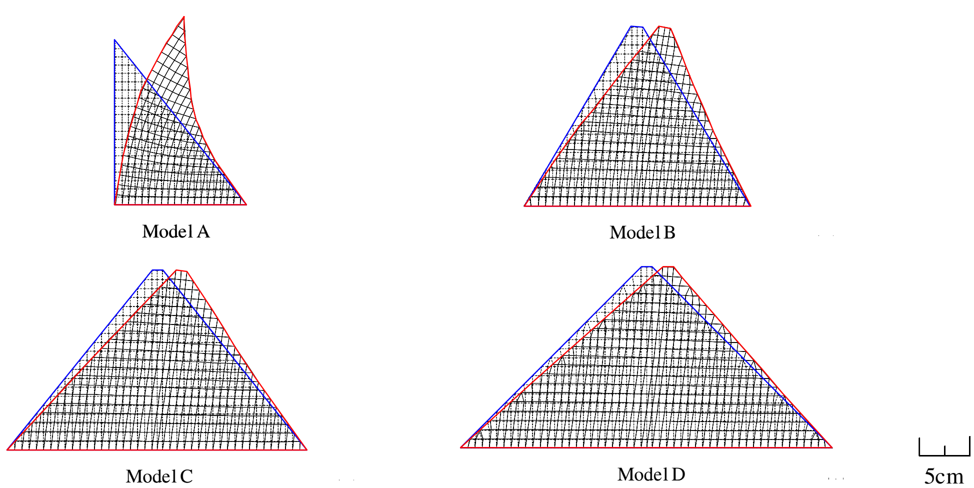


Fig.11 Maximum deformation of dam bodies during earthquake

DYNAMIC MATERIAL PROPERTIES OF CSG

Test conditions

In order to investigate dynamic material properties of CSG under earthquake conditions, cyclic loading tests of CSG were carrying out by the uniaxial compression test in a laboratory. Photo 1 shows the uniaxial compression instrument used for tests. The raw material of CSG was excavated muck obtained at an actual dam site. The geology of raw material was tuff breccia and the maximum grain size was 80mm. The sizes of CSG test specimen were 300mm in height and 150mm in diameter. CSG test specimen was made by mixing the raw material with cement (80 kg/m^3) and water (105-135 kg/m^3), and compacted by hand vibrator. Table 2 summarizes the test cases of cyclic loading tests and Figs.12 – 17 show the patterns of cyclic loadings. Loading speed was set in 0.2 MPa/sec and deformation of the test specimen was measured by strain gauges.

Photo 1 Uniaxial compression test of CSG

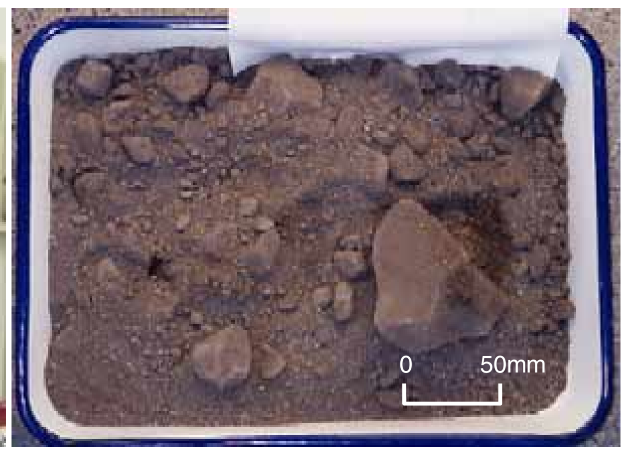


Photo 2 Raw material of CSG (Tuff breccia)

Table 2 Test cases

Case	Estimated compressive strength of CSG		Pattern of cyclic loading
	Peak Strength σ_P (MPa)	Linear limit Strength σ_L (MPa)	
1	7.5	4.9	Peak load: 0.50σ_L Number of cycles: 5
2	7.5	4.9	Peak load: 0.75σ_L Number of cycles: 5
3	11.8	8.0	Peak load: 0.66σ_L Number of cycles: 20
4	10.2	6.1	Peak load: 0.45σ_L, 0.85σ_L, 1.25σ_L, 1.50σ_L Number of cycles: 1 in each maximum load
5	7.3	4.3	Peak load: 0.50σ_L, 1.15σ_L, 1.35σ_L Number of cycles: 3 in each maximum load
6	7.9	4.8	Peak load: 1.15σ_L Number of cycles: 50

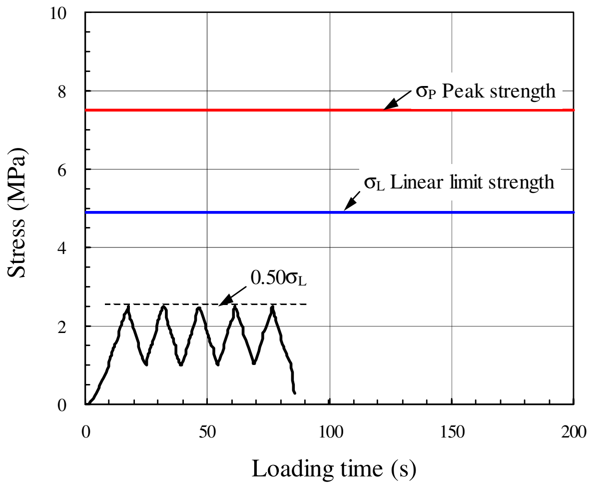


Fig.12 Loading pattern (Case 1)

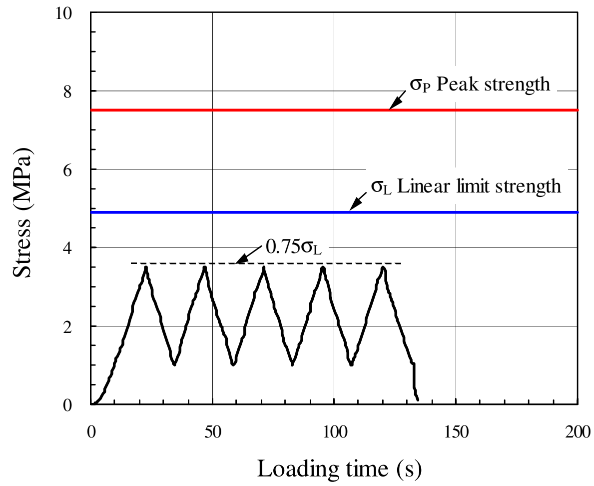


Fig.13 Loading pattern (Case 2)

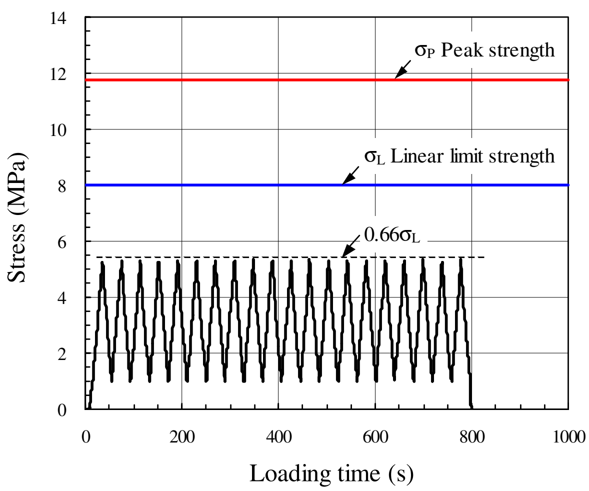


Fig.14 Loading pattern (Case 3)

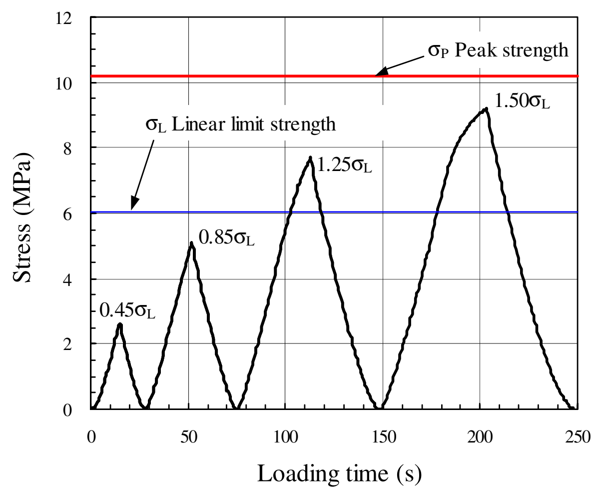


Fig.15 Loading pattern (Case 4)

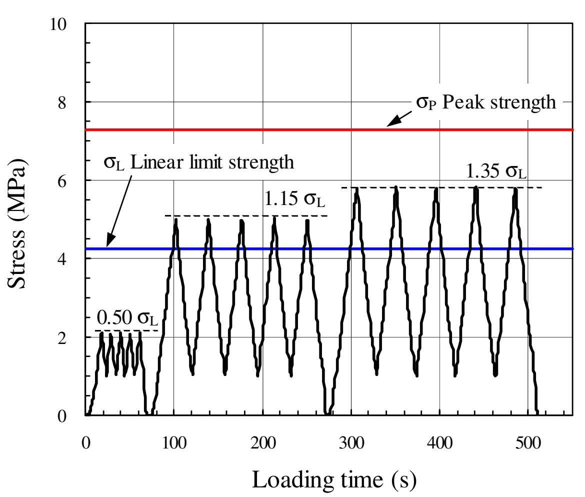


Fig.16 Loading pattern (Case 5)

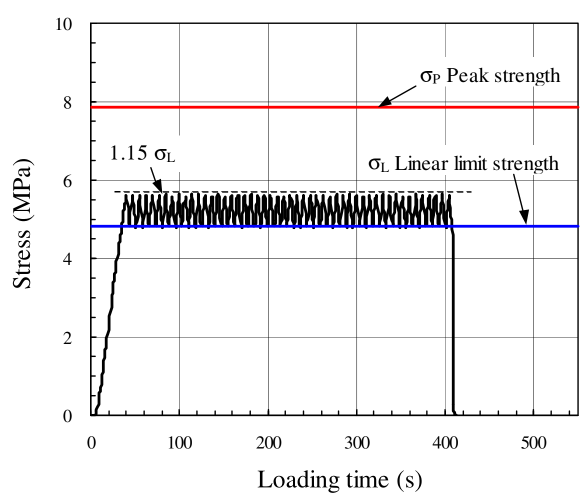


Fig.17 Loading pattern (Case 6)

Results of cyclic loading tests

Figs.18-23 show the results of cyclic loading tests. From the results shown in Figs.18 and 19, the linearity of stress-strain relationship was observed when the maximum compressive load did not exceed the linear limit strength (σ_L). The linearity of stress-strain relationship was also confirmed by the result of Case 3, shown in Fig.20, even if the number of loading cycles increased.

In Case 4, peak loads were increased by cycles and exceeded the linear limit strength (σ_L). From the result of this case, it is observed that the elasto-plasticity was clearly appeared in the stress-strain curve and the residual strain increases cumulatively when a cyclic load exceeded the linear range of CSG, shown in Fig.21. In Case 5, peak loads were also increased similar to Case 4. The number of cycles was 5 in each peak load. From this result, shown in Fig.22, the linearity of CSG was kept in the first step of cyclic loading that was not exceeded the linear limit strength (σ_L). However, the residual strain appeared after the second step of cyclic loading that the peak load exceeded the linear limit strength (σ_L), and the value of residual strain increased according to the load that exceeded the linear limit strength (σ_L). In Case 6, the cyclic loads were set between the linear limit strength (σ_L) and 115% of σ_L, the residual strain increased in proportion as the number of cycles, shown in Fig.23.

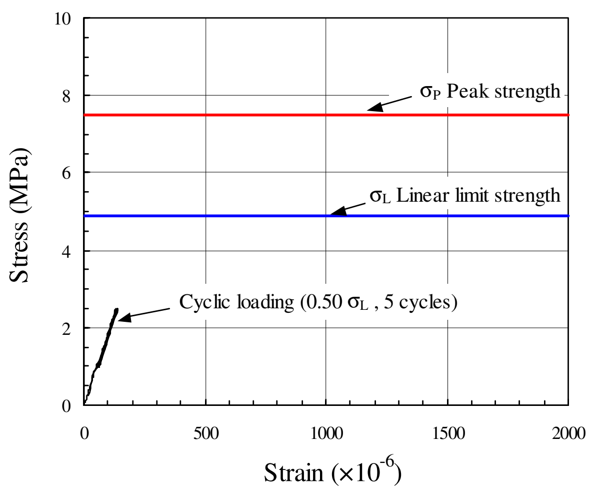


Fig.18 Stress-strain curve (Case 1)

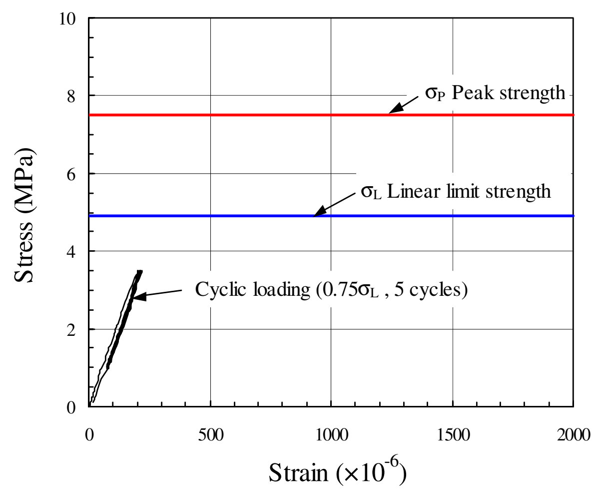


Fig.19 Stress-strain curve (Case 2)

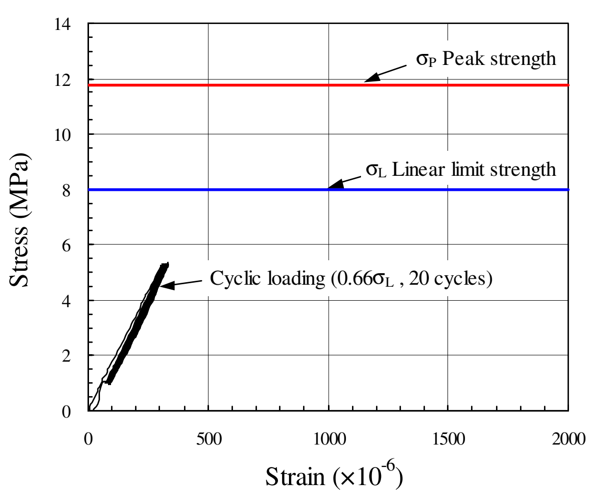


Fig.20 Stress-strain curve (Case 3)

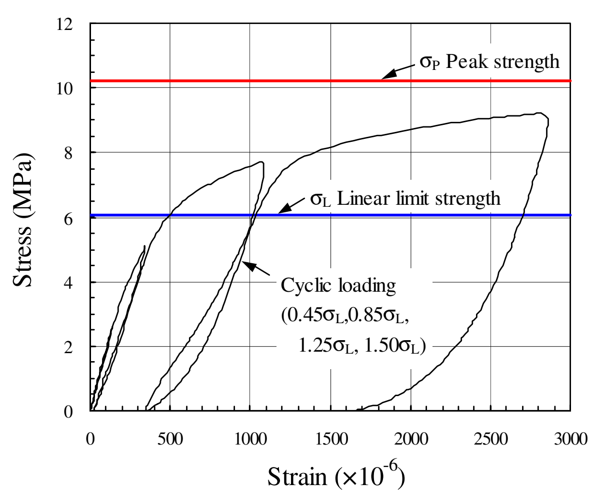


Fig.21 Stress-strain curve (Case 4)

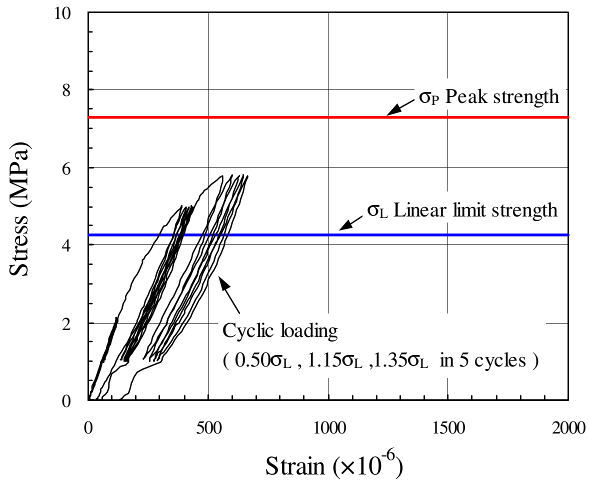


Fig.22 Stress-strain curve (Case 5)

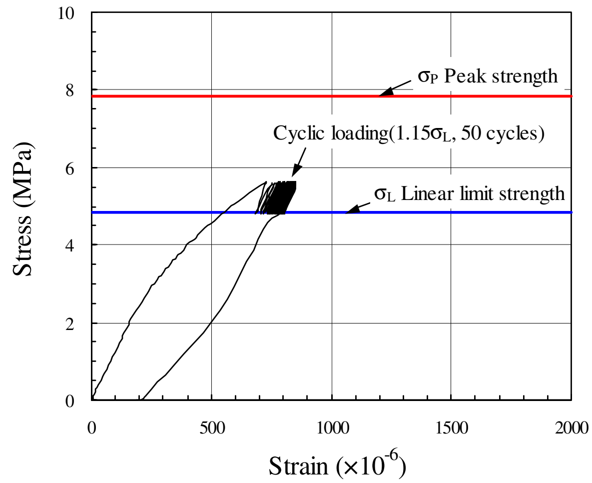


Fig.23 Stress-strain curve (Case 6)

CONCLUSIONS

In this paper, the characteristics of the trapezoid-shaped CSG dam and dynamic material properties of CSG that were clarified by laboratory tests were described. The results of analyses and material tests are summarized in the following.

1) Compared with a conventional concrete dams, stress generated in a dam body of a trapezoid-shaped CSG dam is small. In addition, the maximum stress is decrease in proportion as increment of the upstream and downstream slope gradient.
2) Basic material properties of CSG were confirmed by laboratory tests. Particularly, it is confirmed that the stress-strain curves obtained by uniaxial compression tests were non-linear.
3) Dynamic properties of CSG were confirmed by cyclic loading tests. The linearity of stress-strain curve was confirmed when the maximum compressive load did not exceed the linear limit strength of CSG. In addition, it was also confirmed that the elasto-plasticity was clearly appeared when a cyclic load exceeded the liner limit strength of CSG.

In a basic design of a trapezoid-shaped CSG dam, the strength and the modulus of elasticity in linear range should be used as material properties of CSG. Therefore, even if the large load that exceed the linear limit strength acted on a dam body in case of an unexpected serious earthquake etc., brittle failure would be hard to occur in the trapezoid-shaped CSG dam because CSG has a wide range of plasticity. It means that the trapezoid-shaped CSG dam has a enough safety margin against severe earthquakes.

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