

CHARACTERISTICS OF STRESS DISTRIBUTION IN TRAPEZOID-SHAPED CSG DAM DURING EARTHQUAKE

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SUMMARY

Trapezoid-shaped CSG dam is a new type of dam made by Cemented Sand and Gravel (CSG), which is made by adding cement and water to quarried material such as riverbed gravel or excavation muck that can be obtained easily near dam site, and mixing it with a simple device. The CSG is expected as a new material for dam body to reduce the cost for dam construction because the cost for producing it will be much lower than usual dam concrete.

The material strength of CSG, however, is much smaller than usual dam concrete. So, it is proposed to make the shape of cross section trapezoidal so as to reduce the stress inside dam body to a lower level than material strength of CSG, while the cross section of conventional concrete gravity dam is designed to be a triangle with almost vertical upstream surface. The characteristics of stress distribution inside Trapezoid-shaped CSG dam may be so different from conventional gravity dam.

Since it is necessary to examine the dynamic behavior of Trapezoid-shaped CSG dam carefully so as to evaluate the safety of this new type of dam during earthquake, we have conducted comprehensive dynamic analysis using FEM. Based on the results of our analysis, we discuss the effects of dam shape and deformability of foundation on dynamic behavior of Trapezoid-shaped CSG dam during earthquake. Main results of our study are as follows:

- 1) It is confirmed that the stress generated inside dam body of Trapezoid-shaped CSG dam during earthquake is quite lower than concrete gravity dam with conventional triangle shape.
- 2) The stress distribution inside dam body of Trapezoid-shaped CSG dam is affected largely by relative deformability of foundation to CSG. The larger the tensile stress become, as the deformation is relatively softer.

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1. INTRODUCTION

In Japan, dam design method, construction technologies and material utilization must be further rationalized to deal with the present shortage of dam sites with good conditions and to respond to the demand for cost reductions and the preservation of the environment.

Cemented Sand and Gravel (hereafter, it is referred as CSG in this paper)¹⁾ that is a new material for dam body was developed to realize the making the best use of materials produced near the site during dam construction.

CSG is a super lean mix material made by adding cement and water to lock-like materials such as riverbed gravel or excavation muck after removing its large sized stones.

Using the CSG will bring a benefit for cost reduction in material gathering. It can also reduce the cost of material production because the material production system can be much more simplified than an aggregate production plant generally required at concrete dam construction site.

To realize dams made of CSG, however, it is essential to apply a rational design method that accounts for the fact that its material strength is not as high as that of usual concrete for dams.

The "trapezoid-shaped CSG dam" ²⁾ which is a new concept of dam type concerning dam made of CSG and with a trapezoidal cross section has been proposed to solve this problem. A trapezoidal cross section can minimize stress inside the dam body and reduce its fluctuation during an earthquake.

In Japan where earthquakes occur with very high frequency, it is extremely important to design dams that guarantee the required seismic performance. In the case of trapezoid-shaped CSG dams, it is particularly important to evaluate their dynamic response properties during earthquakes. This report presents the results of a study of the dynamic behavior of a trapezoid-shaped CSG dam during an earthquake based on the results of the dynamic analysis of the stress distribution inside the trapezoid-shaped CSG dams using finite element method (FEM). The study was conducted to research the following two subjects.

- 1) Effects of the dam size and the deformability of the foundation ground on the dynamic behavior of a trapezoid-shaped CSG dam during an earthquake
- 2) Differences between the dynamic behaviors of a trapezoid-shaped CSG dam during an earthquake and that of a conventional concrete gravity dam

2. EARTHQUAKE RESPONSE ANALYSIS OF TRAPEZOID-SHAPED CSG DAMS

2.1 Outline

Figure 1¹⁾ shows the general cross-section of the trapezoid-shaped CSG dam that has been proposed. For this study, the dam body of a trapezoid-shaped CSG dam and its foundation ground were modeled as a 2D FEM. Based on the assumption that the dam body material is a linear elastic body in the small strain range, the dynamic analysis that accounts for static loading (self-weight of the dam body and hydrostatic pressure produced by the reservoir water) and dynamic loading during an earthquake (inertia acting on the dam body and hydrodynamic pressure produced by the reservoir water) was performed to obtain the distribution of displacement of each part and of stress produced inside the dam body.



Figure 1. Typical Cross Section of a Trapezoid-shaped CSG Dam¹⁾

2.2 Analysis condition

In order to estimate the size (or dam height) of a trapezoid-shaped CSG dam that can be realized and ground conditions necessary to construct a trapezoid-shaped CSG dam, this study set a number of analysis cases with varying conditions, focusing on dam height and the deformability of the foundation ground. The index of the deformability of the foundation ground was E_d/E_r that is the ratio of the modulus of elasticity of the dam body, E_d and the modulus of elasticity of the foundation ground, E_r . And as a special case, a study case where only the dam body was modeled but not the foundation ground was added. This special case corresponds to conditions where the foundation could be considered to be extremely hard bedrock.

In order to compare the characteristics of the stress distribution inside the trapezoid-shaped CSG dam with that of a normal concrete gravity dam, a comparative case for a dam with a right-angled triangle cross section was also performed.

Table 1 summarizes the analysis cases, and Table 2 shows the physical properties of the material used for the analysis of the various cases.

Case	Dam Type	Dam	Upstream	Foundation	Notes
		Height;	Downstream	Deformability;	
		Н	Slope	E_d/E_r	
Case 1	Trapezoid-	50m	1:1.0	$E_d/E_r = 2$	Basic condition
Case 2	shaped CSG	30m	1:1.0	$E_d/E_r = 2$	To study effects of
Case 3	dam	70m		$E_d/E_r = 2$	dam size
Case 4		50m	1:1.0	$E_d/E_r = 1$	To study effects of
Case 5				$E_d/E_r = 4$	deformability of
Case 6				No Foundation Model	foundation ground
				(Rigid Foundation	
				Condition)	
Case 7	Conventional	50m	Downstream;	$E_d/E_r = 2$	To comparison with
	concrete		1:0.8		a concrete gravity
	gravity dam		Upstream;		dam
			Vertical		

Table 1. Analysis Cases

Dam Body	Unit Mass	Young's	Poisson's	Notes
Material	[t/m ³]	Modulus of	Ratio	
		Elasticity ; E _d		
		[MPa]		
CSG	2.2	2.0×10^{3}	0.25	For Case-1 – Case-6
Concrete	2.3	2.0×10^{4}	0.25	For Case-7

Table 2. Physical Properties used for the Analysis

2.3 Analysis models

Figure 2 shows an example of a finite element (FE) model used for the study.

Because the purpose of the study was to evaluate the basic dynamic behaviors of a trapezoid-shaped CSG dam during an earthquake, the detailed structures inside the dam body such as concrete face for watertightness, shown in Figure 1 were not considered in the FE model.

In this study, the horizontal earthquake motion was input from the bottom of the foundation ground model so that the dynamic response properties of the dam body could be assessed accounting for the dynamic behavior of the foundation ground.

The boundary conditions of the foundation ground model were viscous boundary for the bottom and energy transmission boundary for both the upstream and downstream ends because it is necessary to remove the impact of the reflected waves produced inside the foundation ground of the analysis model by the input waves.

The range of the foundation ground model was decided based on the results of a past study ³; double the dam base length in the upstream and downstream direction and double the dam height in the depth direction.

The value of damping ratio was as set at 10% for the entire system including the dam body and the foundation ground

Regarding the reservoir water, the depth was set equivalent to 90% of the dam height (downstream side not considered), and in the dynamic analysis it was assumed to be an incompressible fluid and its effect during an earthquake was considered based on a consistent added mass matrix. The deposit sediment pressure was not considered.



Figure 2. Example of a FE Model

2.4 Input earthquake motion

The time history wave form of the input earthquake motion was set by adjusting the wave form installed from the bottom of modeled foundation ground so that the response wave at the center of the base of dam

would agree well with the "Hitokura wave" with its maximum acceleration enlarged to 250gal from original 183 gal.

"Hitokura wave" is one of the most typical wave form of earthquake motion actually observed in the lower inspection gallery of the Hitokura dam during the Hyogo-ken Nambu Earthquake in 1995. The dam is located near the epicenter of this earthquake that caused severe damage in the Kobe region.

The input earthquake motion used for the analysis is shown in Figure 3. Figure 4 indicates the acceleration response spectrum of the input motion shown in Figure 3.

In Case-6 shown in Table 1, where the foundation ground was not modeled, an enlarged acceleration observed at the Hitokura Dam was input directly into the base of the dam body.



Figure 3. Enlarged Hitokura Wave (Maximum Acceleration 250 gal)



Figure 4. Acceleration Response Spectrum of Enlarged Hitokura Wave

3. ANALYSIS RESULTS AND CONSIDERATION

3.1 Stress distribution at an usual loading condition (not during an earthquake)

The stress distribution of the model of Case-1 only for the static load is shown in Figure 5.

Table 3 shows the maximum values of the principal stress obtained in each model. The stress values are marked as positive for the tension side and as negative for the compression side. Overall trends of the stress distribution inside the dam body are roughly similar to those in Figure 5 concerning the other cases for trapezoid-shaped CSG dams; Case-2 - Case-6.

The values in figures for stress distributions presented in the remainder of this report are maximum values and the locations they occurred in the dam body of the principal stress on the tension side and on the compression side.

The following facts concerning the basic properties of the stress distribution inside a trapezoid-shaped CSG dam at an usual load condition can be found.

The results of the calculation of the tension side principal stress (σ_1) show that almost no tensile stress was occurred inside the dam body in all the analysis cases, although in Case-5 with the largest deformability of the foundation ground ($E_d/E_r = 4$), slight tensile stress is calculated for the center part of the dam base. This is the result of the fact that in a dam with a wider dam bottom, under conditions where the foundation ground is more easily deformed than the dam body, relatively large settlement of the center of the dam base is primarily caused by the self weight.

The compression side principal stress (σ_3) is obtained at maximum value at the downstream end in almost all cases.



Figure 5. Stress Distribution at an Usual Loading Condition (Case-1)

Case	Tension side	Compression side
	principal stress	principal stress
	σ ₁ [MPa]	σ ₃ [MPa]
Case-1	-0.00	-1.23
Case-2	-0.01	-0.78
Case-3	-0.01	-1.93
Case-4	-0.01	-0.77
Case-5	+ 0.06	-1.79
Case-6	+ 0.04	-0.92

Table 3. Maximum Stress at an Usual Loading Condition

3.2 Stress distribution during an earthquake

3.2.1 Outline

Figure 6 shows the maximum stress distribution inside a dam body obtained from the results of earthquake response analysis considering both static load and dynamic load during an earthquake in analysis Case-1.

Table 4 shows the maximum values of the principal stress obtained in each case including the other analysis cases. Overall trends of the stress distribution inside the dam body are roughly similar to those shown in Figure 6 in the other cases hypothesizing a trapezoidal CSG dam. However, of course, a look at the details reveals special characteristics that reflect the conditions of each case.

The following is a discussion of the basic characteristics of the stress distribution inside the body of a trapezoid-shaped CSG dam during an earthquake based on the above results.



(a) Tension side principal stress(σ_1)

(b) Compression side principal stress(σ_3)

Case	Tension side	Compression side
	principal stress	principal stress
	σ_1 [MPa]	σ ₃ [MPa]
Case-1	+ 0.51	-2.46
Case-2	+ 0.08	-1.56
Case-3	+ 1.29	-4.52
Case-4	+ 0.80	-1.97
Case-5	+ 0.59	-3.69
Case-6	+ 0.34	-1.17

Table 4. Maximum Stress during an Earthquake

3.2.2 Effect of dam size

The effect of dam size (dam height) on the stress distribution properties inside a dam body was studied by comparing the analysis results for three cases with differing dam heights (Case-1, Case-2, and Case-3 with dam heights of 30m, 50m, and 70m respectively).

Figure 7 shows the results of plotting the relationship of dam height with the maximum stress occurred in the dam body during an earthquake. It reveals that the higher a dam body, the larger the maximum value of both the tensile stress and the compressive stress.



Figure 7. Relationship of the Size (Dam Height) of a Trapezoid-shaped CSG Dam with Maximum Stress during an Earthquake

3.2.3 Effect of the deformability of the foundation ground

The effects of the deformability of the foundation ground on the stress distribution properties inside a dam body were studied by comparing the analysis results for three cases; Case-1, Case-4, and Case-5, with different ground conditions and a special case; Case-6 for rigid foundation.

From among the analysis results, Figure 8 shows the relationships of the deformability of the foundation ground (Ed/Er) with the maximum stress for three cases including foundation ground. It shows that overall, the higher the deformability of the foundation ground, the larger the stress occurred in a dam body during an earthquake.

The maximum values of both the tension side principal stress and the compression side principal stress were appeared at the upstream end or downstream end both in Case-4 ($E_d/E_r = 1$) and in Case-1 ($E_d/E_r = 2$) where the foundation ground were relatively stiff. In Case-5 ($E_d/E_r = 4$) where the foundation ground was relatively soft, however, the maximum value of the tensile stress occurred inside the dam base. This is considered to be a result of the effect of settlement by the self weight of the dam body as aforementioned.



Figure 8. Relationship of the Foundation Ground Deformability of a Trapezoid-shaped CSG Dam with Maximum Stress during an Earthquake

Next, the analysis results for Case-6 that did not model the foundation ground (dam height 50m) and Case-1 that modeled the foundation ground with the same conditions of the other properties as Case-6 were compared.

Figure 9 compares the distribution of stress along the dam base in the two cases. The figure shows that in the analysis results of the model including the foundation ground (Case-1), overall the stress shifts upwards (to the tension side) and the stress is larger at both the upstream and downstream ends compared with the Case-6.

These differences are considered to be a result of the fact that in the analysis model that did not include the foundation ground, the displacement of the base of the dam was limited to the horizontal direction due to the constraint of the displacement in the vertical direction, while in the model that considered the deformation of the foundation ground, the settlement of the dam body into the foundation ground at both the upstream and downstream ends are simulated.

As a reference, Figure 10 shows the deformation of Case-1 where deformation of the foundation ground was considered.



Figure 9. Stress Distribution along the Dam Base



Figure 10. Deformation of the dam at the Time of Maximum Stress Occurred (Case-1)

3.3 Comparison with a concrete gravity dam with right-angled triangle cross-section

The analysis results presented in section 3.2 were compared with the results for Case-7 of a concrete gravity dam with a right-angled triangular section shape, in order to compare the characteristics of the state of stress of a trapezoid-shaped CSG dam with those of a concrete gravity dam.

Figure 11 shows the distribution of the maximum stress in the Case-7. Figure 12 presents the results of a comparison of the stress distribution along the dam base of two cases; Case-1 and Case-7. The horizontal axis in Figure 12 represents the normalized distance obtained by dividing the distance from the upstream end of the dam by the length of the model in each case.

Figure 12 shows that in a trapezoid-shaped CSG dam, both the tensile stress and the compressive stress during an earthquake are overall, much lower than in a concrete gravity dam. This is considered to be a result of the fact that a trapezoidal section disperses the stress more than usual concrete gravity dam

section, because its dam base is much wider. This reconfirms that a trapezoidal section is the rational shape for a dam body made of material such as CSG with lower strength than concrete used to construct conventional concrete dams.



(a) Tension side principal stress(σ_1)







(Trapezoid-shaped CSG Dam and Concrete Gravity Dam with Right-angled Triangle Cross-Section)

4. Conclusions

In this study, the dynamic analysis using 2D FEM of dam body and foundation ground are performed in order to evaluate the stress state during an earthquake of a trapezoid-shaped CSG dam that has been proposed as a new type of dam in Japan.

Based on the results of the analysis concerning the stress distribution inside the dam body, the effects of dam size and deformability of the ground on the dynamic response properties during an earthquake of a trapezoid-shaped CSG dam were discussed.

Additionally, differences between these results and those for a conventional concrete gravity dam were also studied.

The following is a summary of the findings obtained by this study.

- 1) The stress of a trapezoid-shaped CSG dam rises as its height is increased and it is also dependent on the relative deformability of the foundation ground to the dam body. The more likely the foundation ground is to be deformed relative to the dam body, the greater the stress produced inside the dam body.
- 2) It has been confirmed that in a trapezoid-shaped CSG dam, the stress during an earthquake is much lower than that of a conventional concrete gravity dam.

The stress inside a trapezoid-shaped CSG dam body obtained from this analysis is sufficiently lower than that in a conventional concrete gravity dam, but in a case where the ground deformability is particularly large, slightly larger stress is calculated though localized at both the upstream and downstream ends. In the future, further study of appropriate design methods for trapezoid-shaped CSG dams suited to ground conditions will be studied considering such points accompanied by the material strength and other physical properties of CSG material⁴⁾.

Acknowledgments

The authors wish to take this opportunity to thank Nagahara Hiroshi, Researcher in the Water Management and Dam Division of NILIM for his assistance with the preparation of this report.

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