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FAILURE MECHANISM OF CONCRETE SABO DAM BY ROCK IMPACT

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Abstract. *This paper presents a computational approach on the failure mechanism of concrete sabo dam by rock impact. First, the site survey after a debris flow disaster was performed in order to investigate the failure mechanism of a concrete sabo dam and examine the size and velocity of rocks. Especially, it was observed that cracks occurred on the rear face of concrete sabo dam. Therefore, we assumed four scenarios of a rock impact onto a concrete dam. Case 1 is a small rock with a diameter of 1.1m and impact velocity of 7.01m/s onto the upper part of the dam, and Case 2 is a small rock onto the lower part of the dam. Case 3 is a large rock with a diameter of 6.7m and impact velocity of 9.7m/s onto the upper part of the dam, and Case 4 is a large rock onto the lower part of the dam . The impact analysis was conducted for four scenarios of a rock onto a concrete sabo dam by using the AUTODYN.*

1 INTRODUCTION

In order to prevent debris flow and sediment-related disasters, many concrete sabo dams have been constructed in the mountainous area of Japan, as shown in Figure 1. However, some concrete sabo dams have collapsed due to rocks in the debris flow, as shown in Figure 2. These disasters may have resulted due to torrential downpour as a result of unusual weather conditions [1, 2] .

Many studies have been devoted to the failure due to impact load by rock collisions [3,4,5] and impulsive fluid load [6]. However, the effects of the impact velocity and the size of impacting rocks on the concrete sabo dam have not been sufficiently investigated thus far.

To this end, this paper presents a computational approach relevant to the failure mechanism of a concrete sabo dam, in order to examine the effects of the size and the velocity of a rock in debris flow.

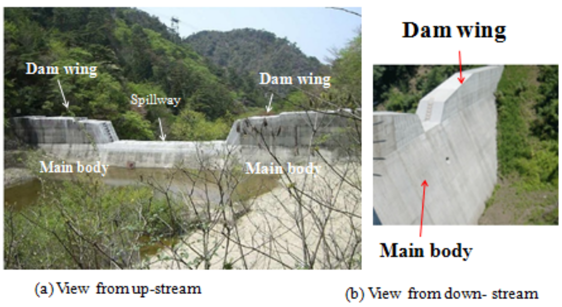

Figure 1: Concrete sabo dam

Figure 2: Collapse of concrete sabo dam

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First, the site survey after disaster was performed in order to investigate the failure mechanism of a concrete sabo dam and examine the size and velocity of rocks. Second, an impact analysis was conducted to examine the impact behavior of a concrete sabo dam against small and large rocks by changing the impact point of the dam. In the impact analysis, the AUTODYN [7] was used by incorporating CAPROUS model [8,9] which was conformed in the low velocity impact [10].

Figure 3: Cracks on the rear face of the dam

2 FIELD SURVEY

At the planning of dam construction, a design load was assumed as a rock diameter with 1.1m and flow velocity with 7.01m/sec by the field survey before the disaster. After the debris flow disasters, we surveyed the disaster site to investigate the failure mechanism of concrete sabo dams, the size and velocity of rocks. We discovered the cracks on the rear face of a concrete sabo dam with the width of about 10m, as shown in Figure 3. We also found out the largest rock with the diameter of 6.7m, as shown in Figure 4(a). However, the diameters of rocks at the site were almost 1m, as shown in Figure 4(b). The flow velocity of debris flow was estimated as 9.7 m/sec by measuring the peak flux of debris flow of 730m^3/sec and computing based on the Manning formula.

(a)Largest rock diameter of 6.7m (b)Average rock diameter of 1m

Figure 4: Remaining rocks at the field survey

3 SCENARIOS OF ROCK IMPACT ONTO A CONCRETE SABO DAM

The impact analysis was conducted for four scenarios of a rock onto a concrete dam as shown in Figure 5 by using the AUTODYN based on rock and concrete material parameters as shown in Tables 1 and 2.

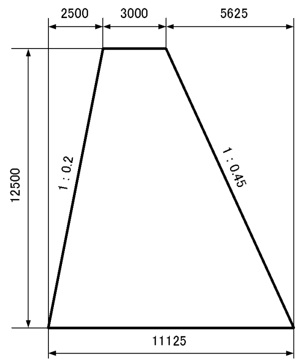


Figure 5: Concrete sabo dam for analysis

Table 1: Rock material parameter

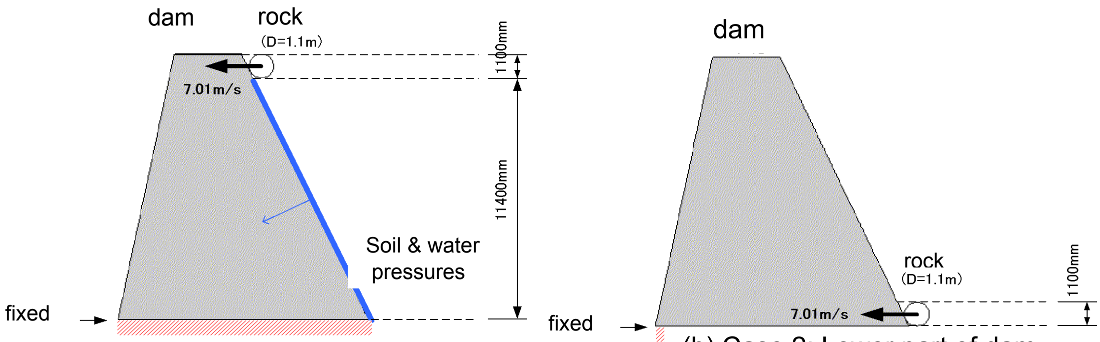
Item	Value
Density (kg/m^3)	2598
Constitutive law	Elastic
Young's modulus(GPa)	49.0
Poisson's ratio	0.23
Volume elastic coefficient (GPa)	30.2
Elastic shear coefficient(Gpa)	19.9

Table 2: Concrete material parameter

Item	Value
Density (kg/m^3)	2300
Constitutive law	CAPROUS model
Young's modulus(GPa)	22.0
Poisson's ratio	0.2
Elastic shear coefficient(MPa)	9.17
Compressive strength (MPa)	18.0
Tensile strength (MPa)	1.58
Failure law	Spalling due to CAPROUS model

3.1 Case 1: A small rock impact onto upper part of concrete sabo dam

A small rock with diameter of 1.1m and velocity of 7.01m/sec hit on the upper part of concrete dam after acting of the soil and water pressures as shown in Figure 6(a).
The failure process by computation of case1 was obtained as shown in Figure 7(a). At the time of 10ms, the cracks have occurred at the impact point, and then the shearing failure occurred partially at the back side of base. This may be caused by the dam vibration of the horizontal displacement –time realtion. Therefore, the failure of case 1 was only locally at the impact point and the bottom.



(a)Case1:Upper part of dam (b) Case 2: Lower part of dam

Figure 6: A small rock impact onto the dam

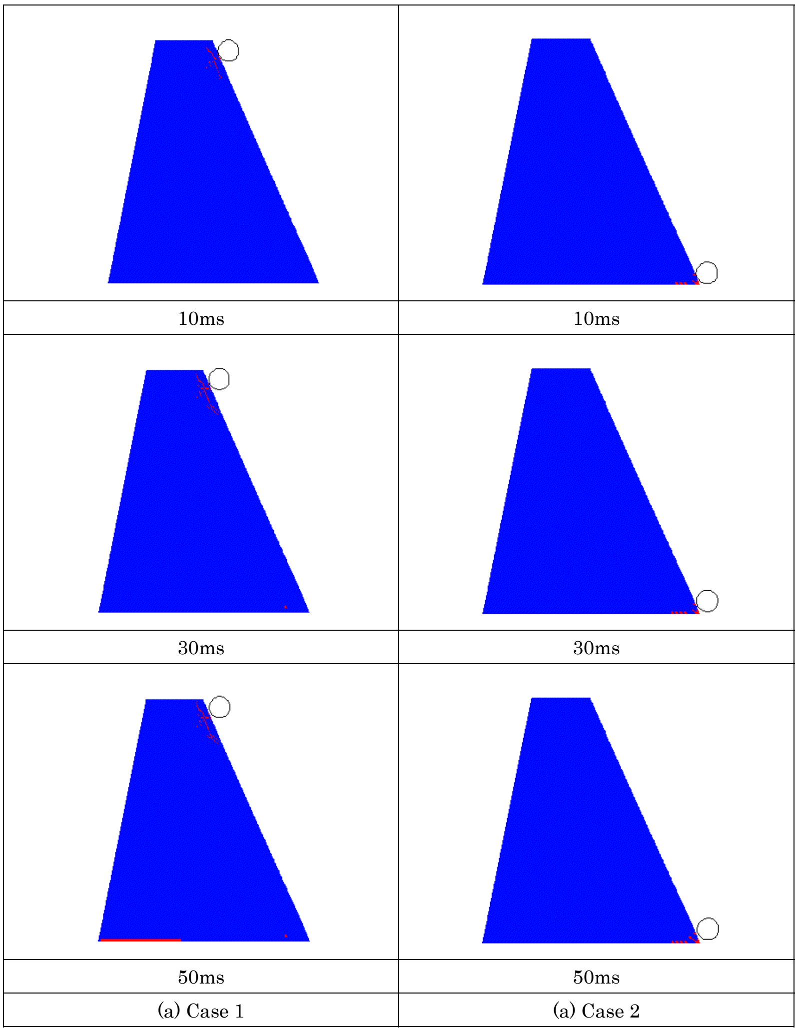


Figure 7: Failure mechanisms of Cases 1 and 2

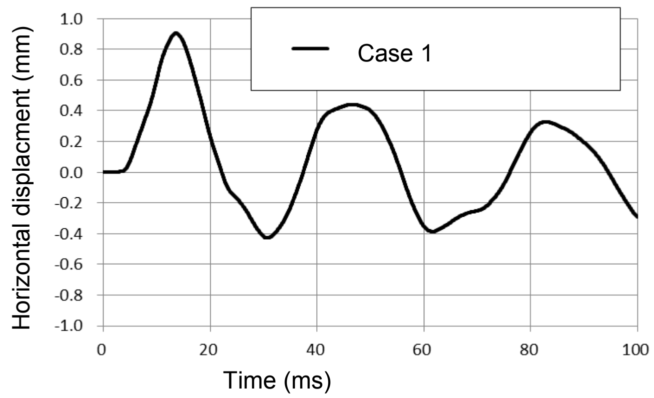
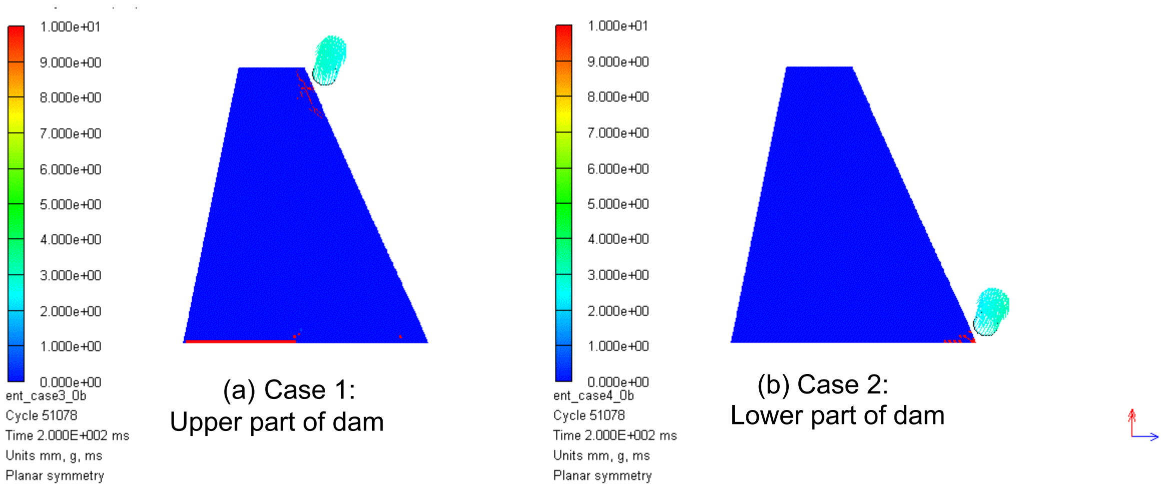


Figure 8: Horizontal dispalcement-time relation

Figure 9(a) shows a velocity distribution of a small rock onto the upper part of the dam at the time of 50ms. It was found that a rock jumped up to the top of dam and dropped down to the opposite side of impact direction.

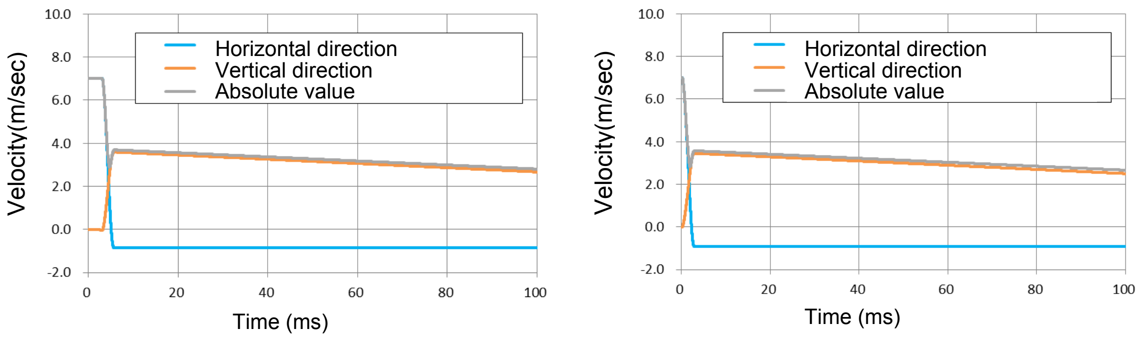


(a) Case 1: Upper part of dam

(b) Case 2: Lower part of dam

Figure 9: A small rock impact velocity distributions

Figure 10(a) illustrates the relationship between impact velocity and time against a small rock. It was confirmed that the horizontal direction of impact velocity was suddenly decreased from 7.01m/sec at 0ms to -0.5m/s at 5ms which means the opposite direction of impact. On the other hand, the vertical direction of impact velocity was increased to 3.8m/sec at 6ms, but decreased to 3.0m/sec at 100ms due to the gravity effect. Therefore, the absolute velocity became the same one as vertical direction after the time of 6ms.



(a) Case 1: Upper part

(b) Case 2: Lower part

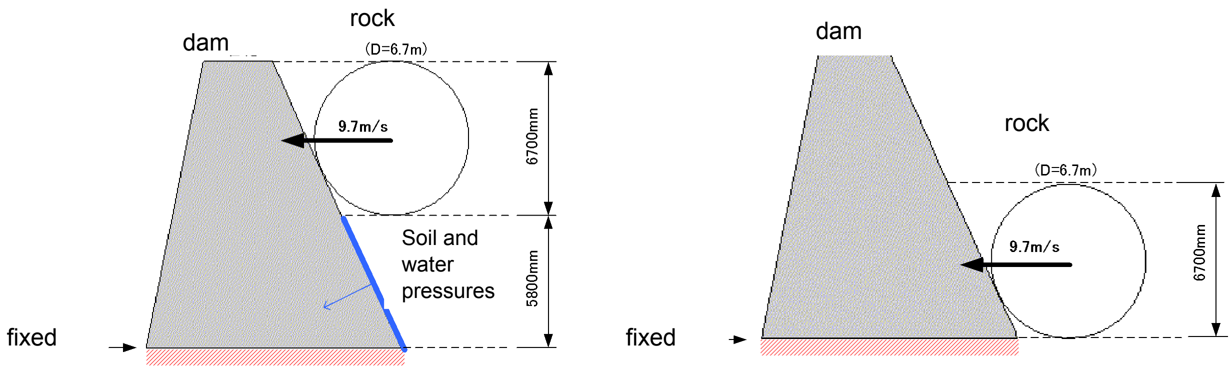
Figure 10: Rock velocity-time relation of a small rock

3.2 Case 2: A small rock impact onto the lower part of dam

A small rock with diameter of 1.1m and velocity of 7.01m/sec hit on the lower part of the dam without soil and water pressures, as shown in Figure 6(b).
The failure process of case 2 was obtained as shown in Figure 7(b).
At the time of 10ms, the cracks have occurred at the only impact point of the bottom, but the failure has not enlarged at the bottom of dam. Therefore, case 2 was locally failed at the only impact point of the bottom.
Figure 8(b) shows a velocity distribution of a small rock onto the lower part of the dam at the time of 50ms. It was found that a rock jumped up to the dam and fell to the opposite side of impact direction.
Figure 9(b) illustrates the impact velocity – time relation of a small rock onto the lower part of the dam. It was recognized that the horizontal direction of impact velocity was suddenly decreased from 7.01m/sec at 0ms to -0.4m/s at 3ms which means the opposite direction of impact. On the other hand, the vertical direction of impact velocity was increased to 3.7m/sec at 3ms and decreased to 2.7m/sec at 100ms due to the gravity effect. Therefore, the absolute velocity became the same one as the vertical direction after the time of 3ms.

3.3 Case 3: A large rock impact onto upper part of dam

A large rock with diameter of 6.7m and velocity of 9.7m/sec hit on the upper part of concrete sabo dam after acting of the soil and water pressures, as shown in Figure 11 (a).



(a) Case 3: Upper part of the dam

(b) Case 4: Lower part of dam

Figure 11: A large rock impact onto the dam

(a) Failure mechanism

The failure process of case 3 was obtained as shown in Figure 12.
At the time of 10ms, the cracks have occurred at the impact point, and then tensile failure has extended at the front side of bottom of the dam at the time of 15ms, and then, the shearing failure occurred from the impact point to the back end of the bottom at the time of 20-25ms. The compressive wave has propagated to the rear face and then,reflected to the front direction. This is called as a spalling phenomenon occurred at the rear face. Consequently, the failure mechanism of case 3 was widely occurred by the shearing and tensile failures at the same time. Especially, the cracks at the rear face of the dam as shown in Figure 3 may be caused by the spalling phenomenon at case 3.

(b) Rock and dam body velocities

Figure 13(a) and (b) show the rock and dam body velocity distributions against a large rock impact onto the upper part of the dam at the time of 50ms, respectively. It was found that a rock jumped up to the top of dam and fell to the opposite side of impact direction. It was also observed that dam body vibrates widely to the downstream. Then, it was confirmed that the dam body rotated about the back end of the base and tended to overturn to the downstream.

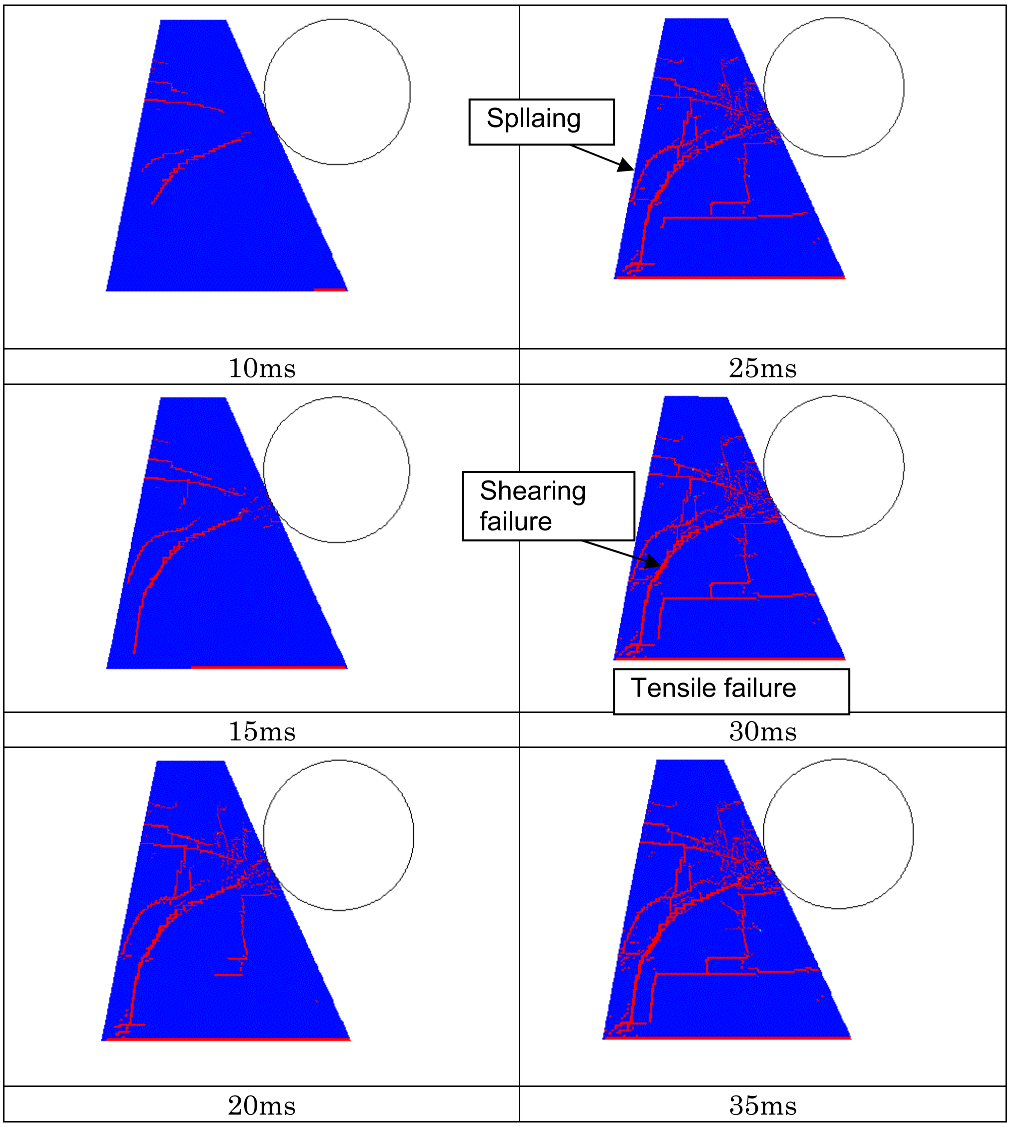
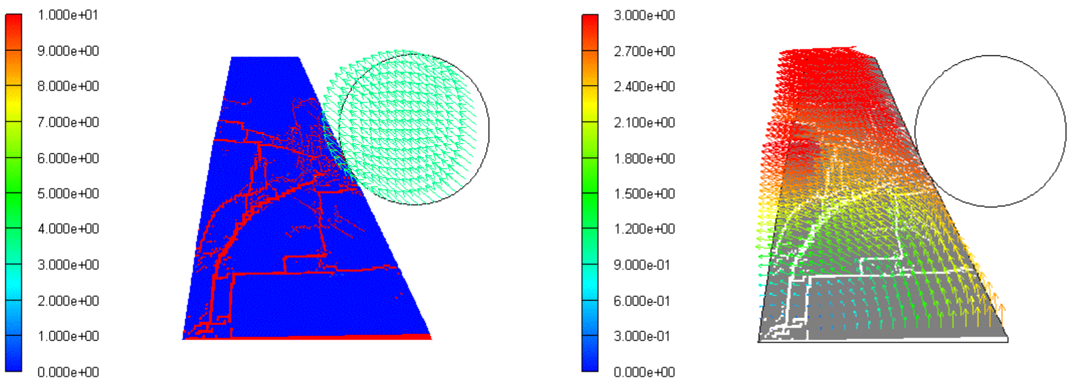


Figure 12: Failure mechanism of Case3



(a) Rock velocity (b) Dam body velocity

Figure 13: Rock and dam body velocities of Case 3

(c) Rock velocity-time relation

Figure 14 illustrates the rock velocity – time relation of a large rock impact onto the upper part of the dam (case 3). It was recognized that the horizontal direction of impact velocity 9.7m/s was suddenly decreased to 3.7m/s at 13ms, and became 3.0m/s at 100ms.
On the other hand, the vertical direction of impact velocity increased to 2.5m/sec at 15ms, but decreased to 2.2m/sec at 100ms due to the gravity effect. Therefore, the absolute velocity became 4.0m/sec after the time of 20ms. Consequently, the remaining rock velocity became constant of about 4.0m/sec, and therefore, it was confirmed that the dam body would tend to overturn to the downstream due to the tensile failure at the base and the diagonal shearing failure of main body.

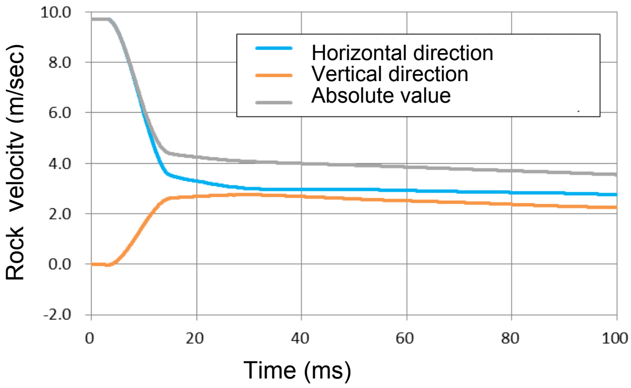


Figure 14: Rock velocity-time relation of Case 3

3.4 Case 4: A large rock impact onto lower part of dam

A large rock with diameter of 6.7m and velocity of 9.7m/sec hit on the lower part of concrete dam as shown in Figure 11 (b).

(a) Failure mechanism
The failure mechnism of case 4 was obtained, as shown in Figure 15. At the time of 10ms, the compressive wave has propagated to the rear face and then, reflected to the front direction. Therefore, the cracks occurred at the rear face due to spalling effect of wave propagation. The shearing failure has started at the back side of bottom of the dam at the time of 10-15ms.The another shearing failure has extended from the impact point to the rear face of the dam, at the same time of 20-25ms. Consequently, the failure mechanism of case 4 was widely occurred by the two shearing failures at the bottom and the main body simultaeously. Espeacially, the cracks at the rear face of the dam as shown in Figure 3 may be also considered by the spalling phenomen at case 4.

(b) Rock and dam body velocities

Figure 16(a) and (b) show the rock and dam body velocity distributions against a large rock impact onto the lower part of the dam at the time of 50ms, respectively. It was found that a rock jumped up to the upper direction and fell to the opposite side of impact direction. It was also observed that dam body has widely moved to the direction of downstream.

(c) Rock velocity-time relation

Figure 17 illustrates the rock velocity – time relation of Case 4 that a large rock impact onto the lower part of the dam. It was recognized that the horizontal direction of impact velocity 9.7m/s was suddenly decreased to 2m/s at 15ms, and became 1.2m/s at 100ms. On the other hand, the vertical direction of impact velocity increased to 3.5m/sec at 15ms, but decreased to 2.5m/sec at 100ms due to the gravity effect. However, the absolute velocity of rock was 4.0m/s at the time of 15ms and became 3.0m/s at 100ms.

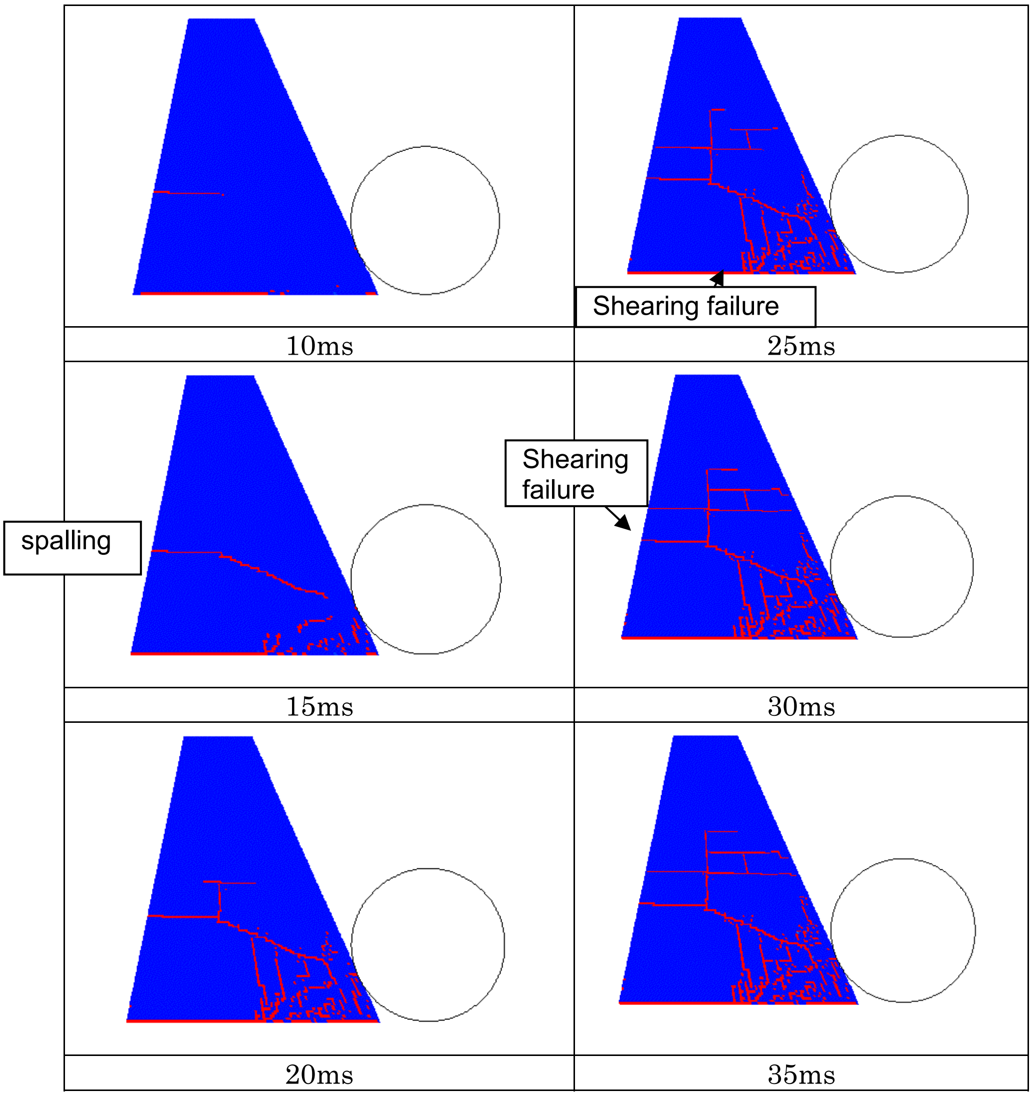


Figure 15: Failure mechanism of Case 4

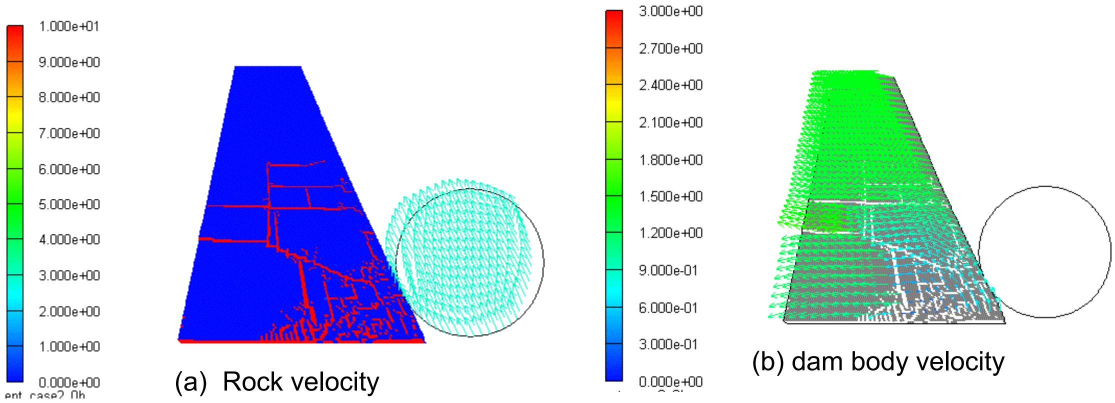


Figure 16: Rock and dam body velocities of Case 4

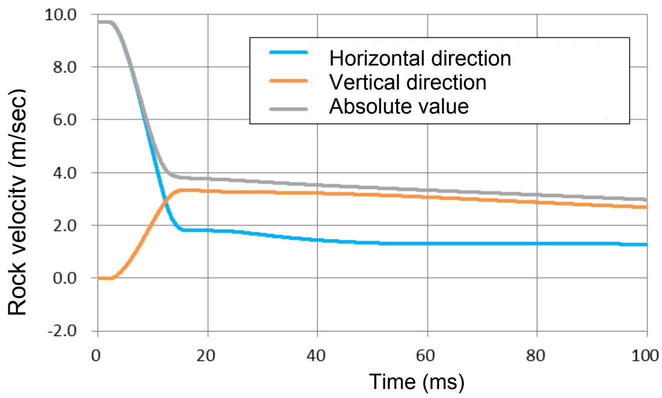


Figure 17: Rock velocity-time relation of Case 4

4 CONCLUSIONS

This study has presented the failure mechanisms of concrete sabo dams against small and large rock impacts onto the upper and lower parts of the dam, respectively.

The following conclusions are drawn from this study.

(1) As the results of field servey before a debris flow disaster, the design rock load was the diameter of 1.1m and velocity of 7.01m/s (which were used in case 1 and case 2). However, after the debris flow disaster, we found the largest rock with diameter of 6.7m and velocity of 9.7m/s(which were used in case 3 and case 4).

(2) In case 1 (A small rock impact onto upper part of dam), the failure was locally at the only impact point and the bottom.

(3) In case 2 (A small rock impact onto lower part of dam), the concrete dam was locally failed at the only impact point of the bottom.

(4) In case 3 (A large rock impact onto upper part of dam), the failure mechanism was widely occurred by the shearing and tensile failures at the same time. The dam body rotated about the back end of the base and tended to overturn to the downstream.

(5) In case 4 (A large rock impact onto lower part of dam), the failure mechanism was widely occurred by the two shearing failures at the bottom and the main body simultaneously.

(6) The cracks occurred at the rear face of the dam may be considered by the effect of spalling phenomenon at cases 3 and 4.

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