RIPRAP DETERIORATION AND ITS INFLUENCE ON SLIP STABILITY OF ROCKFILL DAMS

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ABSTRACT

This research introduces past study cases on riprap deterioration and discusses the thickness of riprap appropriate for slip stability of rockfill dams. We examine the appropriate thickness of riprap in Japan considering our investigation results and other studies' results. Moreover, we also conduct numerical analysis of how riprap weathering and deterioration affects the slip stability of the dam body. As the result, we confirmed that no major reduction in slip safety factor within the practically conceivable scope of deterioration range and strength reduction ratio.

INTRODUCTION

There is a growing strong demand for appropriate maintenance of many existing dams to elongate their service life. Rockfill dams are constructed by compacting natural geotechnical materials. On the other hand, concrete dams are constructed with concrete, which gains strength by chemically bonding with cement. Because rockfill materials themselves are natural ones, authors consider that rockfill dams are considered to be more resistant to aging deterioration than concrete dams.

Now, the surface of a rockfill dam is exposed to external conditions such as waves, wind, rain, temperature change, or change of the reservoir water level. Thus, one of the major slope protection work called riprap is constructed over the surface. The general procedure is to use rock lumps with excellent hardness and durability. But some dams suffer from weathering, deterioration and breaking of the riprap

Currently there are no specific methods to study riprap deterioration and no specific judgment criteria for the necessity of riprap repair. Under these circumstances, past surveys of deterioration of riprap materials provide very useful information. This research presents past studies of riprap deterioration at Midorikawa dam located Kumamoto prefecture in Japan, and discusses the thickness of riprap appropriate for the slip stability

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of rockfill dams. And we also conduct numerical analysis of how riprap weathering and deterioration affects the slip stability of the dam body of rockfill dams.

SURVEY ON RIPRAP DETERIORATION

Dam to survey

The Midorikawa Dam, the subject of this survey, is a central earth core type rockfill dam constructed in 1971 in Kumamoto prefecture (32 degrees north latitude) as a multi-purpose dam by the Kyushu Regional Construction Bureau, Ministry of Construction (currently Kyushu Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism). It measures 35 m in dam height, 244.0 m in crest length, and 367,400 m^3 in dam body volume. The typical cross-section of this dam is shown in Figure 1. Five kinds of rock are used as the riprap materials, which are granite porphyry, foliated granodiorite, weakly altered granodiorite, hornblende granite, and diorite, while granite porphyry and foliated granodiorite are used as the rock materials.

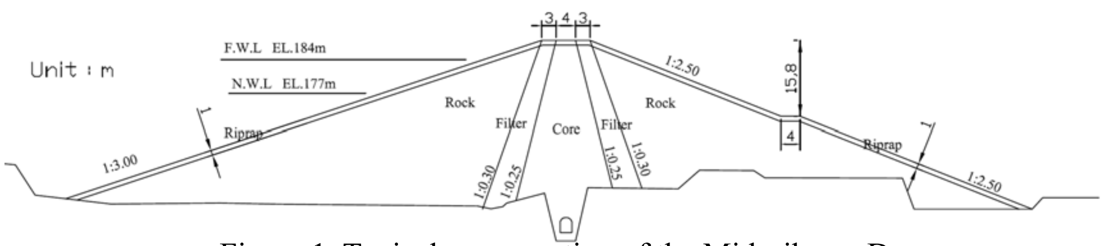


Figure 1. Typical cross-section of the Midorikawa Dam

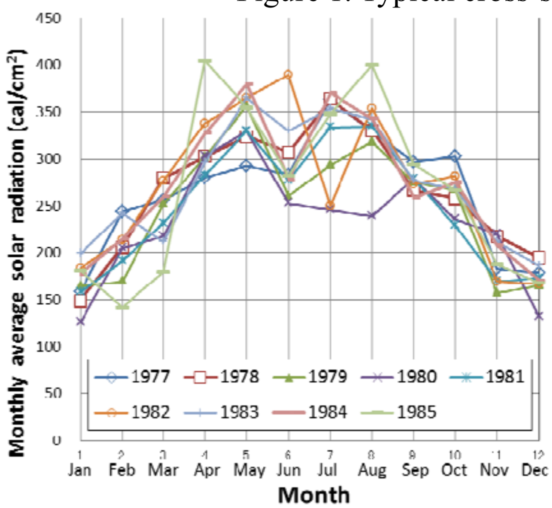


Figure 2. Changes in monthly average temperature (1981 to 1985)

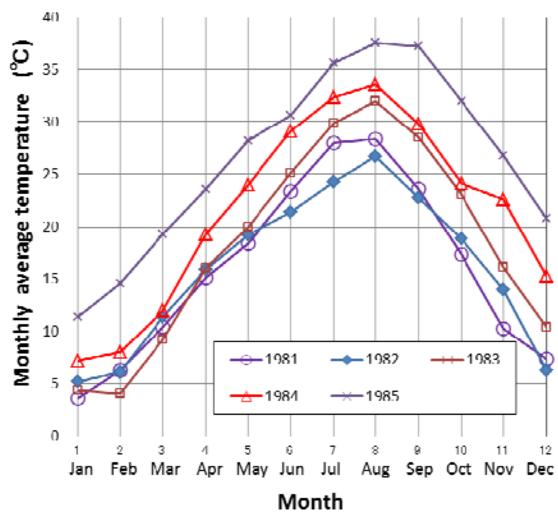


Figure 3. Changes in monthly average insolation (1981 to 1985)

Meteorological conditions around the subject dam

Average temperature: Changes in monthly average temperatures from 1981 to 1985 are shown in Figure 2. Figure 2 indicates that the difference between the monthly average temperatures in the hottest month (August) and the coldest month (January) is about 21.0

to 26.0℃. There is a large variation in annual average temperatures from 1981 to 1985 when they ranged between 16.1℃ and 26.5℃ with the average temperature in the entire period being 19.7℃.

Amount of insolation: Changes in the monthly average amount of insolation from 1977 to 1985 are shown in Figure 3. According to Figure 3, the monthly average amount of insolation remains high from April to August, and the maximum monthly average amount of insolation in each year ranges from 330 to 400 cal/cm^2. The annual average amount of insolation is about 230 to 270 cal/cm^2, indicating a smaller variance among those years. These variances are assumed to be affected by the amount of rainfall and the amount of cloud.

Outline of the survey

Field surveys were conducted three times at the Midorikawa Dam in 1979, 1983, and 1987 in order to understand the status of deterioration of the riprap materials and of the rock materials located under the riprap.

Field survey: Weathering status of riprap materials on the upstream and downstream surfaces of the Midorikawa Dam were evaluated at intersections of 20-m interval grids as shown in Figure. 4. The survey area was a 2m × 2 m square centering on the measurement coordinates of each survey location. Each survey area was sketched in detail, and the evaluations, mainly by visual check and hammering, were classified in five degrees shown in Table 1.

Table 1. Evaluation criteria for the degree of weathering

Degree of weathering	Condition of weathering	point
I	Rock surface is not almost at all discolored or only slightly discolored. When hit by a hammer, a clean sound is generated. Almost no change occurred since completion except for discoloration.	5
II	Rock surface partially shows some weathering and deterioration. Although the surface is discolored in brown to dark green, a clean sound is emitted when hit by a hammer.	4
III	Rock surface shows some weathering and deterioration in whole. The surface is discolored in brown, but the rock quality is relatively hard. The rock showed cracking, and its strength was slightly reduced.	3
IV	Rock surface peels along the cracks. Rock has many cracks, and its binding power has been decreased. Many cracks are open. Rock can be manually crumbled along the cracks.	2
V	Rock has almost lost its binding power. When you only touch the rock with your fingers, the rock crumbles into pieces beyond its original shape.	1

Based on the sketched drawings, the cover area of each rock type was calculated with a planimeter, and the results were summarized by main rock type of each mesh and by weathering degree as shown in Figure 5. By the way, weathering degree classification is based on the field survey results at the time of 1979 and 1985. It is, therefore, not clear if such weathering and deterioration has progressed with time after construction of the dam or such situation already occurred when the dam was constructed.

As shown in Figure 4, a trench excavation was conducted at the following 2 locations; Point X located on the upstream surface at a lower elevation, where riprap was not much weathered, and Point Y located on the downstream surface at a higher elevation near the top of dam, where riprap weathering was seriously progressed. The purpose of this trench excavation was to check the status of weathering of rock materials covered by riprap materials. The trench depths are deeper than riprap thickness 1m.

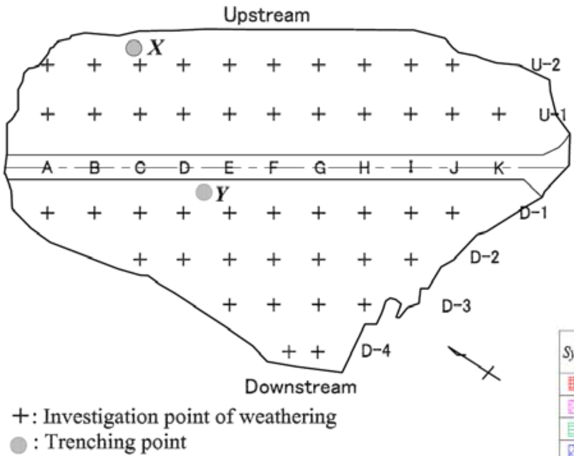


Figure 4. Survey points at Midorikawa dam

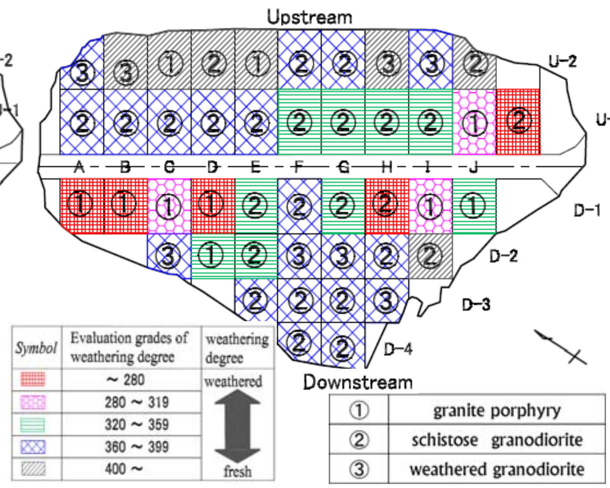


Figure 5. Rock type classification & weathering degree classification

Laboratory test: Specific gravity and water absorption test were conducted for the each rock types. Granodiorite and granite porphyry, which content ratio in riprap was particularly high, were put to soaking and drying test, microscopic observation and X-ray analysis. Rock materials investigated by trench excavation of Point Y were also sampled and applied to grain size analysis and specific gravity and water absorption test.

Outline of the riprap material survey results

Survey on the degree of weathering and deterioration: The evaluation grades were calculated by multiplying the classified area by degree of weathering. As a result, the weathering degrees of each rock type were evaluated as shown in Figure 6. From this figure, we confirmed that all types of rock show weathering and deterioration, and the weathering degree of granite porphyry is especially high.

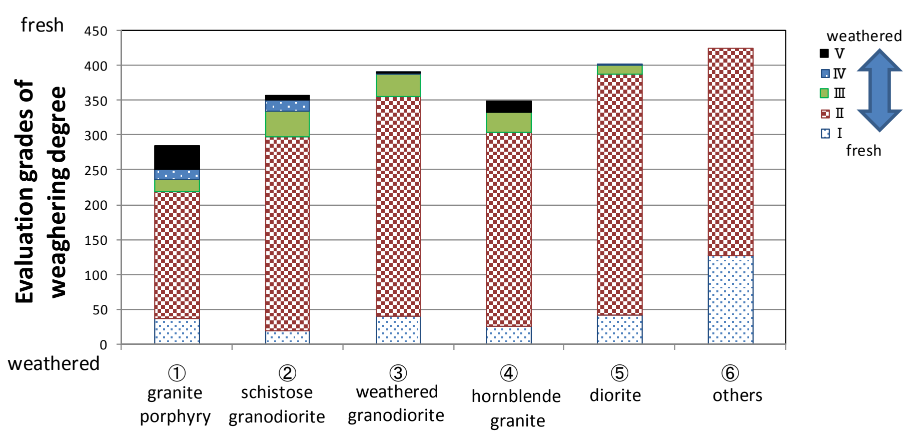


Figure 6. Weathering degree evaluation grades of riprap materials

We analyzed weathering characteristics of riprap by focusing on the relationship between weathering degree and the location. According to Figure 5, it is confirmed that the weathering degrees of the same materials is more advanced in the downstream surface than in the upstream surface. Considering the elevation, weathering degree is more advanced at higher locations in the both of surfaces.

Since the downstream side of the Midorikawa Dam faces southwest, it is exposed to insolation longer than the upstream side. The component ratio of granite porphyry is higher in the material at higher locations. These factors are considered to be causes of weathering and deterioration.

Laboratory test results: We confirmed following facts by laboratory test results for riprap materials (Yamaguchi et al. 2010). The specific gravity is high and that water absorption is small, less than 1.0%, for all types of rock. The weight loss by soaking and drying of granodiorite and granite, however, did not progress almost at all for the fresh rock but that the weathered rock suffered serious progress of weight loss.

According to the results of microscopic observation and X-ray diffraction of grandiorite and granite porphyry (Yamaguchi et al. 2010), it is clearly shown that mineral alteration was promoted with the progress of weathering. Particularly it is laumontite not contained in fresh rock that is presumably the cause of rock weathering.

Outline of the rock material survey results

Survey on the degree of weathering and deterioration: The degree of deterioration is low at Point X, and high at Point Y. Although the riprap material was not weathered at Point X, slightly weathered alteration was partly observed in the rock material. At Point Y characterized by weathered riprap, the rock contained a slightly larger amount of weathered materials than at Point X, but there is no major difference in the overall degree of weathering between rock materials at Point X and Point Y. Since the degree of rock material weathering and deterioration is small regardless of the degree of weathering and deterioration of the riprap, the degree of deterioration over time after construction of the dam is estimated to be small at the Midorikawa Dam.

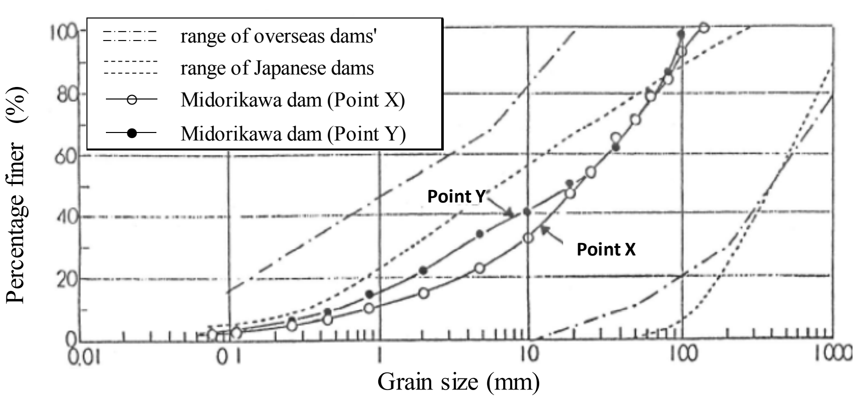


Figure 7. Grain size distributions of rock materials

Table 2. Outline of grain size measurement and specific

grain size (mm)	sample of Point X			sample of Point Y		
	specific gravity		water absorption (%)	specific gravity		water absorption (%)
	saturated surface-dry condition	oven dry condition		saturated surface-dry condition	oven dry condition	
~ 63.5	2.71	2.69	0.80	2.72	2.70	0.79
63.5 ~ 25.4	2.71	2.68	0.96	2.71	2.68	0.91
25.4 ~ 4.76	2.68	2.65	1.14	2.66	2.52	1.64

Grain size analysis and specific gravity and water absorption test: Grain size analysis and specific gravity/water absorption test of these samples were performed. Figure 7 shows the grain size distribution curves, and Table 2 shows the results of specific gravity and water absorption test.

Figure 7 contains the grain size distributions of the rock materials of some overseas and Japanese rockfill dams. The maximum grain size of Midorikawa dam's rock material is 300mm, and the representative distribution curves of Midorikawa dam's rock material fall inside the range of Japanese dams'.

The findings from those diagrams are summarized in Table 3.

Table 3. Rock material survey results

(1)	The rock material of this dam has a high content of particles relatively finer in size. The maximum grain size at Point X and Point Y were accidentally less than 300mm, but Midorokawa dam's distribution curves (Point X,Y) are within those of rock materials used for rockfill dams in overseas.
(2)	The content ratio of fine particles 0.075 mm or smaller is below 3%, and no grain refining by weathering is observed.
(3)	The specific gravity of each particle is high, and its water absorption is low. In particular, the water absorption of rocks whose particles 63.5 mm or larger is below 1%, and it almost equal to that of fresh rocks.
(4)	Permeability estimated from grain size distribution is considered to fully satisfy the drainage performance of the rock zone.

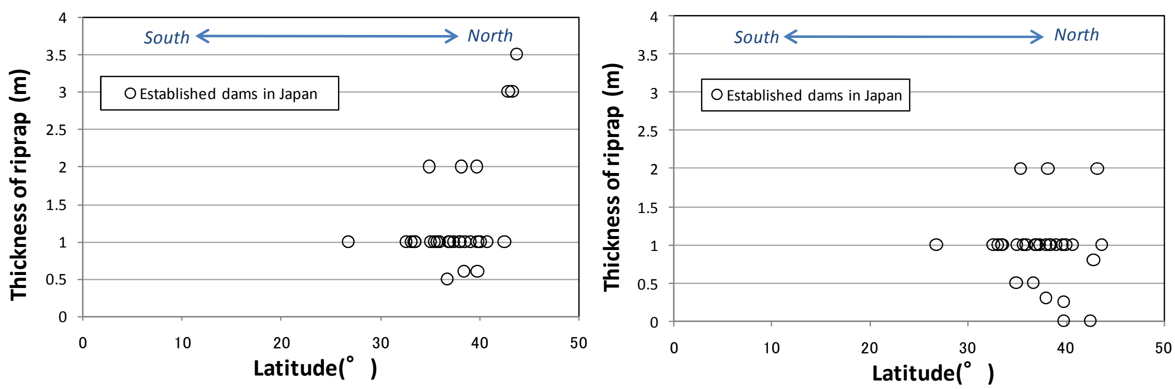
Those survey results indicate that even if some weathering and deterioration observed in rock materials had occurred over time after dam construction, such change has had almost no effect the functions of the rock material.

Discussion on the necessary thickness of riprap

At first, we defined the normal direction against the slope as the direction of riprap thickness. According to the earlier mentioned research results, we found that even when the riprap materials with poorer weathering resistance were used as like point Y, if the riprap covering is 1 m thick, the rock material, lying immediately under the riprap would suffer almost no weathering or deterioration even if the rock material was originally relatively less durable.

Nishida (1984) confirmed that the thickness of weathered riprap was 50cm or less, by a similar survey at rockfill dam in cold region of Japan. He also confirmed the following facts by field investigations at the dam. The influence of change of air temperature is decreasing inversely proportional to the distance from surface of dam body. Within about 1m from the dam surface, the degradation conditions related to the freeze-thaw and dry-wet resulting from temperature change are remarkably eased. Inside about 1.5m from dam surface, there is almost no influence of air temperature. In addition, similar survey results were reported from the other field surveys of rockfill dams in Japan (e.g., Eto et al. 1997, Japan Dam Engineering Center 2005).

We investigated and arranged relations between latitude of rockfill dams in Japan and their riprap thickness, as shown in Figure 8. This figure indicates that thicknesses of upstream riprap were designed as 1m or more in almost dams constructed in the region south of 40 degrees north latitude. The designed value of 1m in the region is considered is to be appropriate, considering the survey results at Midorikawa dam and other dams. It can be considered that the riprap with 1m thickness has a significant effect to the dam in Hokkaido region located north of 40 degrees north latitude in preventing deterioration, but trench surveys is necessary to discuss the appropriate value of riprap thickness in Hokkaido region



(a) Upstream (b) Downstream

Figure 8. Distribution of thickness of riprap in Japan

On the other hand, in more than half of the cases, the thickness of downstream riprap is designed as 1m or more, but in some cases, the thicknesses of downstream riprap were designed as less than 1m. In such cases, the downstream surface is assumed as not affected by waves and change of the reservoir water level, so the design thickness of downstream riprap is set as less than the upstream riprap thickness. However, the survey results of Midorikawa Dam show that the influence of insolation is as great as other weathering factors. Thus, there might be some cases in which weathering and deterioration of downstream riprap has been proceeding faster than in upstream riprap as seen at Midorikawa Dam. Therefore, if thickness of riprap is less than 1m, it is necessary to pay attention to its weathering and deterioration over time in considering the environmental conditions around such dams.

EVALUATION OF THE INFLUENCE OF RIPRAP DETERIORATION ON SLIP STABILITY BASED ON NUMERICAL ANALYSIS

Analysis method and analysis conditions

We conducted numerical analysis under the condition that the material strength in the deterioration range is reduced. In the analysis, the thickness of deterioration range (*t*) and the rate of strength reduction (*Ds*) are set as parameters and multiple slip stability analyses are done to evaluate the relationship between those parameters and the slip safety factor.

Table 4. Material properties for numerical analysis

Zone	wet density (kN/m^3)	saturated density (kN/m^3)	shear strength				note
			seismic coeffiecient method $\tau_f = c + \sigma_n \cdot \tan\varphi$		modified seismic coeffiecient method $\tau_f = A \cdot \sigma_n^b$		
			cohesion c	internel fliction angle φ	A	b	
Core	21.9	21.8	0	35	-	-	
Filter	22.0	20.9	0	36	-	-	
Rock	21.1	19.0	0	42	1.778	0.804	base strength

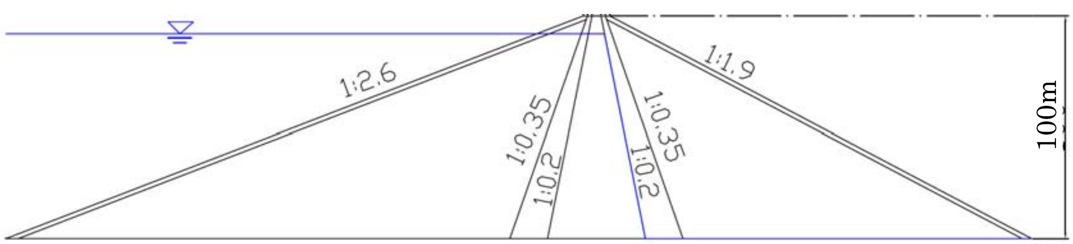


Figure 9. Analysis model

Analysis model: The dam used as a model is a central earth core type rockfill dam with dam height of 100 m. The cross-section of the model is determined by the Japanese dam design standard based on the seismic coefficient method using the material properties considered as typical value from the survey results of existing rockfill dams. The material properties are shown in Table 4. The analysis model is shown in Figure 9.

We assumed that the surface layer is deteriorated to a fixed depth as shown in Figure 10. The thickness of deterioration range is defined as the thickness in the direction normal to the slope surface as shown in Figure 10. In this analysis, the thickness is set to 0.5 m to 2.0 m based on the riprap thicknesses of the existing dams shown in Figure 8.

Physical properties used in analysis: Major physical properties used for slip stability analysis are summarized in Table 4. Shear strength of the rock material is shown in Figure 11.

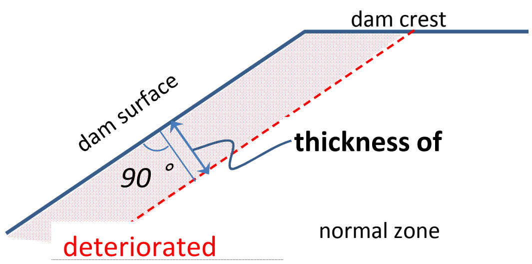


Figure 10. Thickness of deterioration

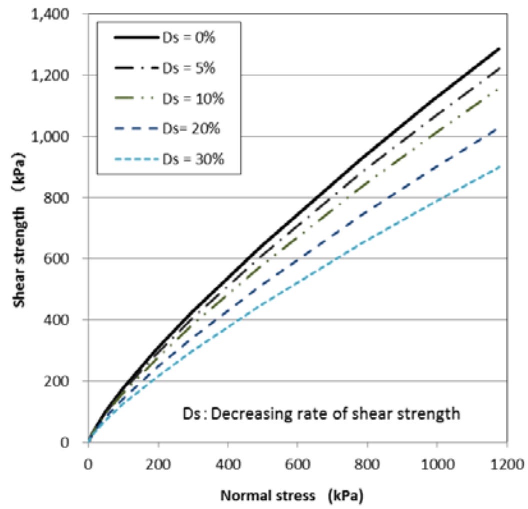


Figure 11. Shear strength of rock material

Analysis method: We calculated slip stability using the modified seismic coefficient method (River Bureau, Ministry of Construction, Japan 1991).

In the method, the strength of rock material is determined as the curve approximate expression based on the results of large-size triaxial compression test using cylindrical specimen of 300mm in diameter, and 600mm in height.

The seismic horizontal load is then determined as the value of the dead weight of the slip mass uniformly multiplied by the dam body seismic force coefficient (k). The dam body seismic force coefficient (k) is defined as the product of the design ground seismic intensity (k_F) and the response magnification factor, which is determined depending on the distance from dam crest to the lower end of the slip circle y and dam height (H). The distribution of response magnification factor (k/k_F) is specified by River Bureau of Ministry of Construction (1991). The design ground seismic intensity used is 0.18, which is the design value for the strong seismic region in Japan.

Analyzed cases: Table 5 shows 20 cases analyzed in this research. Four thicknesses (t) were set for the deterioration range of 0.0 m, 0.5 m, 1.0 m, and 2.0 m. Then, the strength reduction rate (Ds) of 0%, 5%, 10%, 20% and 30% was set for each thickness. In the slip stability analysis, we examined the slip circle depth of which in the direction normal to the slope surface, d, is 1 m or more. The minimum d value of 1m is determined in considering the typical value of maximum grain diameter of riprap material in Japan.

Table 5. Analysis cases

CASE	rate of strength reduction *Ds*	thickness of deterioration range *t*
case1-1,2,3,4,5	0%, 5%, 10%, 15%, 20%	t=0.5m
case2-1,2,3,4,5	0%, 5%, 10%, 15%, 20%	t=1.0m
case3-1,2,3,4,5	0%, 5%, 10%, 15%, 20%	t=1.5m
case4-1,2,3,4,5	0%, 5%, 10%, 15%, 20%	t=2.0m

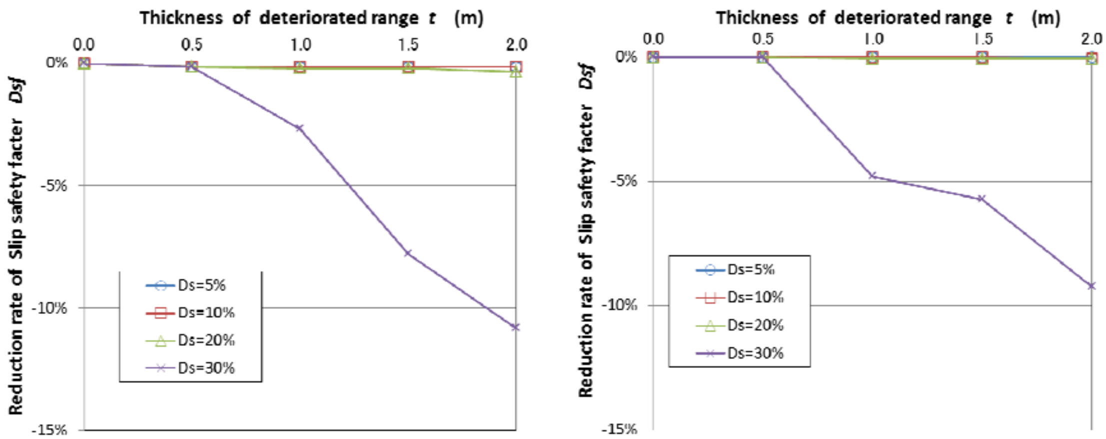
In general, when we conduct a large-size triaxial compression test under low confining pressure less than 50kPa, it is difficult to maintain appropriate accuracy during the test. We, therefore, have done some research focused on shear strength under low confining pressure condition by using new test equipment which we developed. (Yamaguchi et. al 2011) According to the results, even if we make exponential approximation of shear strength using test results by large-size triaxial compression test under confining pressure conditions more than 50kPa, the exponential approximation give us an appropriate value under low confining pressure condition. According to this research result, we can appropriately set rock material sear strength, which assures accuracy in slip stability analysis in which *d* is 1m or more.

Analysis results

Figure 12 graphically plots the relationships involving the thickness of deterioration range (*t*), strength reduction rate for the deterioration range (*Ds*), and reduction rate of slip safety factor (*Dsf*). According to these graphs, when strength reduction rate (*Ds*) is 20% or less, almost no reduction in slip safety factor occurs, but when the thickness of deterioration range (t) increases under the condition, 30% as the strength reduction ratio, the slip safety factor decreases. The maximum reduction rate of the slip safety factor is 12% under these analysis conditions. We investigated minutely the slip circular arcs whose safety factor is the lowest in every case. Then, in the cases the safety factors of which are decreased, the depths of the arcs of the minimum safety factor are equal to the deterioration ranges. In other words, the slip safety factor decreases easily in the case of a shallow slip circle which passes only through the deterioration range.

On the other hand, the thickness of deterioration range of existing rockfill dams is less than 1m according to the results of the riprap deterioration survey discussed in this paper and other reports of Japanese rockfill dam deterioration surveys. Moreover, strength of the rock material almost equal to that of the filter materials would have been obtained if 10% strength reduction for the rock materials has been considered. These corroborate our view that there is a small possibility that strength reduction by over 30% will occur due to deterioration over time.

It is, therefore, thus concluded that no major reduction in slip safety factor for shallow arcs will occur within the practically conceivable scopes of deterioration range in Japan and strength reduction rate.



(a) Upstream (b) Downstream

Figure 12. Analysis results

CONCLUSIONS

We showed past study cases on riprap deterioration and discussed the thickness of riprap appropriate for prevention of design section deterioration. Moreover, we also conducted numerical analysis of how the deterioration of riprap affects the slip stability of the dam body of rockfill dams. We summarize the results of those studies as follows.

From the investigation results, some weathering and deterioration observed in rock materials had occurred over time after completion of Midorikawa dam, however such change has had almost no effect on the functions of the rock material covered by riprap.

We investigated relations between latitude of rockfill dams in Japan and their riprap thickness, and confirmed the typical value of riprap thickness 1m, except for Hokkaido region, are appropriate considering results of our surveys and other engineers' surveys in Japan. And, we should pay attention to its deterioration over time at the rockfill dam with riprap the thickness of which less than 1m.

We conducted numerical analysis in which we changed the deterioration range (*t*) and rate of strength reduction (*Ds*) as parameters so as to evaluate the relationship between those parameters and slip safety factor (D_{Sf}). As the result, we confirmed that D_{Sf} reduction is not expected within the practically conceivable scope of *t* and *Ds*.

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