Experimental Study of Grouting for Mechanical Improvement of Bedrock

S.Utsuki[a]*

[a] HAZAMA ANDO Corporation, Tokyo, Japan
*utsuki.shinji@ad-hzm.co.jp (corresponding author's E-mail)

Abstract

Grouting is performed to mechanically improve the deformation and strength characteristics of bedrock by filling cracks with cement so that the entire bedrock is integrated and homogenized. For verifying the improvement, however, only permeability is currently considered because it is difficult to track other mechanical properties. For this reason, today dam foundation design cannot fully account for improvements, even though many construction activities are carried out to improve the mechanical properties of dam foundations.

Against this background, we compared the results of borehole loading tests and indoor shear tests, before and after grouting. Based on the test results, the mechanical improvement of bedrock by grouting was characterized in order to develop a way to account for the mechanical improvement of bedrock in dam foundation design.

Keywords: Consolidation Grouting, Dam Foundation, Mechanical Improvement, Experimental Study

1. Introduction

Grouting is performed to mechanically improve the deformation and strength characteristics of bedrock by filling cracks with cement so that the entire bedrock is integrated and homogenized. For example, consolidation grouting for a dam foundation is carried out to improve mechanical properties and to reduce seepage flow. For verifying the improvement, however, only permeability is typically considered because it is difficult to track other mechanical properties. For this reason, today dam foundation design cannot fully account for improvements, even though many construction activities are carried out to improve the mechanical properties of dam foundations.

Against this background, we compared the results of borehole loading tests before and after grouting in six types of in situ bedrock at 14 dam sites to examine in detail the improved deformation characteristics for various bedrock and rock types. Furthermore, we quantitatively confirmed the strength improvement by performing indoor shear tests, before and after grouting, using test specimens with cracks. Based on the test results, the mechanical improvement of bedrock by grouting was characterized in order to develop a way to account for the mechanical improvement of bedrock in dam foundation design.

2. In situ bedrock tests and indoor shear tests

2.1 Overview of in situ bedrock tests

In situ tests were carried out at several positions in a borehole before and after the grouting construction as shown in Fig. 1, and the changes in physical deformation parameters were determined by comparing the test results. Fig. 1 shows the in situ test positions in the borehole and the test flow. First,

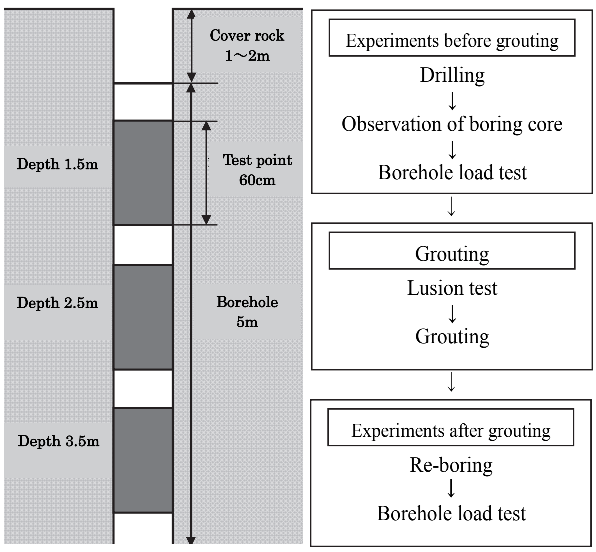


Fig.1 Flowchart of in situ experiments.

a borehole of 66 mm in diameter and 5 m in length was prepared (cover locking portion: 1-2 m; grouting portion: 5 m) the borehole was measured and logged, and borehole load tests were performed at depths of 1.5 m, 2.5 m, and 3.5 m at the center of the 60 cm loading section. The Lugeon test was first carried out to observe the water permeability of bedrock in the 5 m construction section and then grouting was performed. Next, the grout in the borehole was re-bored, and borehole loading tests were carried out at the same positions as before the grouting; the changes in physical properties were examined through a comparison with the results before grouting. These tests were done at the dam construction sites in 14 places and 5 kinds of rock types as shown in Table 1. And, in this study, the rock mass classification at dams in Japan as shown in Table 2 is applied.

2.2 Overview of indoor shear tests

a) Shear test method without considering crack junctions

Grouting was performed using mortar test specimens to model cracks in bedrock, and the before-and-after shear test results were compared to evaluate the improvement of bedrock strength by grouting. Five bedrock blocks containing joint faces of volcanic rocks were collected, and eight test specimens per joint face were fabricated by first making a highly liquid silicone mold for the upper and lower joint faces and then pouring mortar into it. The test specimen is 30 cm wide, 30 cm deep and 20 cm tall (Fig. 2); a joint face is located in the middle of the test specimen. The mortar was composed of a 4:2:1 mix of sand, cement, and water and was water-cured for two months after grouting.

An injector device was fabricated to perform grouting along the joint face in four out of eight specimens prepared for each type of joint face. In evaluating the improvement effect of grouting on the shear strength of bedrock, shear strength was compared between the test specimens with and without grouting. Four levels of vertical stress were applied to the five sets of test specimens that model cracks, with each set composed of a pair of specimens before and after grouting, and direct shear tests were performed by applying the shear load with a displacement speed of 1 mm/min.

b) Shear test method considering the junctions of cracks

We assume the continuity of a joint is limited in bedrock; the joint may not be completely separated and may have initial adhesion strength. Therefore we fabricated test specimens with artificial junctions having initial adhesion strength. After fabricating test specimens by pouring mortar into a mold as described for the in situ bedrock tests, boreholes of 40 mm in diameter were prepared as shown in Fig. 3

Table 1 Rock types of experimental sites.

Rock type		Measuring points	
Igneous rock	Granite	H dam	313 points
		Y dam	
		N dam	
		K1dam	
	Rhyolite	K2dam	87 points
		O1dam	
	Andesite	G dam	62 points
Sedimentary rock	Sandstone	S dam	66 points
	Tuff breccia	M dam	136 points

Table 2 Rock mass classification in Japan

Rock mass classfication	Deformability		Strength		Elastic wave velocity (km/s)
	Modulus of deformation (N/mm^2)	Modulus of elasticity (N/mm^2)	Cohesion (N/mm^2)	Angle of internal friction (°)	
B～CH class	～2,000	～4,000	～2.0	～40	～3.0
CM class	2,000～500	4,000～1,500	2.0～1.0	45～30	3.0～1.5
CL～D class	500～0	1,500～0	1.0～0	38～15	1.5～0

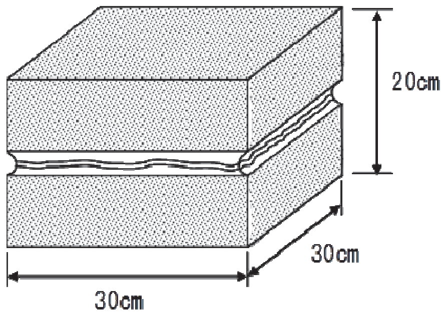


Fig.2 Test specimen for shear tests.

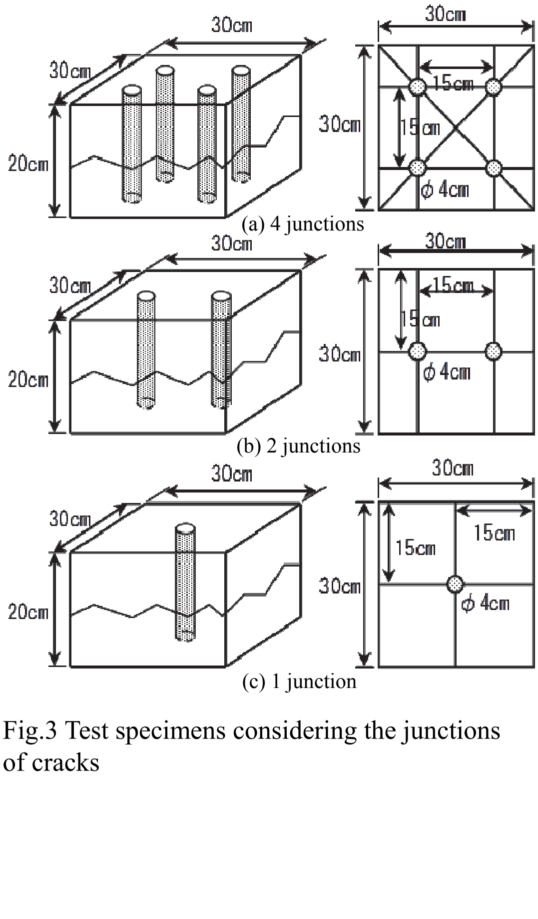


Fig.3 Test specimens considering the junctions of cracks

in eight test specimens per joint type, and junctions were prepared by filling with mortar. For joint 1, in addition to the layout in Fig. 3(a), eight test specimens were fabricated for layout (b) and also for layout (c).

3. Improvement effect on bedrock deformation characteristics

3.1 Integration of bedrock

The integration of bedrock means the improvement of mechanical properties such as deformation characteristics by hardened cement, which was filled into the cracks of the bedrock. Here, we discuss the improvement of the modulus of deformation of the bedrock for (a) various deformation modulus classifications and (b) various rock types.

Fig. 4 compares the moduli of deformation at the same positions before and after grouting for every deformation modulus classification. The figure shows an increase in the modulus value at most of the positions, indicating that the bedrock is integrated by grouting. Fig. 5 shows in more detail the logarithmic frequency distribution for every deformation modulus classification before and after grouting. For ranks CH and CM-1, the minimum value barely increases whereas the mean value increases more rapidly than that of other ranks. In contrast, for ranks CM-2 and CL-1, the increase in the modulus of deformation is sharper because the average value increases moderately and the minimum value increases rapidly; in particular, for rank CL-1, all the measurement points exhibit values above the minimum value for rank CM. For ranks CL-2 and D, however, there are some points that show hardly any increase whereas both the average and average ± standard deviation increase rapidly.

b) Improvement effects for various rock types

Fig. 6 compares the logarithmic mean values before and after grouting for each rock type within the same rank of modulus of deformation. The figure shows that, in ranks CH to CL, the mean value increases more rapidly in igneous rock than in sedimentary rock within every rank. The increased values of physical parameters might be due to the easier injection of cement milk, a hypothesis supported by larger continuous cracks being more frequently found in igneous rock, especially volcanic rock, than in sedimentary rock when evaluated by geological observation and measurement and borehole logging at the dam site.

3.2 Homogenization of bedrock

The homogenization of bedrock leads to reduced variation in mechanical characteristics. The results for bedrock before and after grouting (Fig. 7) show that for every rank of modulus of deformation, the

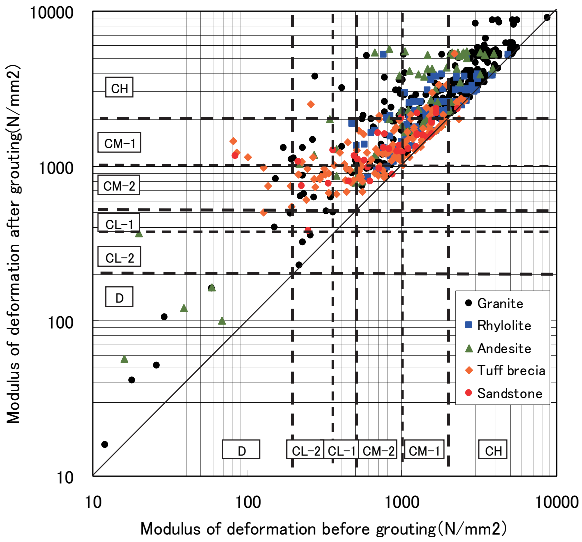
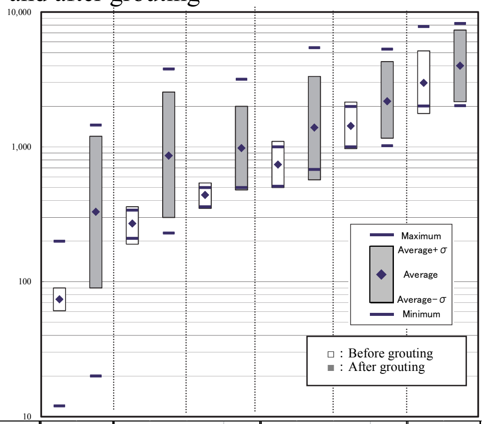


Fig. 4 Moduli of deformation at the same positions before and after grouting



Rock mass classfication	D		CL				CM				CH	
	−		CL2		CL1		CM2		CM1		−	
Modulus of deformation	0～200		200～350		350～500		500～1,000		1,000～2,000		2,000～	
Number	25	25	33	33	29	29	179	179	124	124	244	244
Maximum value	200	1,450	340	3,780	500	3,170	1,000	5,440	1,990	5,310	7,800	8,230
Average＋σ	90	1,200	360	2,550	540	2,000	1,100	3,330	2,150	4,290	5,150	7,350
Average	74	330	270	860	440	980	740	1,390	1,430	2,180	2,980	4,000
Average－σ	61	90	190	300	350	480	500	570	970	1,160	1,770	2,160
Minimum value	12	20	210	230	360	500	510	680	1,000	1,020	2,010	2,020
Standard deviation	67	470	44	670	45	500	150	920	274	850	920	1,280
Coefficient of variation	0.91	1.42	0.16	0.78	0.10	0.51	0.20	0.66	0.19	0.39	0.31	0.32

Fig. 5 Logarithmic frequency distribution before and after grouting

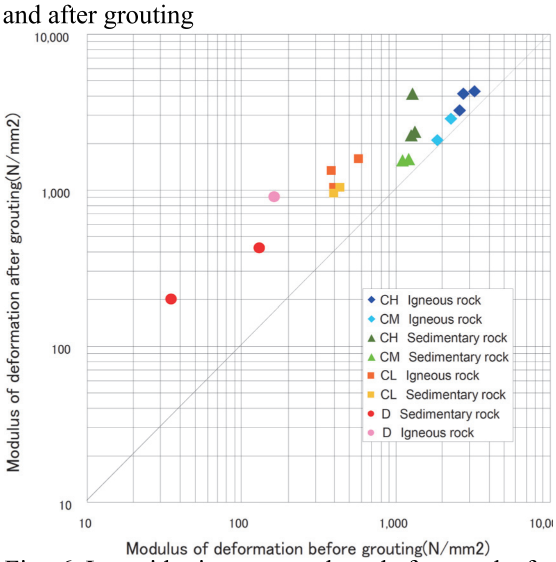


Fig. 6 Logarithmic mean values before and after grouting for each rock type

variation coefficient tends to increase after grouting for all ranks and tends to be greater at lower ranks. In addition, in ranks CH to CL-1, the minimum value of the increase in the modulus of deformation increases more rapidly in lower ranks.

Taking the above into consideration, after grouting the modulus of deformation increases, in which it fluctuates toward larger physical parameters within the same rank. However, since the increase in minimum value and the upward variation are small at higher ranks and large at lower ranks, when calculation is performed using all data, a smaller variation coefficient is obtained after grouting, in other words, homogeneity is considered to increase.

4. Improvement of bedrock strength

4.1 Evaluation of indoor shear test results

a) Shear test results without considering crack junctions

Without considering junctions, direct shear tests were carried out using the test specimens before and after grouting. Fig. 8 shows the relationship between the vertical stress applied to the joint face and the maximum shear stress for every type of joint face. The maximum shear stress after grouting exceeds that before grouting in all specimens with cracks, clearly showing that the shear strength is improved. In addition, the slope of the straight line remains almost unchanged before and after grouting, and no appreciable change is observed in the internal friction angle. The improvement effect of grouting on strength does not exceed the developed adhesive strength of 0.1-0.3 MPa. After the shear test, there was considerable exfoliation at the joint face but the degradation of grouting materials was rarely observed. This suggests that the shear destruction of joint face occurs not in the grouting material but at the interface between grouting material and joint face. Further, almost no change was observed in the internal friction angle, suggesting that the roughness of the shearing plane is not appreciably changed by grouting.

b) Shear test results considering crack junctions

Fig. 9 shows the results of the direct shear test before and after grouting using test specimens with four junctions, and Fig. 10 shows the results for a test specimen with one or two junctions between the cracks in joint 1. In both figures, the maximum shear stress after grouting exceeds that before grouting, indicating the improvement of shear strength. In addition, the slope of the straight line remains almost unchanged by grouting, indicating that the friction angle does not appreciably change or the shear strength improves as adhesive strength improves. This suggests that, even in the presence of a junction, improvement is accomplished by a mechanism like that of a fully separated surface. In the case of four junctions, the

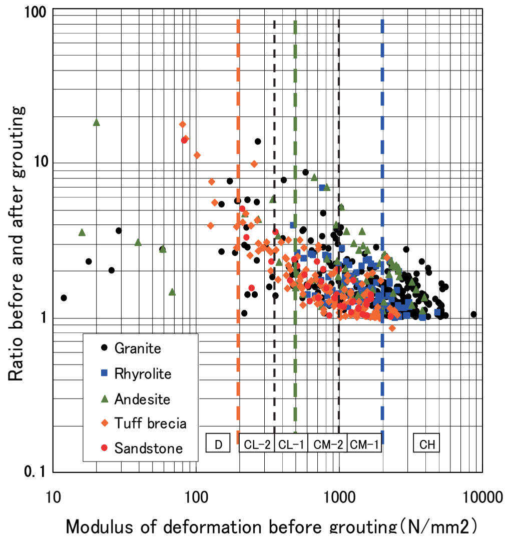


Fig. 7 Variation coefficient before and after grouting

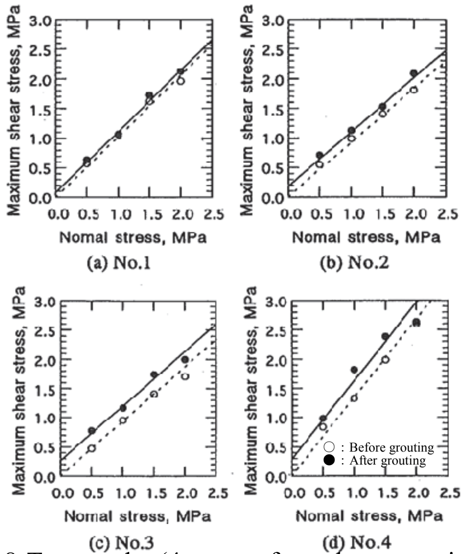


Fig. 8 Test results (4 types of roughness: no intact bridge)

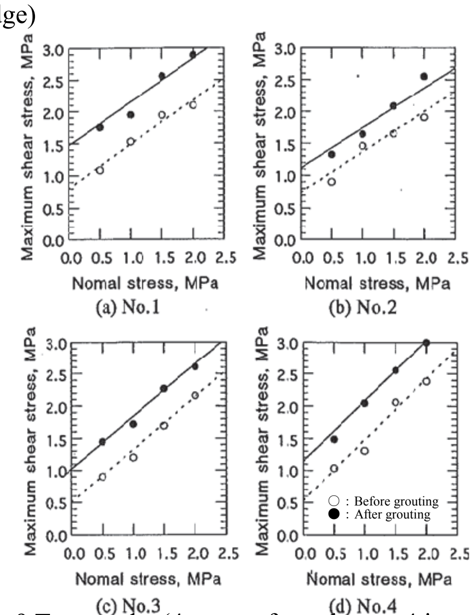


Fig. 9 Test results (4 types of roughness: 4 intact bridges)

increase in adhesive strength by grouting does not exceed 0.4-0.6 MPa. The improvement effect was enhanced by the existence of junctions, as shown by comparison with the results for the case of complete separation in which the increase in adhesive strength was 0.1-0.3 MPa.

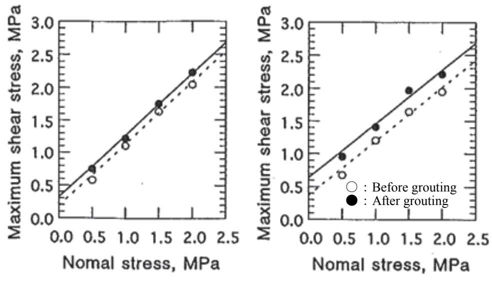
5. Dam foundation design considering mechanical improvement of bedrock

5.1 Concept of conventional design of dam foundation

A usual requirement is to perform stability analysis using Henny's formula to secure the required safety factor of 4.0 in the design of a dam foundation. In the calculation, the shear strengths of foundation bedrock as shown in Table 3, which are based on the in situ shear test results from each dam site, are assumed. In dam A in Fig. 11, for example, the tests are carried out using 3 or 4 points for each bedrock type and the design value of shear strength is derived based on the results. In dam foundation design, we generally perform the stability analysis using Eq. (1) for every block after dividing the foundation into blocks of 15 m in length in the dam axis direction. Thus, as in the example in Fig.12, the calculation will usually show that we can secure the safety factor of 4.0 in C_L class bedrock if the banks are lower than about 40 m in height where forces such as water pressure are relatively small while the foundation should be set on C_M class bedrock if the banks are higher than about 40 m. The shape of the bank foundation is finally designed to secure the desired safety factor in all blocks.

5.2 Study of dam foundation design considering the mechanical improvement of bedrock

Based on the above discussion, in order to set the two values of shear strength by dividing the C_L class into two in dam A shown in Fig. 11, we can use the existing shear strength for the C_L class as the value for the C_{L2} class and assume an adhesive strength of about 1.50 MPa (the average of the C_M and C_L classes) for the C_{L1} class, as shown in Fig. 13, just as discussed in Section 3. Then, with respect to the improvement by grouting, from the discussion in Section 4, we can evaluate the C_{L1} class assuming adhesive strength of about 0.40 MPa without changing the internal friction angle; as the figure shows, there is a very high likelihood that the adhesive strength of the C_{L1} class is improved to 1.90 MPa by grouting, equivalently to that of the C_M class. By evaluating, for example, the excavation shape for the dam foundation shown in Fig. 12, assuming that the area of the C_{L1} class is equivalent to an area of the C_M class due to the improvement by grouting, we can set the excavation line even higher than shown in Fig. 14 at bank depth of 40 m and below, where rock contact of the C_M class or above is usually



(a) 1 intact bridge (b) 2 intact bridges

Fig. 10 Test results (2 types of intact bridges : No.1)

Table.3 Shear strengths of foundation bedrock

Rank	Dam A	Dam B
C_H	C=2.30MPa, ϕ =48°	C=2.50 MPa, ϕ =50°
C_M	C=1.90MPa, ϕ =43°	CM1 : C=1.90MPa, ϕ =45° CM2 : C=1.59MPa, ϕ =45° CM3 : C=1.20MPa, ϕ =45°
C_L	C=1.10 MPa, ϕ =39°	C=0.79 MPa, ϕ =35°

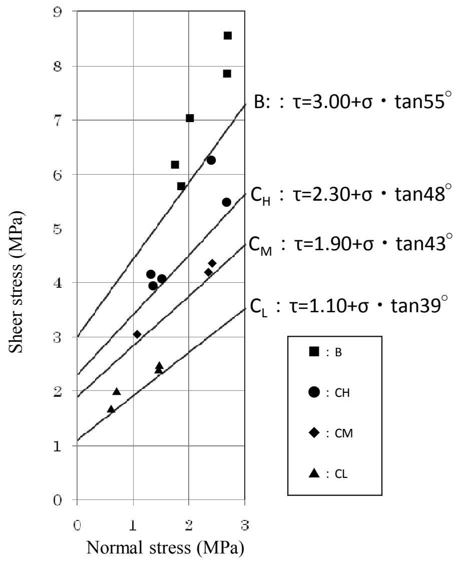


Fig.11 Test result of Dam A

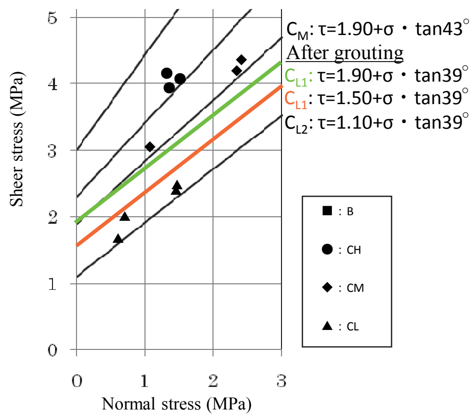


Fig. 13 Shear strengths of foundation bedrock due to the improvement by grouting

required. If we can set a higher excavation line for a C_L-C_M class excavation site, we could decrease the amount of both bank excavation work and concrete placement work simultaneously. Moreover, the improvement would contribute to the aspects of dam construction—Q (quality), C (cost), D (delivery), S (safety), and E (environment)—by reducing the excavation volume in the surrounding area such as the upper part of the bank slope, by reducing the excavation volume at quarry sites through reduced aggregate production, by securing slope stability through reduced height of the excavation slope, by minimizing the alteration of the natural landscape, and by reducing the amount of construction work for slope protection through the reduced slope area.

6. Conclusions

In situ experiments and indoor sheer tests were executed in order to estimate the improvement of bedrock by grouting quantitatively. By the results of these examinations, authors show the design example due to improvement by grouting.

In the future, from the knowledge in this paper, we think that there is a possibility that the improvement about the mechanical properties by grouting can be considered for the dam foundation design.

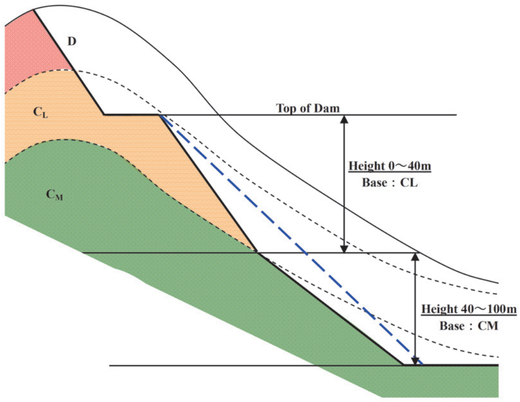


Fig.12 Excavation shape for dam foundation

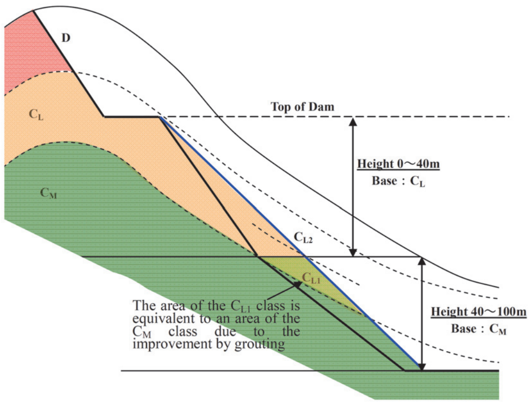


Fig.14 Design example due to the improvement by grouting