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Smooth Blasting in Hard Rock Tunnel Using an Automatic Drilling Machine

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Abstract

This study was made to minimize overbreak and underbreak of the design excavation face by conducting various analyses of data obtained from the automatic drilling robot in a hardrock tunnel.

At the site, it is difficult to minimize overbreak and underbreak, so trial and error must be repeated. We conducted a 3-stage blasting experiment using the numerically controlled drilling robot (automatic drilling machine) and tunnel measuring equipment and found that a proper drilling plan and its execution are very important in minimizing overbreak and underbreak in hardrock tunnels. In the near future, the drilling robot will be used widely for tunnel excavation because it is not affected by the technique or skill of the workers.

1. INTRODUCTION

The objective of smooth blasting (SB) is to minimize the damage to natural ground and to smooth the final section as much as possible by minimizing the impact on the rock bed. Recently, in Japan, the method using rockbolts and shotcrete has been commonly used, and in terms of quality and cost, the importance of SB is increasing. Despite being introduced to Japan a long time ago, systematic research on SB has been limited and trial and error is repeated at each construction site.

The reasons for this lack of research are as follows:

(1) It is difficult to grasp the input/output data to investigate the effects of SB.

(2) The profile after excavation differs even if an identical blasting pattern is used because the rock type and joint condition differ for each excavation cycle.

(3) It is very difficult to evaluate the effects of factors because there are so many that affect SB and interact with one another.

A few years ago, an automatic drilling machine (drilling robot) was developed as computer and control technology made an advance. Use of this robot may solve the problems of SB research. Since the drilling robot can be numerically controlled, drilling can be done as designed and since drilling positions are always recorded, input data can be obtained. Its other advantage is that it is not affected by the technique or skill of workers.

Concerning the measurement of blasting results, data collection is readily accomplished by means of an automatic tunnel measuring equipment that uses laser beams. The drilling robot and automatic tunnel measuring equipment make it possible to investigate the effects of SB without hampering the progress of facing at the construction site.

In this study, we decided to carry out SB research while performing the following experiments (1, 2 and 3) in actual tunnel facing. We used the drilling robot (AD Jumbo made by Mazda) and automatic tunnel measuring equipment (Hazama type), and discussed the effect of SB in hardrock tunnelling on the basis of data obtained.

2. OUTLINE OF EXCAVATION SYSTEM

Fig. 1 shows the excavation system. The flow in the figure can be explained by: the tunnel engineer checks the condition of the tunnel facing and designs a blasting pattern suitable for the natural ground, 2) the blasting pattern is input to the computer and data are input to the drilling robot, 3) the drilling robot automatically drills the facing in accordance with the input pattern, 4) after drilling, charging, blasting and mucking are completed, the excavated tunnel profile is measured, overbreak and underbreak are analyzed, and SB effects are evaluated, and 5) results are immediately fed back for the next blasting work. In this way, blasting is designed to meet the natural ground condition.

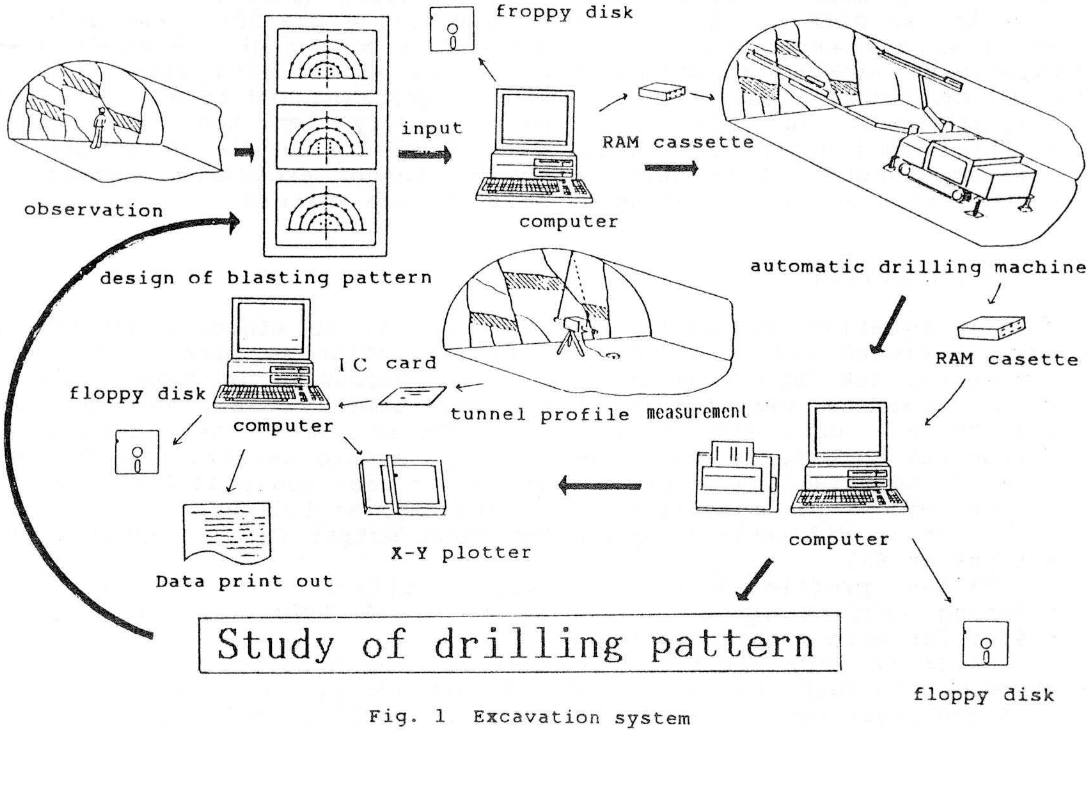


Fig. 1 Excavation system

This system features the possibility of obtaining the drilled condition and blasting results quantitatively in a relatively short time. In order to position the drilling robot, the robot's target is adjusted to a couple of laser beams set at the rear of the tunnel. This requires about 5 minutes, the actual section measuring time takes 1 minute and 25 seconds (4° step per section), and data collection can be completed in about 5 minutes including preparation and removal.

3. OUR WAY OF THINKING FOR SB

The objective of SB is to secure good quality by protecting natural ground, to produce smoothly excavated surfaces and to minimize the cost required for tunnel excavation.

From blasting results, therefore, we decided to consider the effect of SB in the following three stages:

3.1 1st stage: Blasting technique

The SB result in the 1st stage is said to be successful when the blast holes are linked by blast cracks and the drill holes remain in shape. Figure 2 (a) and Figure 2 (b) show the instance where the SB in this stage is successful. The result of SB in the 1st stage is evaluated mainly by the drill hole contour ratio.

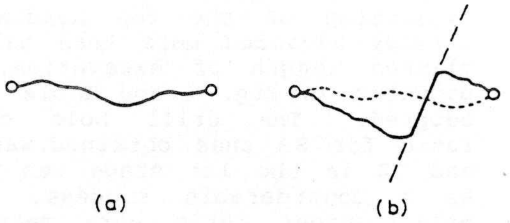


Figure 2 Linkage of holes by cracks

3.2 2nd stage: Realization of designed tunnel profile

When drilling is accomplished in accordance with the designed drilling pattern and when SB in the 1st stage is successful, the 2nd stage is considered to be a success. For this reason, the success or failure of SB in the 2nd stage is judged on the basis of the difference between the design line of the facing and the excavated surface after blasting. Fig. 3 shows the underbreak and overbreak made large due to failure of the 2nd stage, though the 1st stage had been successful.

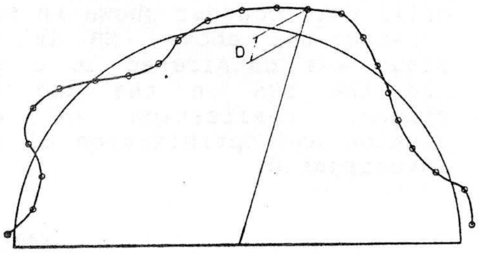


Figure 3 Result of blasting with improperly drilled holes

3.3 3rd stage: Optimal design of SB

SBs in the 1st and 2nd stages are never 100% successful, and comparisons of blasting results against the designed drilling pattern are obtained as statistical data with some dispersion. For this reason, the underbreak and overbreak become realistic problems. SB in the 3rd stage is considered to be successful when such blasting results in minimizing the total cost of underbreak and overbreak.

4. FEATURES OF SB IN THIS STUDY AND EXPERIMENT ENVIRONMENT

This study was made on the west side of the Shiwa Tunnel project, Sanyo Expressway, ordered by Japan Highway Public Corporation. The tunneling method using rockbolts and shotcrete was employed. The rock was granodiorite and the seismic wave velocity was 4.0 - 4.5 km/sec. Concerning the strength of the representative rock, uniaxial compression strength was 119 - 144 MPa (1,210 - 1,470 kgf/cm^2) and the Bragilian tensile strength was 6.7 - 8.1 MPa (68 - 83 kgf/cm^2).

At the onset of this study, excavation of the top heading had already advanced more than half the planned length of excavation. The patterns in Fig. 4 and Table 1 were adopted. The drill hole contour ratio for SB thus obtained,was high and SB in the 1st stage was judged as a considerable success. Drill hole contour ratio here means the ratio of the length of the drill hole contour remaining after blasting to the total drilling length and is calculated using the data obtained from the sketch of the drill hole contour shown in Fig. 5.

From the above, SB in the 1st stage was considered as a success, and the SBs in the 2nd and 3rd stages. realization of designed section and optimization of SB, were investigated.

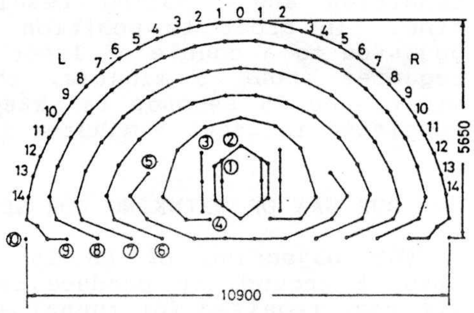


Figure 4

Blasting pattern used in this study

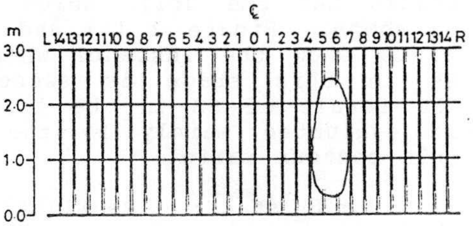


Figure 5 Sketch of drill hole contour

Table 1 Blasting design

1. Rock material : Granite
   Seismic wave velocity : 4.3 km/s
2. sectional area : 49.3 m^2
3. Length of excavation : 2.5 m
4. length of drilling : 2.7 m
5. Bit guage : 41 mmϕ
6. Explosives :
   No.2 Enoki dynamite (30 mmϕ ,100 g)
   Slurry explosive for SB (20 mmϕ ,200 g)
7. volume of blasting : 123.25 m^3
8. Unit amount of explosive : 1.04 kg/m^3
9. Unit number of holes : 2.74 holes/m^2

DSD	Holes	Explosive /hole(kg)	Total amount of explosive(kg)
1	6	1.1	6.6
2	6	1.0	6.0
3	6	1.0	6.0
4	11	1.0	11.0
5	6	1.0	6.0
	4	1.1	4.4
6	14	1.0	14.0
	2	1.1	2.2
7	17	1.0	17.0
	2	1.1	2.2
8	20	1.0	20.0
	2	1.1	2.2
9	31	0.7	21.7
	6	1.1	6.6
10	2	1.1	2.2
Total	135		128.1

5. SITE EXPERIMENT AND DISCUSSION ON 2ND STAGE SB

The following experiments (1, 2 and 3) were conducted:

5.1 Experiment 1 (Drilling by automatic drilling mode)

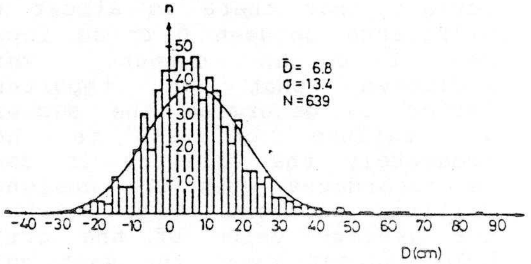


Figure 6 Histogram of the result of measurement of actual blast faces in Experiment 1

The first drilling done on the site was done by automatic drilling mode. In this 1st experiment, all holes were automatically drilled in accordance with the drilling pattern stored in the drilling robot. Fig. 6 shows the results of Experiment 1.

Fig. 6 is a histogram of the difference D between the designed section and the section obtained by measuring with the tunnel measuring equipment in Experiment 1. The abscissa indicates values of D and the ordinate axis the number of cases. N in the figure indicates the total number of places measured in 25 sections of Experiment 1, $\bar{D}$ is the average value of D and σ is standard deviation of D. Negative values of D in the figure indicate underbreak. The curve in the figure is a normal distribution curve obtained by D and σ. $\bar{D}$ in Experiment 1 is 6.8 cm, and the mean value of overbreak is small but σ is as much as 13.4 cm, and as a result, the underbreaks indicated by $D < 0$ are many. The reason for this phenomenon is considered as follows: Although the drilling accuracy of the robot used in this study was ±5 cm in the beginning, its operating time had already exceeded 1,500 hours, and for this reason, play, bending and warping had occurred in robot parts. So as a result, the actual drilling position were largely out of the designed drilling positions and accurate drilling could not be done in the automatic drilling mode.

5.2 Experiment 2 (Drilling by semi-automatic drilling mode)

In the automatic drilling mode of Experiment 1, dispersion due to drilling robot errors was large and many underbreaks and overbreaks occurred. Therefore, in Experiment 2, the drilling was done in the semi-automatic drilling mode where a circle equal to the designed section is sprayed onto the facing and after the boom is manually moved onto the circumference, the mode is switched to automatic drilling.

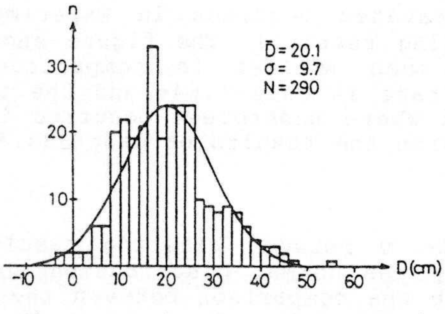
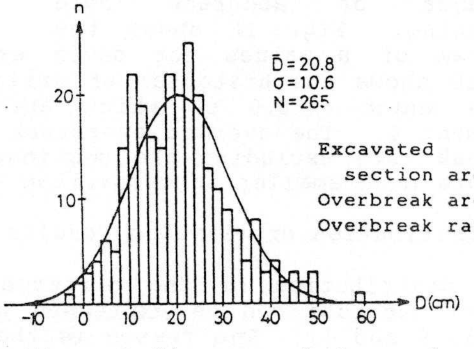


Figure 7 Histogram of the result of drilling in Experiment 2



Excavated

section area	49.72 m^2
Overbreak area	3.07 m^2
Overbreak rate	6.57 %

Figure 8 Histogram of the result of measurement of actual blast faces in Experiment 2

The results of Experiment 2 are shown in Figs. 7 and 8. Fig. 8 shows that $\bar{D}$ is larger at 20.8 cm in comparison with Experiment 1 but σ is smaller at 10.6 cm, and the number of resulting underbreaks of $D < 0$ is almost zero. The average overbreak rate is 6.6% which is rather small. Comparison of Figs. 7 and 8 reveals that there is almost no difference between $\bar{D}$, σ as input and $\bar{D}$, σ as output. This indicates that an important factor to determine the success or failure of SB is how accurately the drilling is done in accordance with the designed drilling pattern. Fig. 9 shows the average value of the drill hole contour ratio for each hole in Experiment 2. In most holes, the average ratio exceeds 70%, and for 5 holes it exceeds 90%.

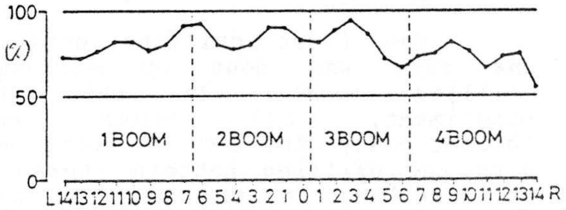


Figure 9 Mean drill hole contour ratio in Experiment 2

From the facts mentioned above, SB in Experiment 2 is successful so far as SB in the 1st stage is concerned. In the matter of SB in the 2nd stage the results are not, however, successful because of relatively large $\bar{D}$ and a somewhat large σ.

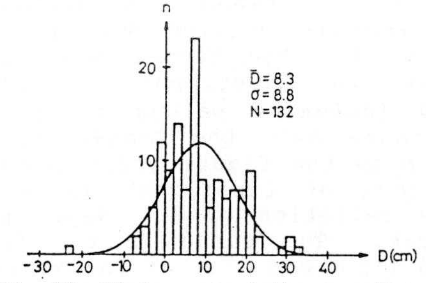


Fig.10 Histogram of the results of drilling in Experiment 3

5.3 Experiment 3 (Drilling by semi-automatic drilling mode)

The following improvements were made on Experiment 2 in an attempt to minimize the average overbreak and reduce dispersion: 1) more accurate centering of the circle and 2) equipping the spray end with a device that prevents paint expansion to draw the circle as fine as possible. The narrower spraying width was also aimed at a psychological effect to make the workers recognize the importance of accurate hole positioning. Fig. 11 shows the histogram of D values for seven excavated sections in Experiment 3. (Fig. 10 shows the histogram of drilling result.) The figure shows $\bar{D}$ = 8.2 cm and σ = 8.0 cm which are much smaller in comparison with Experiment 2. The average overbreak rate is only 1.64% and the average overbreak rate excluding the sections where underbreak occurred is 2.2% which are much smaller in comparison with the results of past SBs.[4)]

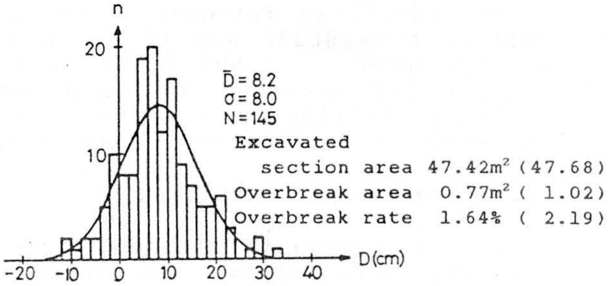


Fig.11 Histogram of the results of measurement of actual blasted faces in Experiment 3
Figures in parentheses are values excluding underbreak.

5.4 Distribution of blasting results

The distribution of the difference D between blasting results and designed sections can be expressed by the normal distribution shown in Figs. 6, 8 and 11. The reason is that the comparison between the number of underbreaks calculated from the normal distribution and the number of actual underbreaks shows good agreement.

5.5 Evaluation of SB in the 2nd stage

It can be said that SB in the 2nd stage achieved a good result by decreasing the value of σ. The value of σ in Experiments 1, 2 and 3 is sequentially reduced from 13.4 to 10.6 and 8.0 cm..

6. OPTIMAL DESIGN OF PERIMETER BLASTING, SB IN THE 3RD STAGE

Even if the holes are successfully linked with cracks through SB in the 1st stage and highly accurate drilling is done in SB during the 2nd stage, that is not enough. Actual execution is necessary to analyze the most advantageous drilling positions. We consider this problem can be solved by treating SB as an optimization problem to minimize the total cost.

6.1 Formulation as optimization problem

In order to optimize the SB hole design, it is necessary to investigate the controllable design parameters. In past SB research, the hole spacing (E) at ultimatic perimeter, burden (V) and amount of explosive (W) shown in Fig. 12 (b) were often investigated. They are considered to be factors that significantly influence SB in the 1st stage. On the contrary, we consider how to minimize total costs through the optimization of SB hole design including probability of underbreak and overbreak. The costs largely affected by SB are considered to be that cost for removing the underbreak and extra concrete required. In the facing shown in Fig. 12, formulation is made as an optimization problem with the radius of the spray-drawn circle $R = R_0 + \Delta R$ and the look-out θ as design variables and the sum of the cost for removing the underbreak and the extra costs required as objective function.

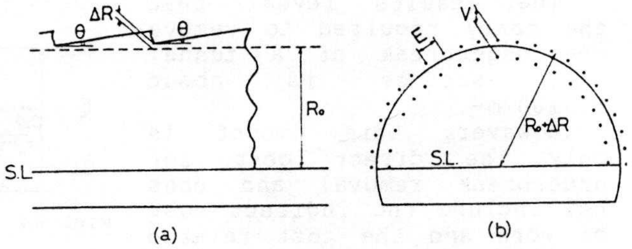


Fig. 12 Top heading excavation of tunnel

Design variables	$\Delta R,\ \theta$
Objective function	$C_T = (C_A.P_A.A_A+C_B.V)/L_C \rightarrow \min$
Constraint	$P_C \leqq P_{ca}$

Where C_T is total cost per excavation length 1 m, C_A cost required for removal per 1 m^2, P_A average underbreak probability in one cycle, A_A total area of wall surface in one cycle, C_B cost of concrete per 1 m^3, V overbreak amount in one cycle, L_C progress length of one cycle, P_C probability of underbreak concerning workability of drifter, and P_{ca} allowable probability of underbreak concerning workability of drifter.

6.2 Formulation of underbreak probability and overbreak

Fig. 13 shows drilling done by the drilling robot. For this drilling look-out θ is automatically set for the imaginary facing, and after the boom is moved, either automatically or semiautomatically, to the drilling start position (Point S in Fig. 13), automatic drilling occurs. From the figure, the difference D(x) between minimum excavation radius R_0 and actual excavation radius was formulated, and on this basis, the underbreak probability and the overbreak amount were formulated. Since the underbreak probability is affected by the workability of the .drifter, constraints were also considered.

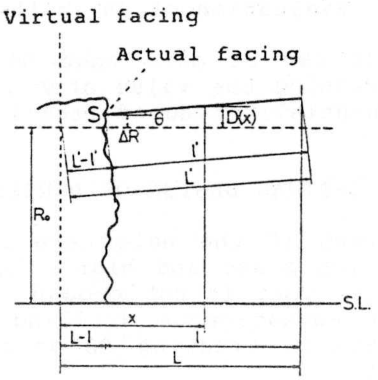


Fig. 13 Drilled Condition using an automatic drilling machine

6.3 Calculation of underbreak removing cost

The distribution of underbreak in section 126 m in Experiment 1 was measured with the automatic tunnel measuring equipment and the results are shown in Fig. 14. The cost required for removing the underbreak is shown in Table 2.

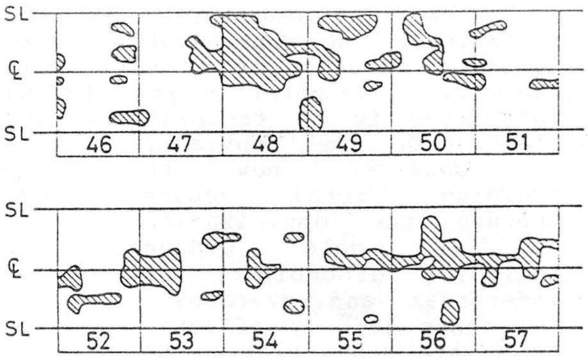


Fig. 14 Underbreak Distribution in 12 spans

The. results reveal that the money required to remove the underbreak of a tunnel wall surface is about ¥7,200/m^2.

However, this amount is only the direct cost for underbreak removal and does not include the indirect cost of work and the cost related to the delay of work. The costs for underbreak removal reviewed from this viewpoint are, therefore, Cases 2 and 3 in Table 3.

Table 2 Cost required for removing underbreak

Cost class.	Breakdown	Unit cost	Quantity	Cost
Labor cost	-----	¥17,000/person	32person	544,000
Material cost	Explosive	¥800/kg	23	18,400
	Detonator	¥200/	230	46,000
	Shotcrete	¥14,000/m^3	52	728,000
	Expendables	¥10,000	1	10,000
Machine fee	Compressor	¥6,000/day		60,000
	Leg-drill	¥10,000		10,000
	total			1,416400

Table 3 Result of Optimization

case	C_A (¥/m^2)	Exp. No.	Ropt (cm)	θopt (°)	Optimum cost (¥/m)			Actual calculation cost	Profit rate (%)
					Underbreak removal cost	Cost of extra concrete	Total		
1	7,240	1	3.07	5.15	22,158	91,213	113,371	116,655	2.9
		2	3.53	4.60	18,128	91,822	109,950	128,735	15.7
		3	3.58	4.58	15,252	91,226	106,478	110,711	4.0
2	11,590	1	9.11	5.14	18,167	104,578	122,745	130,022	5.9
		2	8.40	4.54	15,321	102,322	117,643	130,700	11.1
		3	7.60	4.52	13,138	99,858	112,996	120,817	6.9
3	14,480	1	11.15	5.21	17,359	109,431	126,790	138,933	9.6
		2	10.23	4.55	14,474	106,496	120,970	132,009	9.1
		3	9.21	4.52	12,393	103,423	115,816	127,555	10.1

6.4 Optimal design example and discussion

On the basis of the variables such as ΔR, θ and cost for underbreak removal, optimum design was done using the optimization subroutine COPES[5)] and the results are shown in Table 3.

The optimization costs, those calculated using ΔRopt and θ opt, are obtained as a result of optimization, and for the actual costs, those obtained as a result of the experiment are used.

From Table 4, the following discussion can be made. Regardless of the value of C_A, optimum costs are reduced in the order of Experiments 1, 2 and 3. In these experiments the value of ΔR and accuracy of bit starting position were improved sequentially and, as a result, the cost was reduced in that order. This indicates that the cost relatd to SB can be reduced as much as 6.5 - 9.5% simply by increasing the drilling accuracy. In the case of C_A = ¥14,480/m^2 in Case 3, which is considered most realistic as the underbreak removal cost, there is a difference of about 10% between the optimum cost and actual cost regardless of the experiment number. This means that cost reduction of about 10% on the average can be made through the optimization shown in this study.

Comparison of the actual cost ¥138,933/m of Experiment 1 and the optimum cost ¥115,826/m of Experiment 3 reveals that the optimum cost is about 20% smaller. It reveals that the underbreak removal cost and the extra concrete cost can be reduced nearly 20% by increasing the drilling accuracy and through the optimization mentioned above.

Observation of the values of Δ Ropt and θ opt of Cases 1, 2 and 3 reveals that the value of ΔRopt is larger in comparison with the actual execution and the value of θ opt is smaller. That is, optimization can be achieved by increasing the radius of the circle to be drawn on the facing and decreasing the look-out θ. When the underbreak removal cost increases, therefore it is more advantageous to decrease the probability of underbreak by increasing ΔR rather than to increase the look-out θ. This means that parallel drilling, if possible, is advantageous. In reality, however, there is a constraint in the workability of the drifter expressed by P_C, and to avoid this, adoption of the look-out of about 5° will be an optimal solution. The above results indicate that adopting a minimum angle which can secure drilling workability of the next cycle for the look-out and control the value of ΔR properly leads to cost reduction.

7. CONCLUSION

The results obtained from the experiments are summarized as follows:

(1) Summarizing the ideas on SB, we proposed that SB in the 1st stage had problems related to blasting technology, SB in the 2nd stage had problems with drilling accuracy and SB in the 3rd stage concerned the optimal design of SB.

(2) For the hardrock subjected to this study, it is important not only the 1st stage but also the 2nd stage concerned drilling accuracy. In this study, it can be said that all the experiments were almost successful from the point of the SB in the 1st stage.

(3) The difference D between the actual excavation and designed sections is in conformity with the normal distribution.

(4) Play in the boom of the drilling robot increased the drilling error, and therefore, in order to increase accuracy, the designed drilling line was drawn (in a narrow line to increase the accuracy) on the facing with spray paint. The boom was manually moved onto the line and the mode was switched to automatic drilling so the standard deviation of D could be reduced.

(5) We pointed out that the most important factors for optimization of SB design for hardrock are the look-out and the drilling radius drawn on the actual facing and could formulate the optimization problem using them as the design variables.

(6) As a result of optimization using them, it was clarified that the look-out can be a minimum value to assure the clearance necessary for the drilling of the next cycle and the radius of the circle to be drawn on the facing can be selected in accordance with drilling accuracy..

(7) When the sum of the cost for removing the underbreak and the cost required for extra concrete is taken into consideration in the optimization of SB, costs can be reduced about 7 - 10% by increasing the drilling accuracy and about 6 - 11% through optimization, resulting in total cost reduction of nearly 20%.

These results were achieved because the drilling robot enabled the collection of input/output data and the drilling could be done in accordance with the designed pattern. As mentioned in the text, however, drilling error increased with the elapse of the operating time of the drilling robot, making it impossible to drill just as designed. In the future, development of a drilling robot that can secure drilling accuracy for a long time even under severe environmental conditions must be attempted.

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