Research paper

Relationship between borehole angle and fracture manner in the partial destruction of reinforced concrete (RC) wall

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Abstract

This study considers use of small-scale blasting as a breaching technique in rescue work. This paper focuses on the borehole angle in a reinforced concrete (RC) wall and its influence on fracture manners. In the experiments, the RC wall thickness was 250 mm and the blasting was conducted with a single-charge. Borehole angles were 90° and 45° to the surface of the wall. During breaching, two types of fracture manners were obtained with each borehole angle. While craters were observed on either side (borehole side or back side) at a borehole angle of 90°, craters were observed either on the borehole side or on both sides of the wall at a borehole angle of 45°. For rescue work, breaching needs to remove quickly the concrete of the wall as much as possible, while at the same time produce cracks on the other side without ejecting pulverized concrete. Fracture efficiency was defined to evaluate a fracture, irrespective of where the burden was located. In this study, a borehole angle of 45° resulted in high fracture efficiency in comparison to a borehole angle of 90°. Using the fracture manner in the borehole side at borehole angle of 45° and 90°, the relation between the amount of explosive and the burden required to provide the highest fracture efficiency was proposed, based on experimental results.

Keywords : rescue work, borehole angle, fracture manner, burden, fracture efficiency

1. Introduction

With regard to breaching in rescue work, small-scale blasting has an advantage because it can avoid secondary accidents such as the collapse of remaining structures. Some researchers in this field[1)-4)] studied the internal charge method using a small amount of explosive for each borehole. The methods used in previous studies completely penetrated reinforced concrete (RC) walls and floors with one ignition.

However, blasting for rescue work requires control of fragmentation and flying debris. To accomplish rescue without causing further injuries to the victims, this method is not recommended when victims are on the other side, as only cracks are permitted on the opposite side of the wall where victims are located. Usually this primary fracture with a blasting is followed by a secondary fracture to completely open a hole in the wall, through which a rescue crew can pass and salvage victims.

In our previous studies[5)-7)], the optimal charging condition was sought for breaching in rescue work. The experiments were conducted on 150 mm of wall thickness with single-charge and the fracture manners was investigated by changing borehole lengths and amounts of explosive. In the experiments, the diameter of the borehole and the stemming material were fixed. The set of experiments revealed the most effective borehole length and the amount of explosive corresponding to the acceptable level of fragmentation on the other side of the wall.

The present study focuses on the effects of borehole angle in RC wall. In the experiments, the RC wall thickness was 250 mm and the blasting was conducted with single-charge. The borehole angles were 90° (vertical) and 45° to the surface of the wall.

Vertical boreholes basically allow easier and quicker drilling compared to inclined boreholes. Vertical drilling is employed in mining and quarrying. The generous length of boreholes created by straight drilling allows adequate stemming. However, structural demolition limits the drilling depth, and a borehole angle of 90° cannot provide sufficient depth for stemming to confine the explosive energy needed to achieve adequate destruction. On the other hand, a borehole angle of 45° enables longer stemming to obtain more effective fracture energy of the explosive than a borehole angle of 90° [8].

In this paper, the RC wall thickness was 250 mm and the blasting was conducted with single-charge. The relationship between the burden and the crater depths was examined, and fracture efficiency was defined to evaluate a fracture based on that relationship. Irrespective of where the burden was located, a borehole angle of 45° resulted in higher fracture efficiency than a borehole angle of 90°. The relation between the amount of explosive and the burden to provide the highest fracture efficiency was proposed for borehole angles of 90° and 45°.

2. Model experiments

2.1 RC wall sample

A part of the RC wall was modeled, as shown in Figure 1. The width and height of the sample of RC wall was 750 mm. The diameter of the reinforcing bars was 13 mm, and those bars with a grid pattern were placed at 50 mm from each surface of the wall. The concrete density was 2300 kg/m^3. Four samples were prepared for the experiments, and their concrete compressive strengths were 22.3, 25.3, 25.9, and 27.1 MPa.

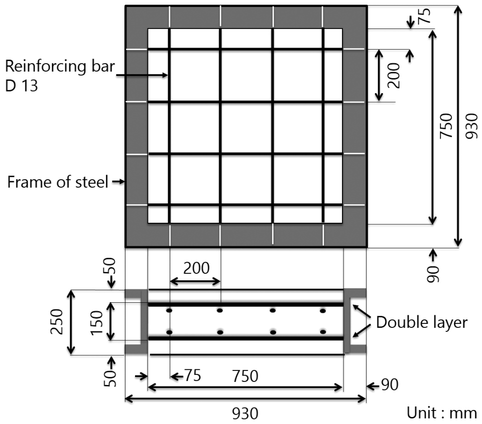


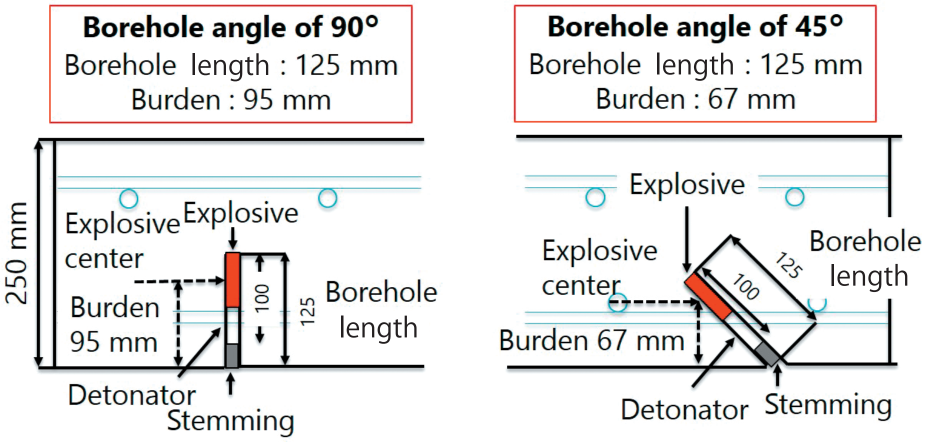
Figure 1 Reinforced concrete (RC) wall sample.

2.2 Borehole angle

The cross-section of samples with borehole angles of 90° and 45° are shown in Figure 2. In this study, the borehole length refers to the length of the drilled borehole. The explosive center is the center position of C-4 explosive length in the explosive device, and the burden is the shortest distance from the explosive center to the free surface. A burden of 45° borehole is shorter than that of 90° when two boreholes have the same length and the same size of explosives are employed for each borehole. As the RC wall has two free surfaces, the burden can be located on the side of the borehole opening (borehole side) or the other side (back side), depending on the position of the explosive center.

2.3 Charge condition

As the amount of explosive per borehole increases, the



(a) Borehole angle of 90° (b) Borehole angle of 45°

Figure 2 Cross-section of samples with borehole angles of 90° and 45°.
Borehole length : 125 mm
Amount of explosive : 8.0 g, The length of explosive : 60 mm
Burden : Borehole side

crater volume usually increases. Meanwhile, the detonation poses a greater impact on the environment as the amount of explosive increases. Because an intense impact is detrimental from the viewpoint of a secondary disaster, such as the collapse of remaining buildings, the amount of explosive was determined several grams per borehole. The amount of explosive changed between 3.0 to 8.0 g per borehole at a borehole angle of 90°, and between 4.0 to 12.0 g per borehole at a borehole angle of 45°.

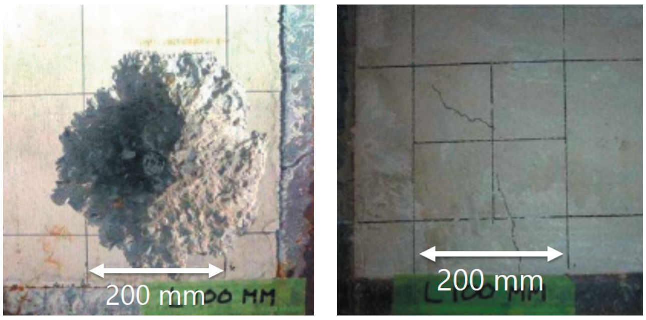
The stemming material and the diameter of the borehole were fixed, as they were in our previous studies[5)–7)]. Clay was used as the stemming material. The diameter of the borehole was 16 mm. An explosive device, which consisted of C-4 explosive and a No.6 electric detonator, was contained in a polycarbonate pipe. The lengths of the explosive device increased as the amount of explosive increased, because the diameter of the pipe was fixed at 13 mm. In the case of 3.0 g of explosive, the length of the device and the length of explosive were 60 mm and 20 mm, respectively. When the amount of explosive increased by 0.5 g, the length of device and explosive increased by 4 mm each.

3. Results and discussion

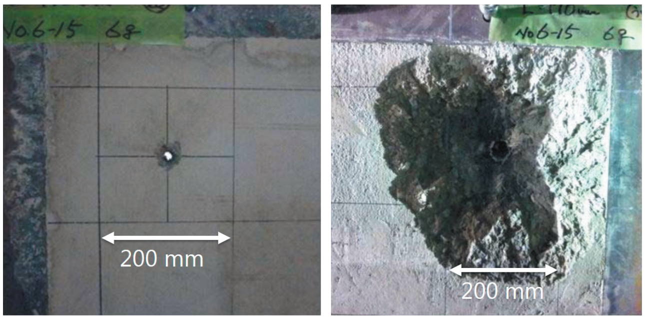
3.1 Borehole angle of 90°

3.1.1 Fracture manners for borehole angle of 90°

The fracture manners caused by 6.0 g of explosive are shown in Figure 3. Overall, experiments with vertical boreholes results in two types of fracture manners. One manner generated a crater only on the borehole side. This fracture manner is called Type A even if crack generation occurred on the opposite side as shown in Figure 3 (a) and (b). Figure 3 (c) and (d) show Type B fracture manner in which no crater was generated on the borehole side, and a crater was generated on the back side. The experimental conditions of this study provided no results that generated craters on both sides of the wall.



(a) Borehole side of Type A (b) Back side of Type A



(c) Borehole side of Type B (d) Back side of Type B

Figure 3 Result of the single-charge experiments. Amount of explosive : 6.0 g
Type A : (a) and (b), Burden : 78.5 mm (Borehole side)
Type B : (c), and (d), Burden : 101.5 mm (Back side)

3.1.2 Craters of borehole angle of 90°

Type A fracture appeared when the burden was at the borehole side. Borehole extending beyond the center of the wall thickness provided a Type B fracture, in which the burden was located on the opposite side. Whether a crater was generated on the borehole side or the back side correlated with the burden position.

The crater depths are plotted versus burdens in Figure 4. The burden required to generate the deepest crater was confirmed with each amount of explosive for Type A. The longest burden did not necessarily generate the deepest crater with each amount of explosive. For example, a 6.0 g of explosive with 78 mm of burden resulted in a deeper crater than one with 103 mm of burden. This relation between the burden and the crater depth was observed when the experiments were conducted with 4.0, 5.0, and 8.0 g explosive.

A burden at the back side (Type B) was more efficient than a burden at borehole side (Type A). For example, the deepest crater among ones obtained with a certain burden was Type B. When the burdens were between 75 and 85 mm, craters of Type B were deeper than Type A, even though Type B craters were generated by smaller amounts of explosive than Type A craters. Burdens between 90 and 105 mm reaching back side provided deeper craters than burdens that remained on borehole side. The experiment with 102 mm of burden and 6.0 g of explosive, which was also Type B, produced the deepest crater among the experiments in this study.

3.1.3 Assessment of fracture efficiency using CD/B value

Our previous study discussed the fracture process[7)]. A small amount of explosive generates a water-pot shape

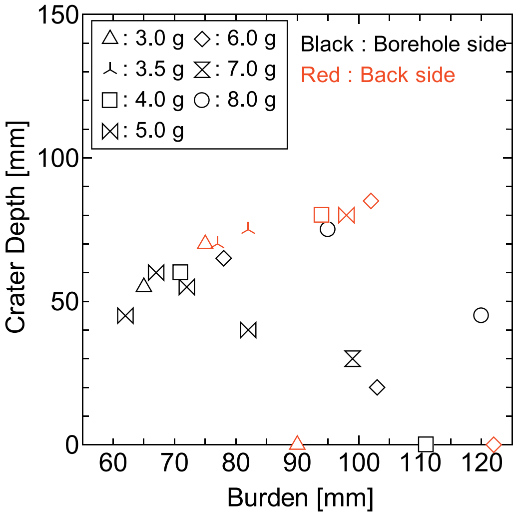


Figure 4 Relationship between the burden and the crater depth.
Black : Type A, The burden at borehole side
Red : Type B, The burden at back side

fracture. The crater depth was shallower than the burden when the fracture occurred. If the burden is optimally placed to achieve adequate destruction, the burden and the crater depth could be the same length. Therefore, in this study, the fracture efficiency was defined as the ratio of generated crater depth to its burden to evaluate a fracture which is abbreviated as CD/B. The desirable fracture efficiency is nearly one ; namely, the crater depth is approximately equal to the burden, and can be estimated as shown in Equation 1 :

$$\textit{The fracture efficiency} = \frac{\textit{Crater depth}}{\textit{Burden}} (CD/B) \tag{1}$$

Figure 5 is a schematic view that indicates the fracture efficiencies according to each crater depth, when the burden is located at the borehole side. Even if the burden is located at the back side, the fracture efficiency is still defined as Crater depth / Burden.

Table 1 rearranged the experimental results shown in Figure 4. The results showed no craters were removed. The rest of the results were divided into Type A and Type B, and arranged in the order of the amount of explosive. No matter where the burden was located, the CD/B was approximately 0.9 regardless of the amount of explosive.

Table 2 summarizes the deepest craters and crater radii for each amount of explosive. The radii of the deepest craters were approximately twice their burdens for each amount of explosive. The phenomena were observed for both type A and B. That means the deepest craters were obtained under the condition of overcharge[9].

Although a crater is neither a perfect cone shape nor a smooth surface, a crater volume can be estimated as follows :

$$CV = \frac{1}{3} \times \pi \times (CR)^2 \times CD \tag{2}$$

where CV is the crater volume [mm^3], CR is the crater radii [mm], and CD is the crater depth [mm].

With regard to the deepest craters among the ones created by a certain amount of explosive, their radii were about twice as long as their burdens, as is mentioned above. Therefore, the crater volume can be estimated as shown below because of the relation :

$$CV = \frac{1}{3} \times \pi \times (2B)^2 \times CD \tag{3}$$

where B is the burden [mm].

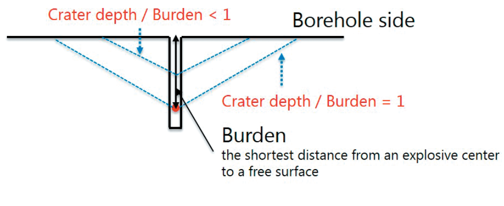


Figure 5 Schematic view which indicates the fracture efficiencies according to each crater depth (Borehole side).

Table 1 Crater depth / Burden (CD/B).

Borehole length [mm]	Amount of explosive [g]	Crater depth [mm]	Burden [mm] none : borehole side (Type A) * : back side (Type B)	CD/B
185	3.0	70	75.0*	0.93
185	3.5	70	77.0*	0.91
180	3.5	75	82.0*	0.91
170	4.0	80	94.0*	0.85
170	5.0	80	98.0*	0.82
170	6.0	85	102.0*	0.83
75	3.0	55	65.0	0.85
85	4.0	60	71.0	0.85
80	5.0	45	62.0	0.73
85	5.0	60	67.0	0.90
90	5.0	55	72.0	0.76
100	5.0	40	82.0	0.49
100	6.0	65	78.0	0.83
125	6.0	20	103.0	0.19
125	7.0	30	99.0	0.30
125	8.0	75	95.0	0.79
150	8.0	45	120.0	0.38

Table 2 Deepest craters and crater radii for each amount of explosive.

Borehole length [mm]	Amount of explosive [g]	Burden [mm] non : borehole side * : back side	Type of fracture [A or B]	Crater depth [mm]	Crater radius [mm]	Crater radius / Burden
75	3.0	65.0	A	55.0	137.2	2.1
185	3.0	75.0*	B	70.0	152.5	2.0
180	3.5	82.0*	B	75.0	165.0	2.0
85	4.0	71.0	A	60.0	180.0	2.5
170	4.0	94.0*	B	80.0	205.0	2.2
85	5.0	67.0	A	60.0	145.0	2.2
170	5.0	98.0*	B	80.0	225.0	2.3
100	6.0	78.0	A	65.0	147.5	1.9
170	6.0	102.0*	B	85.0	210.0	2.1
125	8.0	95.0	A	75.0	200.0	2.1

The desirable fracture efficiency is nearly one ; namely, the crater depth is approximately equal to the burden and crater volume can be estimated as shown in Equation 4 :

$$CV = \frac{1}{3} \times \pi \times (2B)^2 \times B \sim 4B^3 \tag{4}$$

3.1.4 Proposed charge condition design for borehole angle of 90°

Figure 6 shows the relationship between the amount of explosive and the burden providing the highest CD/B among each amount of explosive for Type A craters. In this study, the least-squares method provided the relationship between the amount of explosive and the burden as follows :

$$B = 5.86 \times W + 44.7 \quad (3.0\,\mathrm{g} < W < 8.0\,\mathrm{g}) \tag{5}$$

where W is an amount of an explosive per borehole [g].

As far as 90° to the surface in Type A, the length of burden can be determined to provide the highest CD/B at each amount of explosive in a borehole.

3.2 Borehole angle of 45°

3.2.1 Fracture manners for borehole angle of 45°

The fracture manners caused by 8.0 g of explosive are shown in Figure 7. Two types of fracture manners were

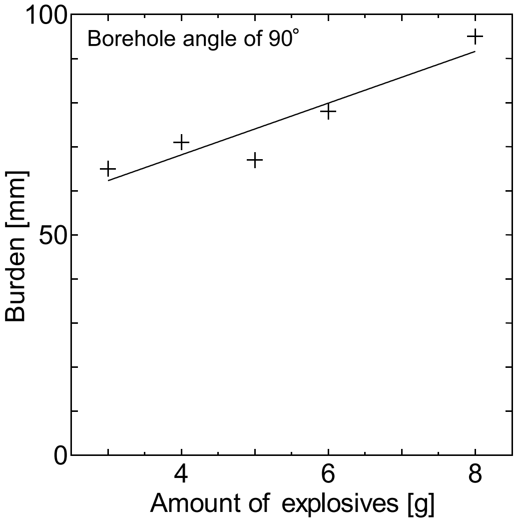
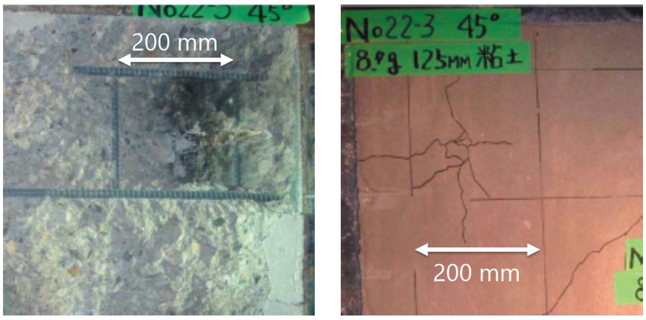


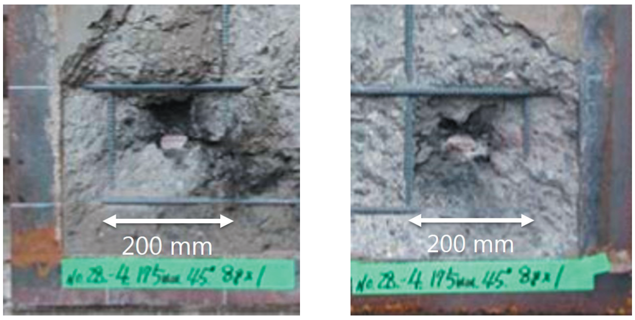
Figure 6 Relationship in Type A between the amount of explosive and the burden for the highest CD/B.

observed. Figure 7 (a) and (b) show Type A where a crater was generated on the borehole side as well as a borehole angle of 90°. However, Type A fracture manner of the back side was different between borehole angle of 90° and 45°. In the case of a borehole angle of 45°, more than 5.0 g of explosive generated cracks on the back side. On the other hand, more than 6.0 g of explosive at a borehole angle of 90° required to generate cracks on the back side.

Another fracture manner type exhibited craters on both sides. This fracture manner identified by Type C, is shown in Figure 7 (c) and (d). The experiments with a borehole angle of 90° permitted craters on one side, while a borehole angle of 45° provided craters on both sides of the wall.



(a) Borehole side of Type A (b) Back side of Type A



(c) Borehole side of Type C (d) Back side of Type C

Figure 7 Result of the single-charge experiments. Amount of explosive : 8.0 g
Type A : (a) and (b), Burden : 103.9 mm (Borehole side)
Type C : (c), and (d), Burden : 96.6 mm (Back side)

3.2.2 Craters of borehole angle of 45°

Table 3 summarizes the experimental results for a borehole angle of 45°. All blasting in which burden is located at the borehole side resulted in Type A fractures. In general, burdens placed at the opposite side provided Type C fractures. Some Type C fractures resulted in penetration of the wall. One of the exceptions was the 119.2 mm of burden at the back side with 12.0 g of explosive that resulted in a Type A fracture. In this case, the explosive center was at 130.8 mm from the borehole side surface, and the ratio between the explosive center and the thickness of RC wall was 0.52. The previous study showed that fracture manner was influenced by concrete compressive strength when the ratio between the explosive center and the thickness of RC wall was 0.5, in the case of a borehole angle of 90°[7]. A ratio affected by the concrete compressive strength could be changed when the borehole angle was 45°.

3.2.3 Proposed charge condition design for borehole angle of 45°

Figure 8 shows the relationship in Type A between the

Table 3 Experimental results with borehole angle of 45°.

Borehole length [mm]	Amount of explosive [g]	Burden [mm] non : borehole side * : back side	Type of fracture [A or C]	Crater depth [mm]	Crater radius [mm]	Crater radius / Burden	Crater depth / Burden (CD/B) * : highest in each amount of explosive
113	4.0	70.0	A	65.0	140.0	2.0	0.93*
127	4.0	79.9	A	65.0	145.0	1.8	0.81
141	4.0	89.8	A	80.0	150.0	1.7	0.89
155	4.0	99.7	A	85.0	180.0	1.8	0.85
127	5.0	77.1	A	70.0	145.0	1.9	0.91
130	5.0	79.2	A	80.0	127.5	1.6	1.01*
141	5.0	87.0	A	75.0	180.0	2.1	0.86
177	8.0	103.9	A	100.0	235.0	2.3	0.96
191	8.0	113.8	A	110.0	225.0	1.98	0.97*
247	8.0	96.6*	C	penetration	penetration	penetration	penetration
247	10.0	102.2*	C	penetration	penetration	penetration	penetration
231	12.0	119.2*	A	130.0	220.0	1.7	no crater on back side
247	12.0	107.9*	C	105	245.0	2.3	0.97

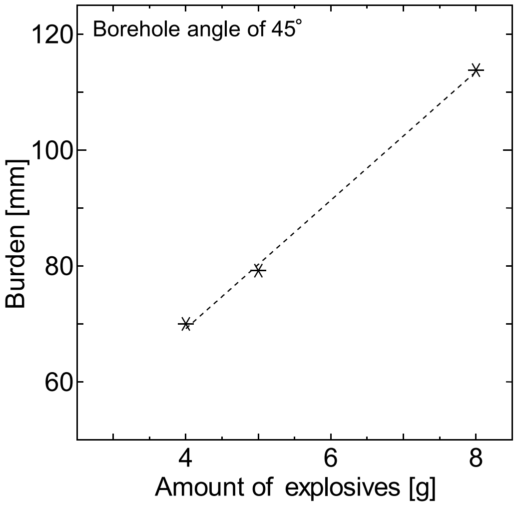


Figure 8 Relationship in Type A between the amount of explosive and the burden of the highest CD/B.

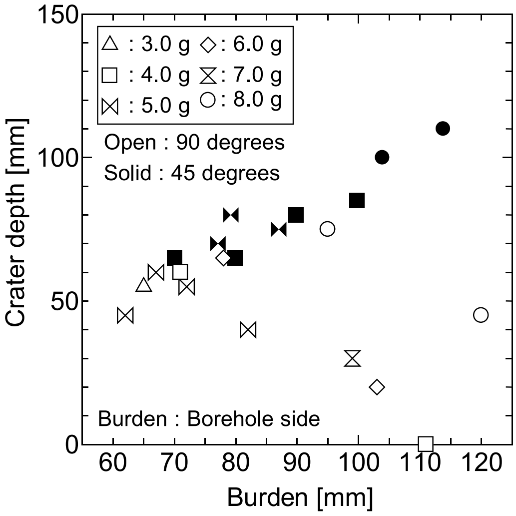


Figure 9 Relationship in Type A between the burden and the crater depth.
Burden : Borehole side
Open : Borehole angle of 90°, Solid : Borehole angle of 45°

amount of explosive and the burden providing the highest CD/B among each amount of explosive. As far as 45° to the surface in Type A, the amount of explosive and the burden giving the highest CD/B can be estimated as follows :

$$B = 11.1 \times W + 24.9 \;\; (4.0\,\mathrm{g} < W < 8.0\,\mathrm{g}) \tag{6}$$

3.3 Comparison between borehole angle of 45° and 90°

Figure 9 indicates the crater depths of Type A craters along the burdens. The open symbols indicate a borehole angle of 90°, and the solid symbols indicates a borehole angle of 45°.

Comparing the results, a borehole angle of 45° consistently provided a greater crater depth than a borehole angle of 90° for each amount of explosive, as shown in Figure 8. The dependency of crater depths on burden was found for 45° of borehole angle ; however, no dependency was found for 90°.

A borehole angle of 45° was considered to obtain more fracture energy of the explosive than 90°, because the length of stemming was longer, even though the length of burdens is same for both. The results of this study clearly showed that borehole angle influenced crater generation and the difference in fracture manner at borehole side was considered to be due to the difference of stemming length.

For rescue crews, crater generation on the borehole side makes secondary fracture easy, because wall penetration can be achieved through the removal of the remaining wall and reinforcing bar. No matter where the burden was located, the fracture efficiency in the borehole side was higher for a borehole angle of 45° in comparison to a borehole angle of 90°. The CD/B with a borehole angle of 45° became higher than a borehole angle of 90°. Highest CD/B values among burden and craters of borehole side was approximately 1.0, which occurred with a borehole angle of 45° as shown in Table 3. As for rescue work, a borehole angle of 45° was favorable because the craters generated on the borehole side in either Type A or C. Meanwhile, Type B caused by a borehole angle of 90° was unsuitable.

4. Conclusion

This paper focused on borehole angle, which were 90° and 45° to the surface of the wall. In general, a borehole angle of 90° is basically a straight drill, which requires less effort and is beneficial for rescue work. However, in the case of a borehole angle of 90°, the crater was generated on the borehole or back side. These fracture manners are not suitable for small-scale blasting for breaching in rescue work, even when no victim is on the other side, because the fracture manner needs to rapidly demolish both sides in these case.

On the other hand, a borehole angle of 45° provided craters on the borehole side or both sides of the wall. The CD/B increased for a borehole angle of 45° in comparison to a borehole angle of 90°. The 45° of borehole drilling would be more suitable for small-scale blasting for breaching in rescue work, because the fracture manner is preferable to that of 90°. The burden to provide a crater with high CD/B was proposed for each amount of explosive. The optimal charge condition for breaching can be decided by using this approach.

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