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Development of low noise and vibration tunneling methods using slots by single hole continuous drilling

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Abstract

We have recently developed a new continuous hole drilling method as a rock fracturing method in hard rock tunnel excavation and as a free face forming method to be used at the time of controlled blasting excavation. In this paper, we overview the continuous hole drilling method and explain the tunnel excavation by the rock fracturing method and the controlled blasting by using this method.

Keywords: Non-blasting; Free face; Rock fracturing; Controlled blasting

1. Introduction

It goes without saying that the adoption of the blasting method is most efficient and very economical for excavating rocks. However, the blasting method brings about loud noises and strong vibrations and would not be suitable for excavating tunnels in urban areas. Despite this, examples of this excavation have increased in Japan.

Machine excavation of hard rock is classified into two kinds, i.e. single machine excavation and rock fracturing method. The single machine excavation has a few problems: excavation in short distance is not economical for using TBM, or compressive strength for drilling is limited for using partial face machine. So, the rock fracturing method is considered most suitable for the excavation of hard rock in short distance at the portal and so on. For the rock fracturing method, a free face is artificially formed at working face. Then, the free face is used to crush rocks.

Although various free face forming methods were proposed (Hagimori et al., 1991; Murata and Yokozawa, 1997), they have such problems as necessity of special forming device, forming efficiency and accuracy in continuity. So, the authors have developed the method to use the general-purpose drill jumbo more efficiently and higher in continuity than conventional methods. In addition, this method is effective for reducing vibrations even in controlled blasting if the free face is formed on the periphery of tunnel.

2. Significance of free face

A free face means a face that does not restrict rupture at the time of crushing. When a tunnel is excavated by blasting, only one free face is formed at the working face. In the case of the blasting method, the crushing force is strong and excavation has become possible even with a free face as the center cut blasting has been devised.

However, the crushing capacity of the rock fracturing method is less powerful than blasting, and crushing with one free face is impossible. In other words, although cracks are caused at the working face by some methods, it is difficult to cause large cracks when only one free face is formed. Two or more free faces enable to secure rock-moving spaces and to make cracks larger. Therefore, it is necessary to artificially form free faces at the working faces of tunnels.

Fig. 1 shows the conceptual diagram of free face formation in tunnel excavation. When a continuous hole is drilled like a groove as shown in the figure, the working face is divided into blocks. This brings about multiple free faces and makes crushing rocks easier. When natural ground becomes hard, it is difficult to

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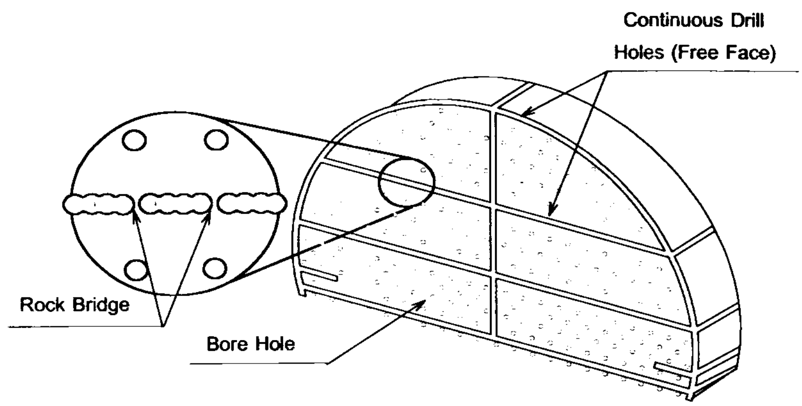

Fig. 1. General concept of the free face formation at the tunnel.

crack it and many grooves should be formed. Continuity and widths of grooves to be formed at the time, influence rock fracturing efficiency. If rock bridges remain that are shown in the figure and these interrupt the continuity of the grooves, a large compressive force is necessary for cracking. Also, the wider grooves to be formed are, the larger rocks moving spaces can be secured and the easier rocks become to cut.

However, it takes considerable labor and time to form grooves on hard rocks. Therefore, it is very important for excavating tunnels by the rock fracturing method to form continuous free faces efficiently and economically. As mentioned above, the usual method requires a special forming device and has some problems in forming efficiency and accuracy of continuity. To solve these problems, a method has been developed to drill single holes more efficiently and continuously than by the conventional method.

3. Free face forming method

As mentioned above, we paid special attention to the following points in developing the new free face forming method:

1. high free face forming efficiency;
2. sufficient maintenance of continuity accuracy; and,
3. possibility to use general purpose drill jumbo.

The following outlines this method and describes its efficiency.

3.1. Free face forming by continuous hole drilling

As the latest drilling technique has progressed, a drifter of 1.5 kN class can provide the drilling speed of 1 m/min for hard rocks of compressive strength of more than 200 MPa if a 100-mm bit is used. For the free face forming method developed, keeping this point in mind, we adopted a general-purpose drill jumbo and the continuous drilling of a single hole so as to display this ability to the maximum.

In case of continuous drilling of a single hole, the rod bit is to drill a hole turned to a neighboring existing hole. They developed the method to drill a continuous hole by inserting a spinning anti-bend (SAB) rod (Ø 89 mm) in a neighboring existing hole and by making a bit touch and strike against a SAB rod by using this property.

Fig. 2 shows the schematic diagram of the SAB rod. Contacting the bit to, and striking it against the SAB rod at the time of drilling a hole does not cause any clearance between the bit and the rod and secure continuity of a free face. This SAB rod is structured to rotate and enables drilling of a hole at high speed when the resistance by contacting and striking at the time of drilling a hole is reduced. The SAB rod is designed to be fitted to the bracket on the tip of the guide cell of a general-purpose rock drill and is inserted and pulled out when the guide cell slides.

Fig. 3 shows the drilling procedures. The drilling procedures are as follows:

1. Insert the SAB rod in an existing hole.
2. Start drilling a hole. The bit drills a hole while it touches and strikes against the SAB rod. The SAB

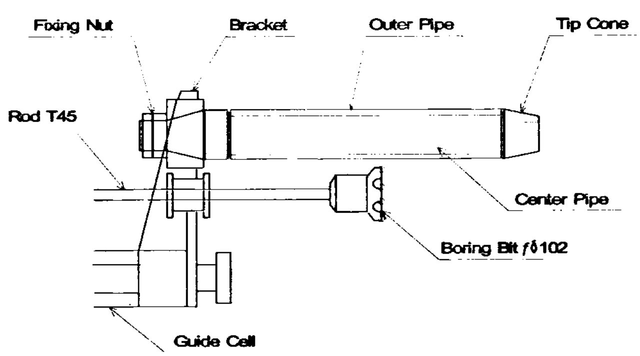

Fig. 2. Concept of the SAB rod.

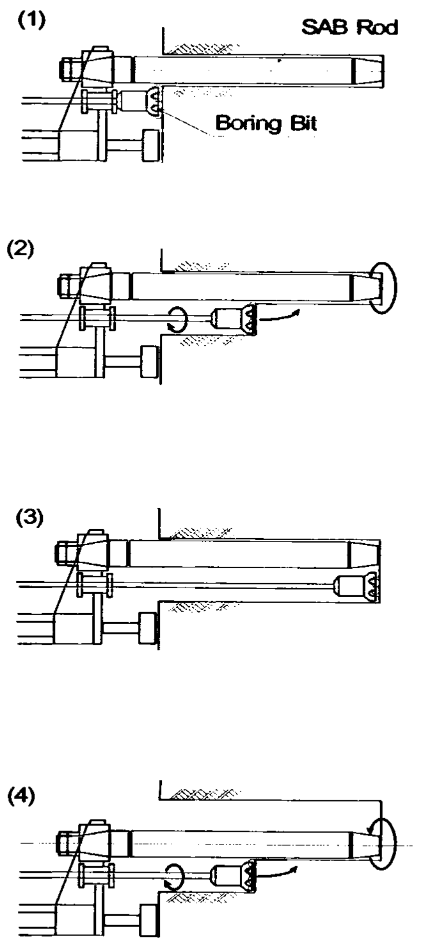

Fig. 3. Procedure of continuous hole drilling.

rod rotates as the bit rotates, and this makes a high speed drilling possible.

3. Keep drilling to the specified depth.
4. Keep inserting the SAB rods one after another and drilling to form a continuous hole (free face). It makes high continuity free face forming possible that the bit touches the SAB rods.

In addition, it reduces wear of rod and bit and makes even the SAB rod itself wear evenly as the SAB rod can rotate. So, the SAB rod can be used for hours. Also, the consumable part of the SAB rod is the thick pipe only. and the SAB rod is very economical.

As mentioned above, the general-purpose rock drill is generally used for fixing rock bolts and drilling fracturing (or loading) holes, but mounting a SAB rod on a general-purpose rock drill makes it possible to drill continuous holes. So, no dedicated machine is necessary. Fig. 4 shows the situation of continuous hole drilling.

3.2. Examination of free face forming efficiency

To represent the free face forming ability quantitatively, we evaluate the continuous hole forming area formed with one boom of a rock drill in 1 h, in this section.

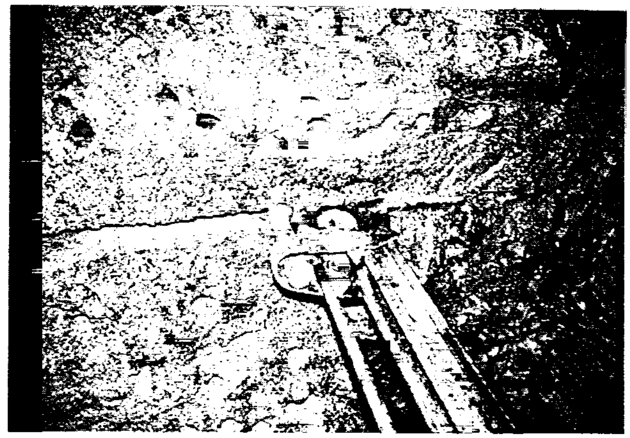

Fig. 4. Continuous holes drilling.

Fig. 5 shows the free face forming ability by this method. This method enables drilling of hard granite of uniaxial compressive strength more than 100~250 MPa to 1.1 m depth with a bit of diameter 102 mm at 3.5~4.5 m^2/h.

We compared drilling speeds against rock strength between a single hole, or fracture hole, drilling and continuous hole drilling to examine free face forming ability. Figs. 6 and 7 show the results of both drilling speeds.

As these figures show, the drilling speed of continuous hole is apparently 10–20% faster. We consider that this results from reduction of drilling area due to overlapped portions in drilling continuous holes and from difference of cuttings forming process at the time of digging. Figs. 8 and 9 show the patterns of the both holes at the time of drilling. At the time of drilling in rock, the striking force and the rotating force transmitted to the bit from

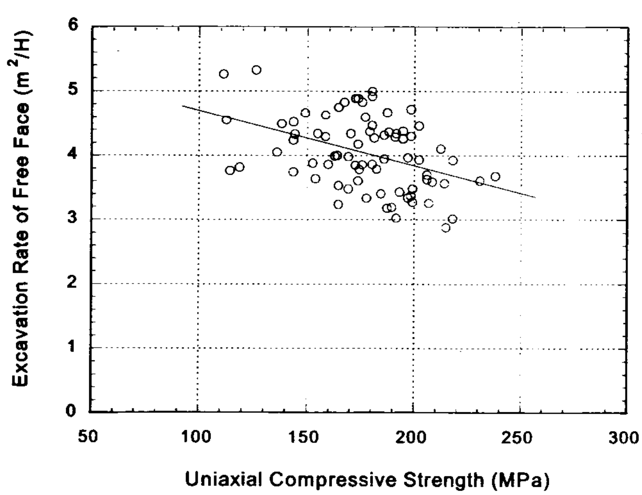

Fig. 5. Relationship between continuous hole drilling ability and rock strength.

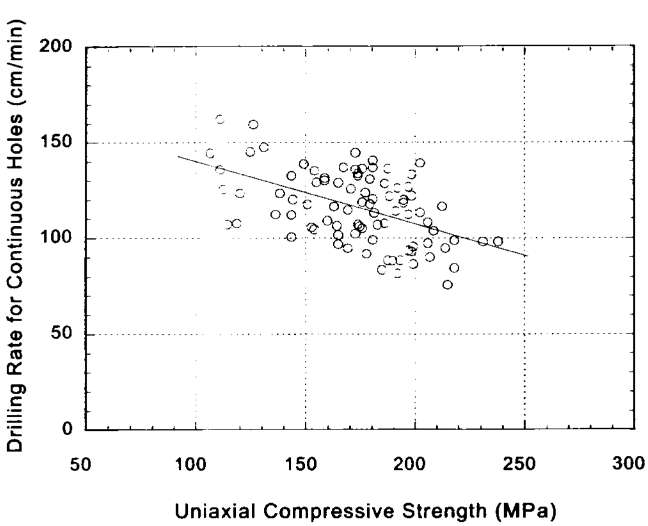

Fig. 6. Relationship between continuous hole drilling rate and rock strength.

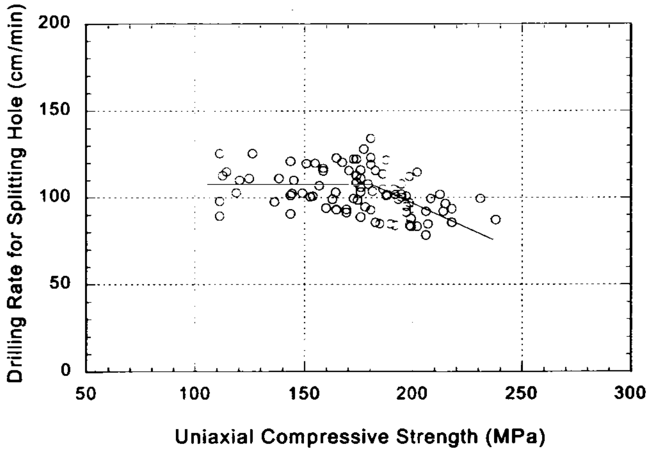

Fig. 7. Relationship between single hole drilling rate and rock strength.

the rock drill fracture the rock into several pieces to 20 mm. In the case of single hole drilling, fractured pieces cannot pass through the clearance between the bit and the rock as shown in Fig. 9 as long as they remain as they are and cannot be discharged outside the hole. Therefore, fractured pieces are fractured again with the bit and are discharged together with drilling hole water as cuttings smaller than 1 mm. However, a continuous hole is drilled making the neighboring hole a free face as shown in Fig. 9. Therefore, the continuous hole is more fragile than a single hole, and the fractured pieces remain as they are and are discharged as cuttings to the existing hole side together with drilling hole water as the SAB rod rotates. We consider that, as a result, the fractured pieces would not necessitate secondary fracturing energy, and rock drill energy would be mostly

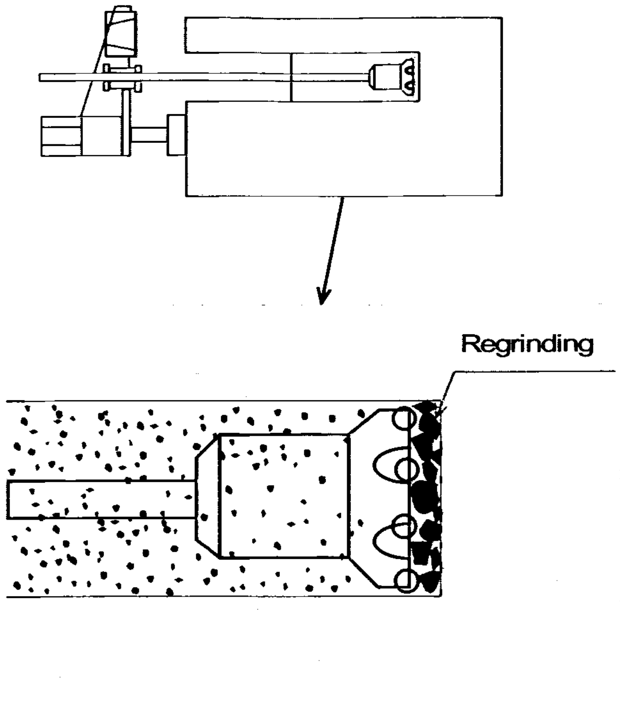

Fig. 8. Diagram of single hole drilling.

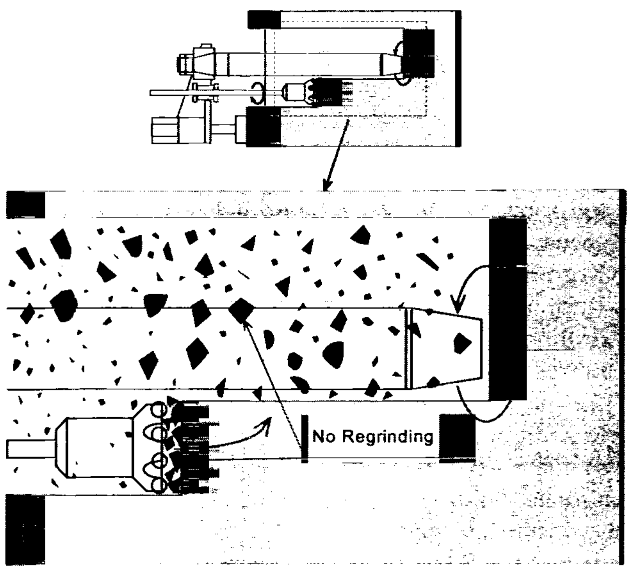

Fig. 9. Diagram of continuous hole drilling.

used for drilling and would make the drilling speed faster.

To verify this conclusion, we sampled the both cuttings at the times of drilling and conducted gain size analyses. Fig. 10 shows the results. The figure discloses that sizes of cuttings discharged at the time of drilling a single hole are smaller than 1 mm and those in drilling a continuous hole are mostly larger than 1 mm.

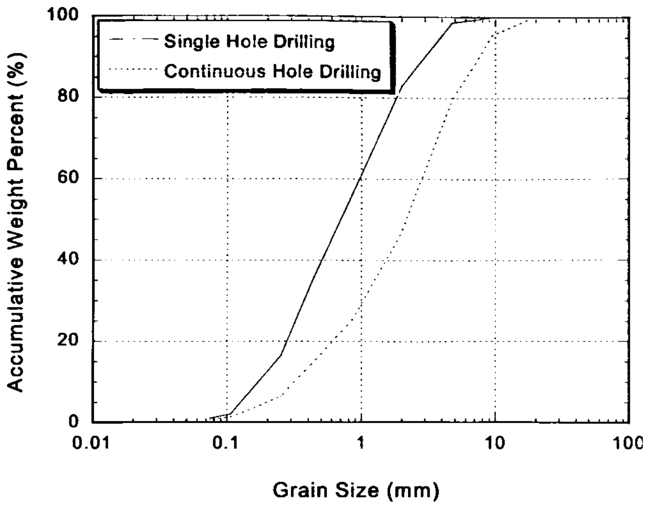

Fig. 10. Grain-size accumulation curve of cuttings.

Then, we consider that the above conclusion was proved correct.

4. Application to rock fracturing method

The Kaminiko Tunnel in Hiroshima Prefecture is a 550 m long two-lane road tunnel. This tunnel was restricted as follows:

1. There were many houses around the construction site.
2. There were many boulders along the tunnel route, and they were expected to fall down due to blasting vibration even if protection measures were provided.

Therefore, the blasting method could not be adopted along the whole tunnel route. In addition, the geology along the tunnel route was granite of compressive strength of more than 100 MPa, and single machine excavation with a partial face machine was not possible. Therefore, free faces were formed on the tunnel working face, and the free faces were used to excavate the tunnel by the rock fracturing method.

As mentioned above, the stronger the rock is, the more difficult it is to drill the rock, and the number of free faces should be increased. Therefore, we prepared the free face forming pattern for the strength for the construction. Fig. 11 shows the free face forming pattern for the hardest working face of the compressive strengths of 200 ~ 250 MPa. Free faces were formed at both corners, along the periphery and along three lines in the tunnel face (one line was in a vertical direction, two lines were in a horizontal direction). For this tunnel, one progress head was 1 m, the depth of formed free face was 1.1 m, and the total free face forming area was approximately 68 m^2. Although the drill jumbo used for the construction was of the three-boom drifter type which weighs 1.5 kN, the free face forming efficiency was very high and the forming time per one progress was less than 6 h.

After the continuous hole drilling, the hydraulic wedge shown in Fig. 12 was used for rock fracturing. The hydraulic wedge has the following features:

1. high crushing capacity;
2. causing wide cracks; and
3. control of crack causing direction.

After these processes, a breaker was used for the secondary crushing to end the rock fracturing. Fig. 13 shows the secondary fracturing situation.

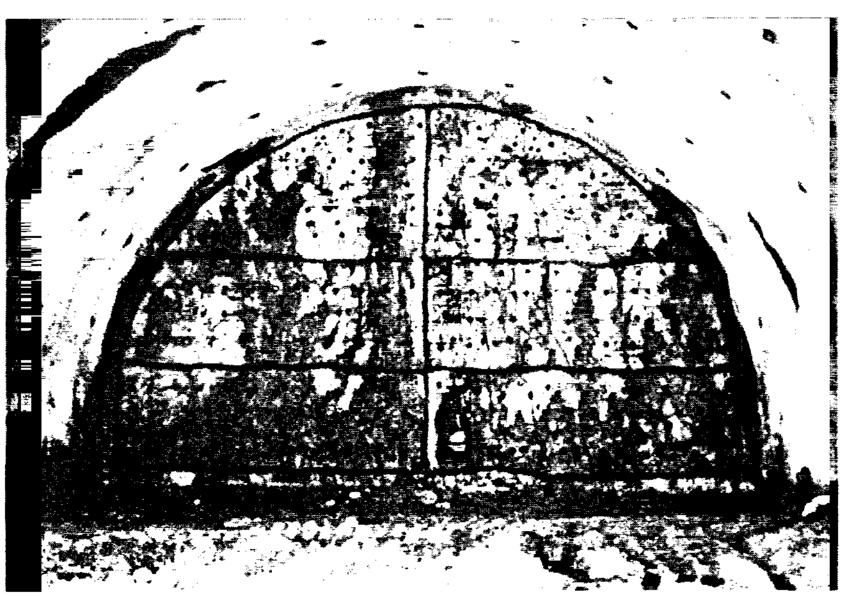

Fig. 11. Tunnel face after forming free face.

Fig. 12. Rock fracturing by hydraulic wedge.

Fig. 13. Secondary fracturing.

5. Application to controlled blasting

In the case of the Yasumiyama Tunnel in Hiroshima Prefecture, the portal was located in the center of a city and there were many houses around. As the tunnel was excavated, the rocks became harder, and granite of uniaxial compressive strength of more than 150 MPa spread beyond 500 m from the portal. Therefore, the single machine excavation with a partial face machine became impossible for the construction. We examined if the blasting method was applicable, but there were houses 70 m above the construction site. Also, we had to consider the environment around the portal.

Therefore, we tested various controlled blasting, compared and examined them to find the most applicable controlled blasting method for the following process. We examined control with a peripheral free face, control with an electronic delay detonator and combination of both. The electric delay detonator enables a delayed time setting at any 1 millisecond (ms) increment and has a high accuracy of 1 ms. By utilizing these features, we were able to initiate hole by hole with 30 ms delay over the entire cross-section of the tunnel instead of normal detonator (Murashita et al., 1998). This makes it possible to minimize the charge per blasting, which is most important for vibration and noise control.

Table 1
Testing pattern of each method

Monitoring site	Distance from tunnel face (m)	Monitoring item
House above tunnel face	Just upside 70	Displacement speed Vibration level meter Noise meter
	Forward 100	Displacement speed Vibration level meter
	Backward 100	Displacement speed Vibration level meter
Portal	500	Noise meter Low frequency noise meter
House beside portal	From portal approximately 40	Low frequency noise meter

We conducted usual blasting by the above methods and with a normal detonator, measured vibrations and noises at the times of blasting, compared their control effects and examined the economy of these methods.

Table 1 summarizes the tests conducted this time, Fig. 14 shows various excavation patterns except division blasting, and Table 2 shows vibration and noise measurements and measuring position. Table 3 shows the results of noise and vibration measurements. We evaluated these methods as follows from the results of these tests:

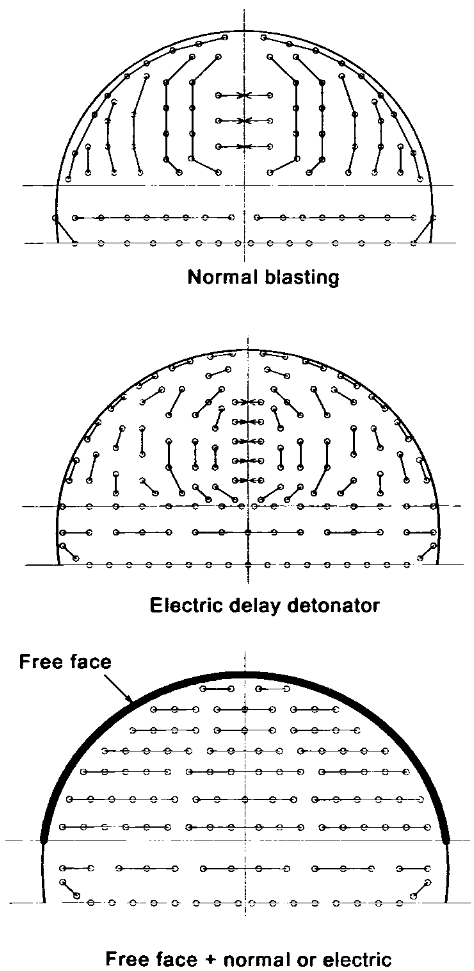

Fig. 14. Drilling pattern for each test.

1. The measured noise values show that the controlled blasting with free face and electronic detonator caused the least noise as expected and that controlled blasting with an electronic delay detonator, controlled blasting with free face and normal detonator and division blasting caused noises at the similar levels. Also, the normal blasting caused the largest noises.
2. In case of normal blasting, the vibration value reduced gradually from the peak at the time of center cut. When the electronic delay detonator was used, the vibration peak value was lower than that of normal blasting. However, the blasting with the electronic delay detonator took more time, and vibration of certain levels continued for a longer time (4∼5 s). When both the free face and normal detonator were used, the vibration value came to the peak at the beginning and reduced quickly.
3. For low frequency noise, there were significant differences between the electronic delay detonator and normal detonator, irrespective of the free face, and remarkable noise reduction was recognized in blasting with the electronic delay detonator.
4. For economy, blasting with the free face and electric delay detonator was most expensive, and division blasting, blasting with free face and normal detonator, blasting electronic delay detonator and normal blasting followed in this order.

Table 2
Monitoring site, monitoring item and distance from tunnel face

Testing method	Detonator	Free face
Electric delay detonator only	Electric delay	×
Electric delay detonator + free face	Electric delay	○
Normal detonator + free face	Normal	○
Division	Normal	×
Normal blasting	Normal	×

Table 3
Results of vibration and noise monitoring

Test pattern	Vibration[a] (dB)			Low frequency noise (dB)		Noise (dB)	
	−100 m	Just upside	+100m	Portal	House beside portal	Portal	Just upside
Electric delay	50	52	54	116	101	77	47
Electric delay + free face	43	48	47	113	100	75	53
Normal + free face	50	52	53	118	111	79	52
Division (max value)	52	50	53	122	112	79	51
Normal blasting	56	57	57	122	117	82	51

[a] $dB = 20 \log (A_{eff}/A_{ref})$; $A_{ref} = 10^{-5}$ m/s^2 (in Japan).

6. Conclusions

We have overviewed our new free face forming method and conclude with the following remarks:

1. No special machine is necessary for forming free faces, and the general drill jumbo will do all drilling works.
2. Even in case of rocks of compressive strength of more than 200 MPa, the free face forming capacity of more than 3.5 m^2/h is available.
3. This method is superior in continuity of free faces to be formed and allows efficient rock cutting fracturing and controlled blasting.

In view of these features, we will gather various construction data further to establish this method as the efficient low vibration tunnel excavation method.

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