研究論文

Effects of rock pressure on crack generation during tunnel blasting

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We performed a stress analysis in the area around a smooth blasting borehole on the expected fracture line of a tunnel in order to clarify the effect of rock pressure on crack generation during tunnel blasting. We also carried out test blasts on PMMA plates, marble plates and sandstone blocks those were assumed the borehole on the expected fracture line in the tunnel was under initial rock pressure. In addition, we made a numerical simulation of a blast and compared with the results of the test blasts.

Our results showed that tensile stress was generated around the borehole by the effect of initial rock pressure. Moreover, around the borehole in the side wall and in the shoulder part of the tunnel, i.e. the intermediate point between the roof and the side wall, tensile stress was always generated vertically with respect to the expected fracture line. However, around the borehole in the roof of the tunnel, the position where the tensile stress was generated varied depending on the state of the rock pressure. Moreover, the results of the test blasts using plates and blocks clearly indicated that cracks were generated and spread in the same direction as the applied pressure, and that blasting in the area around the borehole in the initial stress state had the effect of creating and lengthening cracks. The results of blast simulation showed a good agreement with the experimental results.

1. Introduction

When excavating underground caves and mountain tunnels by blasting, the formation of a flat excavation surface and damage to the walls have to be controlled as much as possible in order to reduce overbreak. For this reason, smooth blasting has been used, and quantitative research by which to assess the level of damage caused by blasting to the surrounding rock mass and the area influenced by excavation has been investigated[1)~5)].

During excavation of caves and tunnels deep underground or in mountains, the initial rock pressure within the rock mass is released and the stress in the bedrock around the underground cave or tunnel is redistributed. Knowing the degree to which stress is concentrated in the side walls of an underground cave or tunnel by such redistribution is important from a safety point of view, and much research on this topic has already been completed[6)~9)].

The fracture mechanism of rock in smooth blasting is now known to be as follows. First, a closed crack is generated in an adjacent hole by the stress

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wave from the blast initially detonated in the borehole. Next, this generated closed crack is developed by the blast in the adjacent hole and a fracture surface is generated[10]. Katsuyama et al.[11] clarified the effect of the guide hall in smooth blasting, and Yamaguchi and Shimomura[12,13] executed an experimental model and gave it theoretical consideration from the viewpoint of the state of the static stress. Moreover, boring and detonation accuracy to control the crack have improved in recent years due to the advancement of technology[14~17]. However, until now, explanations of the smooth blasting mechanism have not considered the concentration of stress inside the side walls around the tunnel that originates from rock pressure. In particular, the effect of the distribution of stress around the borehole is unclear at present.

The purpose of this research is to elucidate how the distribution of stress originating from rock pressure in the area around the borehole affects crack generation when blasting a tunnel. We first performed a stress analysis of the area around the smooth blasting borehole on the expected fracture line. We also carried out test blasts that were assumed the borehole for smooth blasting, and the generation and progress of the crack were confirmed. Finally, we simulated a blast and observed the crack, then compared them with the results of the test blasts.

2. Stress distribution around a smooth blasting borehole

2. 1 Conditions of analysis and analytical model

We employed the finite element method to analyze the distribution of stress in the area around a smooth blasting borehole. For the calculation, we used the general-purpose finite element analysis program ANSYS installed by the calculation center at the Tsukuba Advanced Computing Center of the Agency of Industrial Science and Technology.

In the analytical model, the blast holes other than the borehole for smooth blasting on the expected fracture line were assumed to have already detonated immediately before the detonation of the charge in the borehole for the smooth blasting in the tunnel from the surface of the earth to a depth of 200 m. A complex value for the initial rock pressure was indicated in various places. In our analysis, however, we examined two kinds of rock pressure: a dead load in the vertical direction and hydrostatic pressure acting as rock pressure. We also assumed that the bedrock consisted completely of granite. Table 1 shows the various values of physical properties of the materials. The finite element model (Fig. 1) was divided into elements with 120, 234 nodes and 59, 806 elements. We took the shape of a tunnel cross-section to be the same as the large cross-section tunnel on the second Tomei - Meishin expressway.

Table 1 Physical properties of sample materials

Material	Density ρ [kg/m^3]	ν^* [-]	Cp** [m/s]	E*** [GPa]
Granite	2580	0. 1	3950	56. 8
PMMA	1170	0. 35	2800	5. 37
Marble	2650	0. 12	3145	20. 7
Sandstone	2000	0. 21	2710	6. 50

* : Poisson's ratio
** : Velocity of propagation of longitudinal wave
*** : Young's modulus

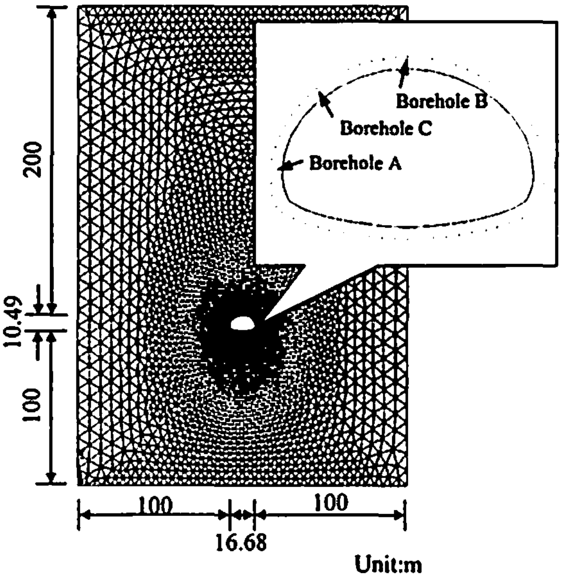
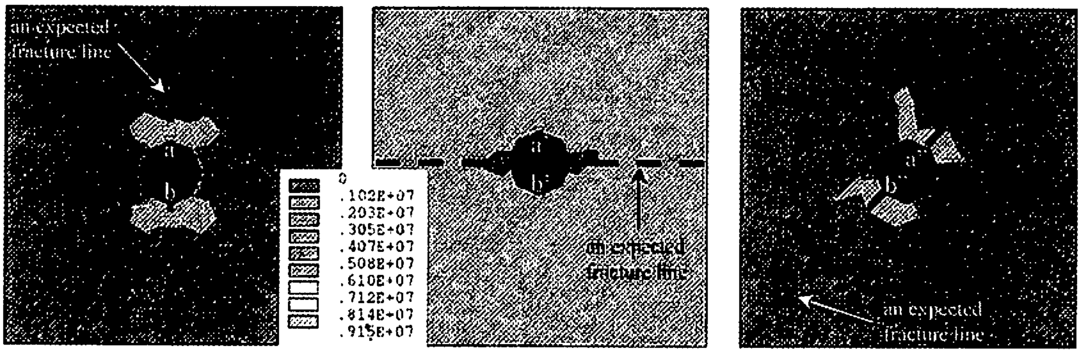


Fig. 1 Finite element meshes of the model

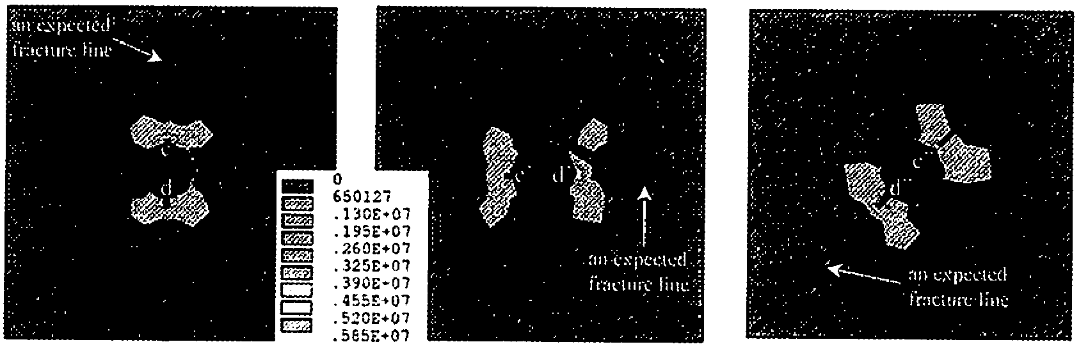
2. 2 Results of analysis

Figs. 2 and 3 show the maximum principal stress distributions around the borehole on the expected fracture line in the tunnel's side wall (borehole A),



(a) Borehole A (b) Borehole B (c) Borehole C

Fig. 2 Stress distribution of maximum principal stress around a borehole (A dead load in the vertical direction)



(a) Borehole A (b) Borehole B (c) Borehole C

Fig. 3 Stress distribution of maximum principal stress around a borehole (hydrostatic pressure)

roof (borehole B) and the intermediate shoulder part (borehole C) with a dead load in the vertical direction and with hydrostatic pressure acting as the rock pressure, respectively. The stress shown is the tensile stress in units of Pascals. First, the rock pressure was taken as a dead load in the vertical direction. At borehole A (Fig. 2(a)), a tensile stress of 5. 64 MPa was generated in a horizontal direction at the top and bottom of the borehole (points a and b). At borehole B (Fig. 2(b)), 5. 45 MPa of tensile stress was generated in a horizontal direction at the top and bottom of the borehole (points a' and b'). In addition, at borehole C (Fig. 2(c)), a tensile stress of 3. 05 MPa was generated perpendicularly at points a" and b" along the expected fracture line.

Secondly, rock pressure was taken as hydrostatic pressure. At borehole A (Fig. 3(a)), 4. 47 MPa of tensile stress was generated in a horizontal direction at the top and bottom of the borehole (points c and d). At borehole B (Fig. 3(b)), a tensile stress of 4. 07 MPa was generated in a vertical direction to the left and right of the borehole (points c' and d'). Finally at borehole C (Fig. 3(c)), 4. 06 MPa of tensile stress was generated perpendicularly at points c" and d" along the expected fracture line.

From the above results, it can be seen that tensile stress was generated around the borehole by the effect of initial rock pressure. Moreover, around the boreholes of the side wall and the shoulder part of the tunnel, the tensile stress was always generated perpendicularly with respect to the expected fracture line. However, around the borehole in the roof of the tunnel, the position where the tensile stress was generated was different according to the state of the rock pressure.

3. Test blasts on plates and blocks

3. 1 Test samples

We used plates made from two kinds of materials in which cracks can be seen easily, marble and polymethyl methacrylate (PMMA), and blocks made from sandstone. Table 1 shows some of the physical

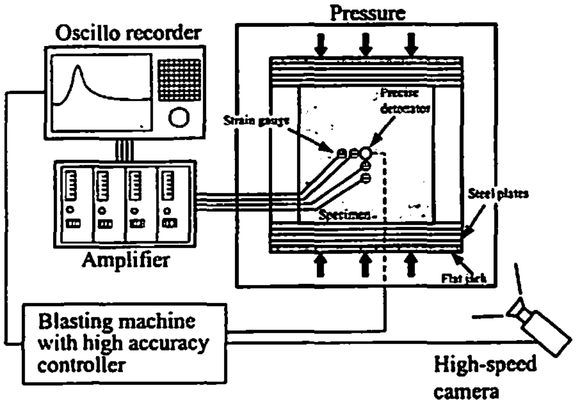


Fig. 4 Schematic diagram of test blast on plates and blocks

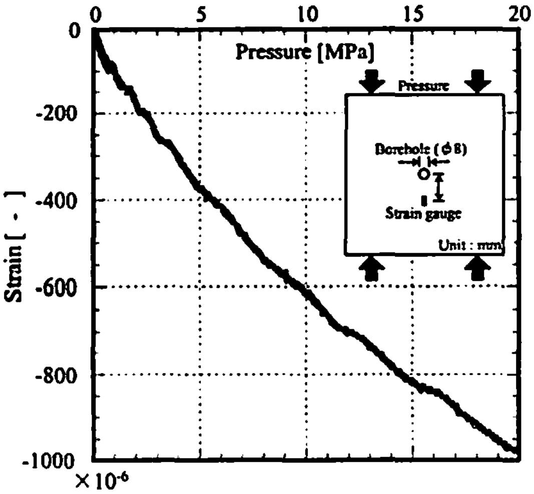


Fig. 5 Relation between pressure and strain

properties of the samples.

3. 2 Test method

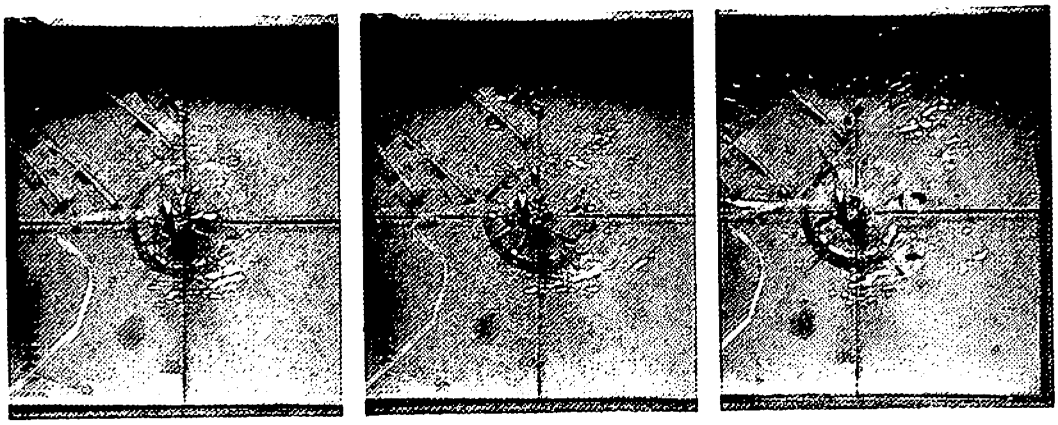
We carried out test blasts on PMMA plates (200 mm×200mm×21 mm), marble plates (200mm× 200mm×23mm) and sandstone blocks (300mm× 300mm×300mm). Fig. 4 shows a schematic of the experimental equipment. In the test, we used a flat jack to apply vertical pressure on the side of the test sample. In this state of applied pressure, a precise detonator[10] set up in the center of the sample was initiated. We used a high-speed camera to check the generation and progress of the cracks caused by the detonation. We used color 35-mm film taking 26 frames at a speed of 2×10^5 frames/s (frame interval of 5 μs). We also performed a test blast without added pressure for comparison. The precise detonator was initiated with an accurately-controlled blasting machine made by Nippon Kayaku K.K., and the high-speed camera we used was the Model 124 Framing Camera made by Cordin. To judge the value of the pressure applied with a flat jack to the side of the test sample, we used a material tester manufactured by MTS, and determined beforehand the relationship between pressure and strain (Fig. 5). Using this relationship the pressure value was obtained from the amount of strain on the test sample due to pressurized flat jack. Strain was measured from a point of 30 mm away from the center of the borehole.

3. 3 Results and discussion

From high-speed camera photographs of fracture process during blasting in a PMMA plate when there was no pressure (Fig. 6), we can observe initially that radial cracks were generated, which continued to progress radially. On a high-speed camera photograph of a blasting test when a pressure of 15 MPa was applied in a vertical direction to the side of a PMMA plate (Fig. 7), radial cracks could clearly be seen 50 μs after detonation. Because the tensile stress is generated horizontally in the upper and lower part of the borehole by vertical pressure, we can observe 70 μs after detonation that the crack was growing only in a direction orthogonal to the direction in which the tensile stress acted, that is, in a vertical direction (the direction of the applied pressure). Then 125 μs after detonation, those cracks had expanded into one long crack (marked with arrows). From photographs of the PMMA plates taken after the test blast (Fig. 8), we can observe that in the case when there was pressure applied there was a large single vertical crack, which was very different from when no pressure was applied.

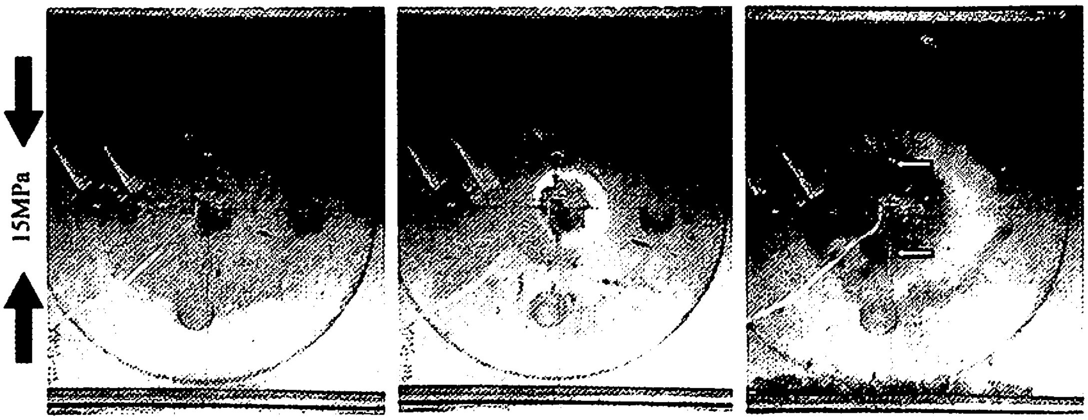
Photographs taken after test blasts on marble plates (Fig. 9) reveal that when pressure was not applied, radial cracks spread mainly in the vicinity of the borehole. However, with a vertical pressure of 5 MPa applied to the marble plate (Fig. 9(b)), we can observe that one long crack was created in the same direction as the applied pressure. This is the same result as obtained with the PMMA plates.

Fig. 10 shows a core with a radius of 100 mm and a length of 300 mm including the vicinity of the



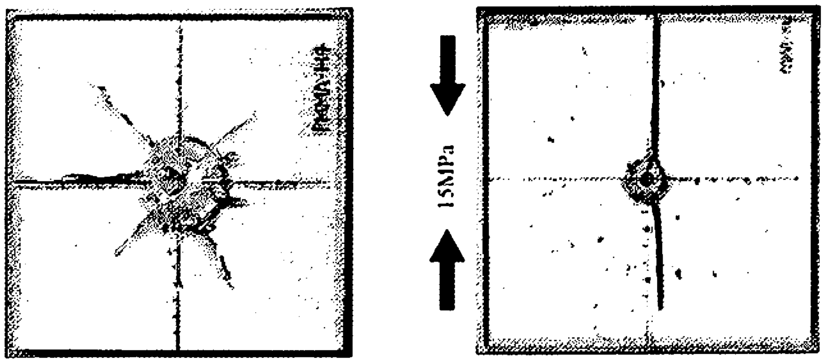
50μs 70μs 125μs

Fig. 6 High-speed camera photographs of fracture process during blasting in a PMMA plate (without pressure on the side of the sample)



50μs 70μs 125μs

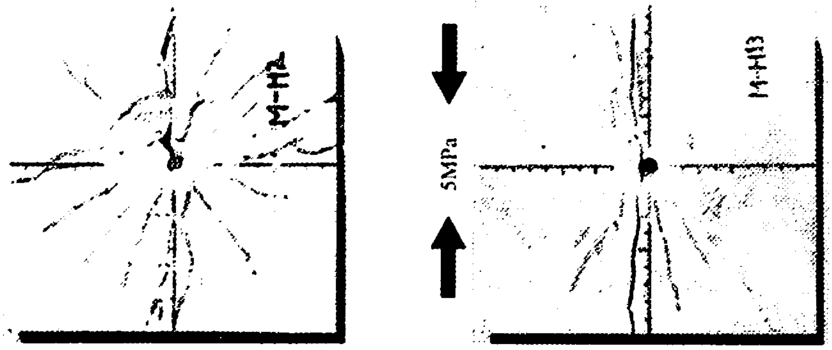
Fig. 7 High-speed camera photographs of fracture process during blasting in a PMMA plate (with pressure of 15MPa)



(a) Without pressure on the side of the sample (b) With pressure of 15MPa

Fig. 8 Photographs of PMMA plates after blasting
Size: 200mm × 200mm × 21mm

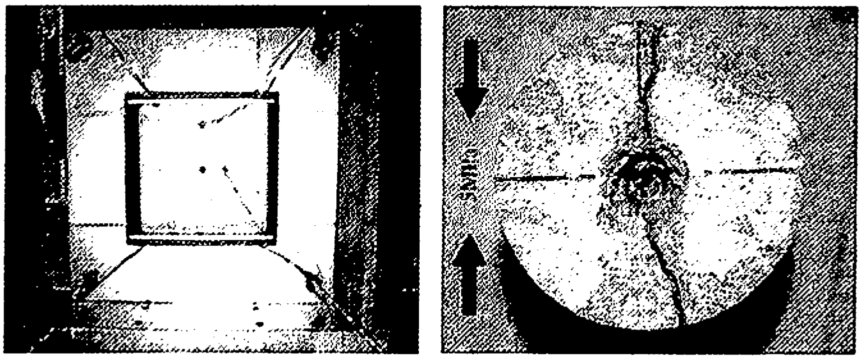
borehole that was taken from the sandstone block after a test blast. We can observe that cracks are generated and extend in the same direction as the applied pressure not only on the free surface but also at the bottom of the borehole. Therefore, we obtain the same results in the blast tests on both



(a) Without pressure on the side of the sample

(b) With pressure of 5MPa

Fig. 9 Photographs of marble plates after blasting
Size: 200 mm × 200 mm × 23 mm



(a) Setup photograph of sandstone block before blasting

(b) Plane photograph

Fig. 10 Photographs of the core near the borehole of a sandstone block before and after blasting (with pressure of 5MPa)
Block size: 300×300×300, Core size: ϕ 100, Length300, Unit: mm

the block and the plate. Furthermore, a vertical pressure of 5 MPa was applied to the sandstone block.

All of the above results confirm experimentally that pressure applied to PMMA plates, marble plates and sandstone blocks affects the generation and development of cracks, and that the cracks appear and progress in the direction in which the pressure is applied.

4. Blast simulation

4. 1 Conditions of analysis and analytical model

We performed a blast simulation using elements that enabled a fracture simulation in ANSYS, a general-purpose finite element analysis program. Our analytical model (Fig. 11) assumes a test blast on marble plates, as described above. A half-scale model was assumed. The figure shows the division of elements in the model; the number of nodes and of elements were 1,322 and 4,724, respectively. We

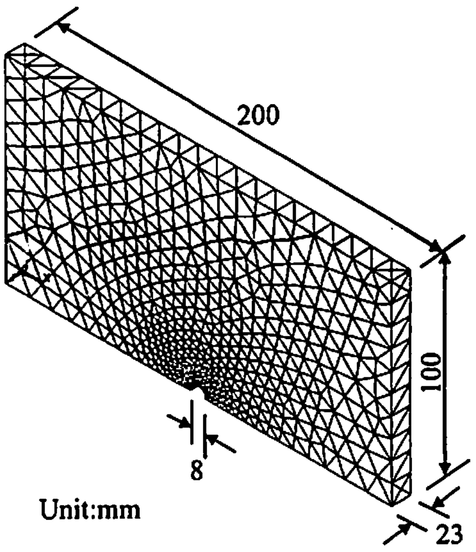


Fig. 11 Finite element mesh of model of marble plate

used dynamic strength for compressive strength and tensile strength which became the judgment standard for crack generation. Table 1 lists the values for various physical properties of the materials.

To find the dynamic strength, we first used results of the blasting test on a PMMA plate to obtain the strain rate ($\dot{\varepsilon}=7.37$ (1/sec)) upon detonation. We then measured the dynamic tensile strength by a method based on Hopkinson's effect. In the case of marble, we were able to obtain a relationship between the dynamic tensile strength S_{dt} and the strain rate ($\dot{\varepsilon}$) that is expressed by

$$S_{dt}=13.86\,\dot{\varepsilon}^{\,0.355} \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate. From this equation, the dynamic tensile strength when the strain rate is 7.37 (1/s) is 28.17 MPa, which is 4.54 times the static tensile strength (6.2 MPa). Because the dynamic compressive strength of the marble was not obtained, a value 4.54 times the static compressive strength of 301.39 MPa was assumed here.

Fig. 12 shows the change of the pressure according to time due to a detonation[20], acting on the inner wall of a borehole. Analysis shows that the results of both the explosion experiment using the PMMA plate and the simulation correspond to the following equation:

$$P=P_o\left(e^{-16000t}-e^{-300000t}\right) \tag{2}$$

where t represents time (μs) and P_o is 1,042 MPa.

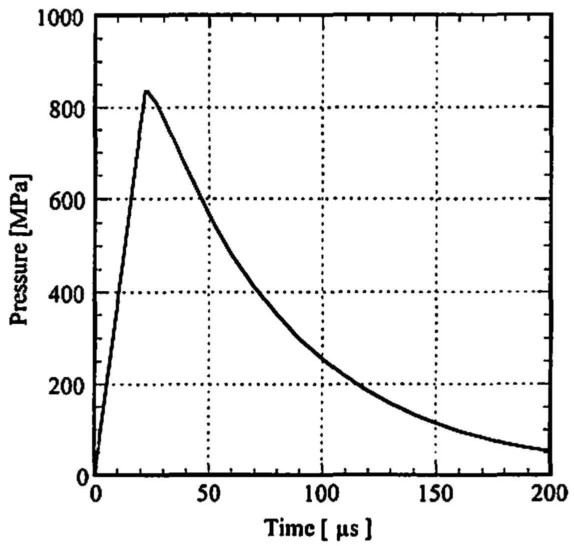
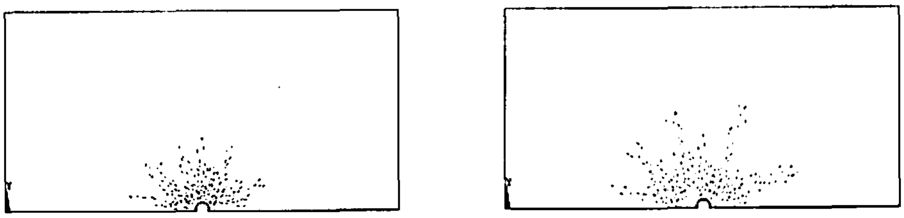


Fig. 12 The pressure formation due to blasting in a borehole

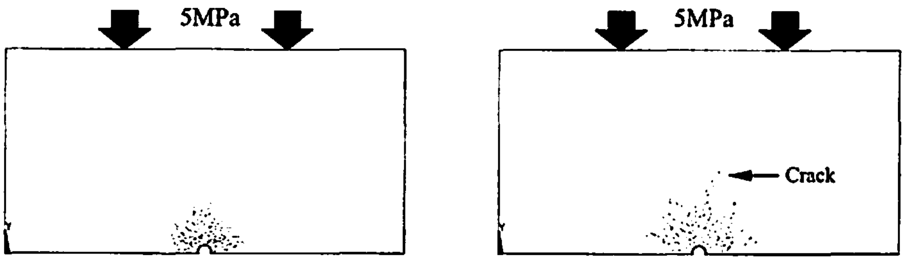
4. 2 Results and discussion

Figs. 13 and 14 show the simulation results for the generation and development of cracks with no pressure applied and with a vertical pressure of 5



(a) 10μs (b) 25μs

Fig. 13 Simulation result for the generation and development of cracks (without pressure on the side of the model)



(a) 10μs (b) 25μs

Fig. 14 Simulation result for the generation and development of cracks (with pressure of 5MPa)

MPa applied, respectively. In the case of no pressure, we observe that radial cracks were generated around the blast hole, and that 25 μs after the detonation, the cracks continued to progress radially.

When a vertical pressure of 5 MPa was applied, radial cracks were initially generated around the blast hole in the same way as when no pressure was applied. And 25 μs after detonation, they became one long crack in the vertical direction.

5. Conclusions

We performed a stress analysis in the area around a smooth blasting borehole on the expected fracture line of a tunnel in order to clarify the effect of rock pressure on crack generation during tunnel blasting. We also carried out test blasts on PMMA plates, marble plates and sandstone blocks which were assumed as a borehole on the expected fracture line in the tunnel under initial rock pressure. In addition, we made a numerical simulation of a blast and compared with the results of the test blasts. We obtained the following information.

(1) The tensile stress was generated around the borehole by the effect of initial rock pressure. Moreover, around the borehole in the side wall and in the shoulder part of the tunnel, i.e. the intermediate point between the roof and the side wall, tensile stress was always generated vertically with respect to the expected fracture line. However, around the borehole in the roof of the tunnel, the position where the tensile stress was generated varied depending on the state of the rock pressure.

(2) The results of the test blasts using plates and blocks clearly indicated that cracks were generated and spread in the same direction as the applied pressure, and that the initial stress in the area around the borehole had the effect of creating and lengthening cracks.

(3) The results of blast simulation showed a good agreement with the experimental results.

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トンネル発破時のき裂生成に及ぼす地圧の影響

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トンネル発破時のき裂生成に及ぼす地圧の影響を明らかにすることを目的として，トンネルの破断予定線上に設けたスムースブラスティング用装薬孔周辺において応力解析を行った。また，初期地圧を受けているトンネルの破断予定線上の装薬孔を想定し，PMMA板，大理石の板および砂岩のブロックを用いた発破実験を行った。さらに，き裂を考慮した発破シミュレーションを行い，実験結果との比較を行った。その結果，初期地圧の影響によって装薬孔周辺には，引張応力が発生することが分かった。また，トンネルの側壁および天盤との中間点である肩部における装薬孔の周辺には，常に破断予定線と垂直に引張応力が生じているが，天盤における装薬孔の周辺には，地圧状態によって引張応力の発生位置が異なることが分かった。また，板およびブロックを用いた模擬実験を行った結果，圧力の影響を受け，加圧方向と同じ方向にき裂が生成および進展し，装薬孔周辺の初期応力状態が発破によるき裂の生成および進展に影響を及ぼすことが明らかとなった。さらに，発破シミュレーションを行った結果，実験結果と非常に良く一致し，正確な発破シミュレーションが可能であることが明らかとなった。

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