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GROUTING IN CONSIDERATION OF PREDOMINANT DIRECTION OF JOINTS IN ROCK MASSES

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ABSTRACT

We conducted a grouting test in rock mass having steep joints with predominant direction, assuming blanket grouting for embankment dams. Vertical holes and inclined holes designed in consideration of the predominant direction of the joints were used as grouting holes, and the hole spacing was determined such that the number of grouting holes per unit area on a joint was the same for both cases. As a result, both tests saw a similar improvement despite the fact that the test using inclined holes had wider hole spacing than the test using vertical holes on the ground surface. We can also reduce the total drilling length of grouting holes if we use inclined holes instead of vertical holes, the hole spacing of which is determined in this manner, and thus we have demonstrated the usefulness of grouting that considers the predominant direction of joints in rock mass.

KEYWORDS

Dam, Foundation Treatment, Blanket Grouting, Jointed Rock Mass, Inclined Hole

INTRODUCTION

Grouting is the most common foundation treatment method performed with the main aim of improving the watertightness of dam foundations.

Grouting can have different effects depending upon the properties of rock mass. In general, grouting tends to easily develop leakage and other problems in soft rock or rock mass having wide joints. In order to perform grouting work efficiently at a site like this, it is necessary to establish work specifications that consider the geological properties of the dam foundation. Particularly in the case of jointed rock mass, it is important to investigate the width and direction of the wide joint that serves as the predominant hydraulic routing in the rock mass.

As regards grouting designed for soft rock, injection methods and grout materials have been developed and improved, sucj as grouting with sleeve tubes and ultrafine cement (Weaver, 1991), and they have been used in many actual cases. We are currently working on the development and research of new methods such as the fracture direction controlled (FDC) grouting method (Fujisawa *et al.*, 1996) and cement powder grouting method (Matsumoto *et al.*, 1996).

In the case of grouting for jointed rock mass, on the other hand, we should determine the drilling direction in consideration of the directional distribution of joints so that grouting holes encounter as many joints as possible, unless the rock mass has a cavity that requires great care in properly plugging the grout materials, or a joint is very wide or ground water in the joint has an extremely high flow rate, and thus injected grout materials are carried away before they harden (Ewert, 1985, Houlsby, 1990). However, there have been few reports that specifically show the different injection effects in jointed rock mass when the drilling direction for grouting holes is changed, based on the results obtained from trial or actual execution.

Therefore, this paper describes the results of a grouting test conducted in lapilli tuff having a steep wide joint with a dip of about 70° in order to investigate the distribution of joints and determine the drilling direction of grouting holes in consideration of the directional distribution of joints. The grouting test was conducted using vertical and inclined holes to analyze changes of permeability and the cement take in the number of sequences. This paper also reviews the drilling direction in which grouting holes are placed effectively on jointed rock mass based on the results of the test.

GEOLOGICAL FEATURES OF TEST SITE

The geological features around the test site are outlined in Fig. 1. Lapilli tuff produced in the Miocene of Neogene period is distributed in the grouting area. Its hardness is such that it can be cracked if hit hard by a hammer. Observations of the drilling core, opencut surface of outcrop and exploratory adit, and drilling hole wall using a borehole TV showed that the joint set distributed in this rock mass has a direction mainly with the strike of N10 ° W and the dip of 70 ° SW (see Fig. 2), and has wide joints with an opening of about 1-4 mm, many of which contain iron oxide and clay. The permeability of the area around the test site is rather high, and is more than 10 Lu in many places.

TESTING METHOD

The grouting test described in this paper was conducted in order to obtain data on the improved properties of rock mass so that blanket grouting can be performed effectively. Blanket grouting is conducted for preventing impervious materials from being carried away and avoiding seepage failure in the rock mass by improving of the imperviousness of the surface of the rock mass that will become the foundation for an embankment dam. The specifications of the grouting test using vertical and inclined holes will be explained in the following paragraphs. Figure 3 shows the plan and section of the grouting test site, and illustrates the relation between the drilling direction of grouting holes and the predominant direction of joints.

Grouting Test Using Vertical Holes

Placement of Holes. Grouting holes were placed according to the split-spacing method as shown in Fig. 4. The primary hole spacing (L in Fig. 4) was set to 6 m, the vertical drilling direction was selected, and the drilling length was set to 40 m (upper 20 m for overburden and lower 20 m for grouting section).

Injection Method. "Down-stage grouting" was adopted as the injection method in which drilling and grouting are repeated for each stage from the top downwards. The stage length was set to 5 m, and the grouting section was divided into stage 1, 2, 3 and 4 from the top.

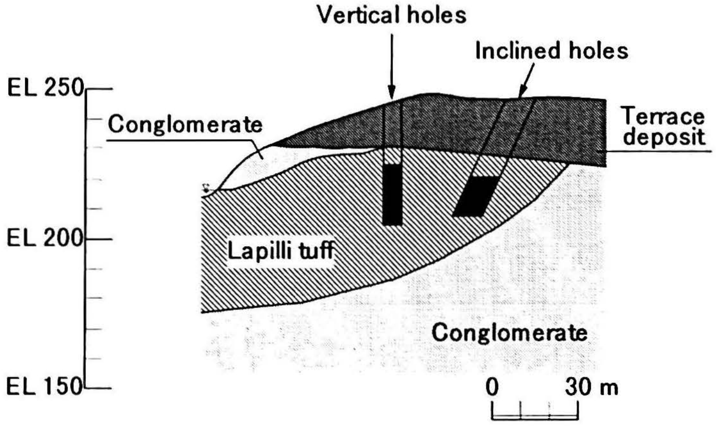

Fig. 1 Geological features of the test site

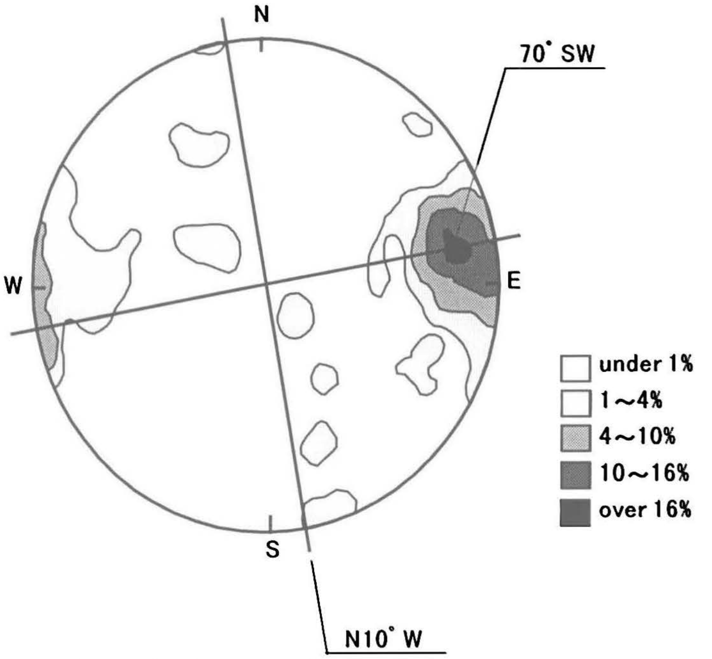

Fig. 2 Directional distribution of joints

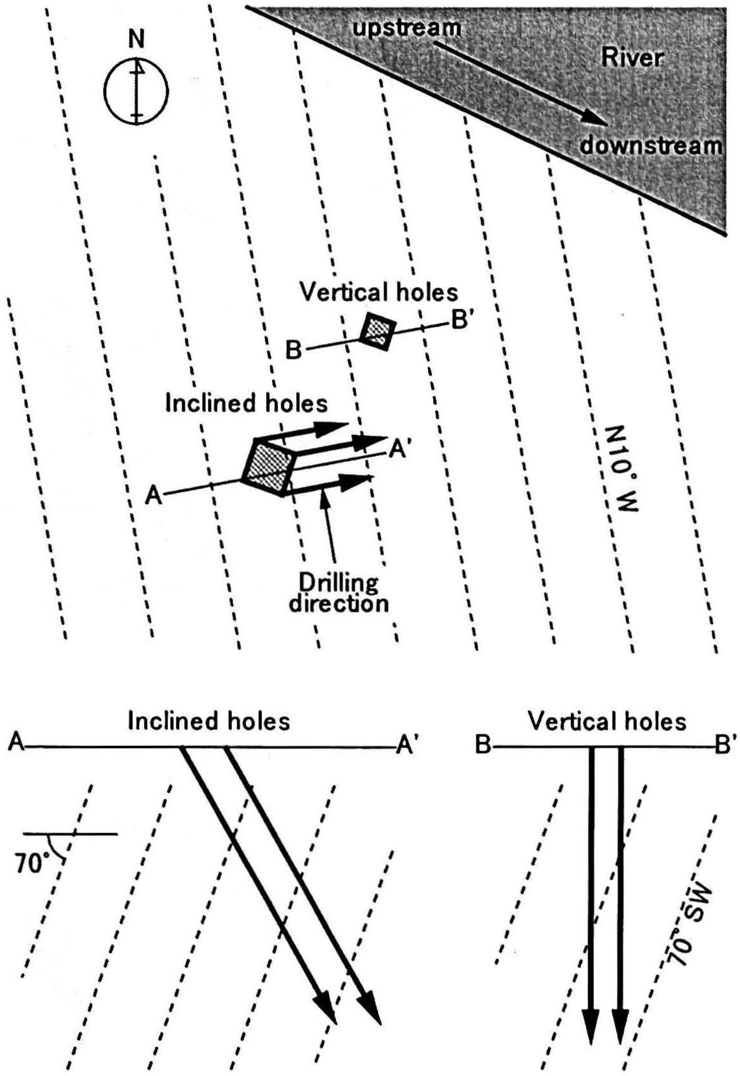

Fig. 4 Plan and section of the test site
(Dotted lines indicate the predominant direction of joints.)

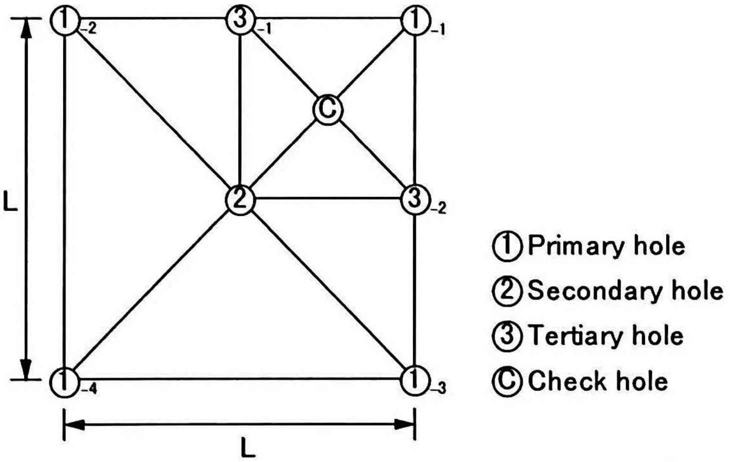

Fig. 4 Placement of holes

Drilling Method. Rotary drilling was selected in consideration of the long drilling length and the need to recover cores.

Lugeon Water Test. This was conducted in accordance with Technical Guides for Lugeon Water Test, River Bureau, Ministry of Construction, Japanese Government (1984).

Grout Materials. In consideration of permeability, durability, economic efficiency, safety and previous execution records, cement suspension that was a mixture of normal Portland cement and water was used. For proportioning, we started to inject cement suspension with a high water/cement ratio by weight (W/C) which has higher permeation ability, and shifted to cement suspension with a lower W/C in phases, and therefore changed W/C in the order of 8-6-4-2-1-0.75. However, in stages where the permeability was quite high or leakage occurred, we omitted the injection of cement suspension with a high W/C.

Injection Pressure and Injection Rate. The force that is applied to the rock mass by grouting increases as the injection pressure and injection rate increase. For this reason, efforts were made to increase the effect of grouting while care was taken not to cause harmful deformation or destructive damage to the rock mass when these specifications were determined.

The injection pressure for primary holes was determined first, based on Pcr + 98 (kPa) or 49d (kPa), whichever pressure was the smaller: where Pcr (kPa) is critical pressure evaluated by the Lugeon water test and d (m) is the upper-end depth of the stage. The injection pressure for the secondary and subsequent holes was set to 294 kPa for stage 1, 490 kPa for stage 2, and 686 kPa for stages 3 and 4, based on the injection pressure for primary holes.

The injection rate was set to 20ℓ/min/st based on cases where grouting was performed on similar rock mass. This injection rate was reduced to half when the lifting of rock mass reached 0.1 mm.

Completion Criteria. Grouting was stopped when the injection rate dropped to less than 1ℓ/min/st under the specified injection pressure, and this state continued for 20 minutes. The grout curing time required before working on the next stage was set to 12 hours or more. When grouting was not expected to complete even after the specified grout take (1,000ℓ) with the lowest W/C (0.75) injected, or there was a large amount of leakage, or the lifting of rock mass reached 0.2 mm, grouting was suspended temporarily, time for curing was allowed, and then grouting was restarted.

Grouting Test Using Inclined Holes

The drilling direction of grouting holes was changed from the vertical direction to inclined direction to increase the number of joints per unit length of grouting hole (joint density) in order to improve the efficiency of grouting. The joint density would be largest if the drilling direction was determined so that the predominant direction of the joint (strike of N10°W, dip of 70°SW) crosses the grouting holes at right angles, i.e. the angle formed by the horizontal plane in the vertical plane of strike of N80°E becomes 20°. However, since the improved depth is fixed, the drilling length of each hole increases as the inclination is made gentler, and so grouting hole walls collapse

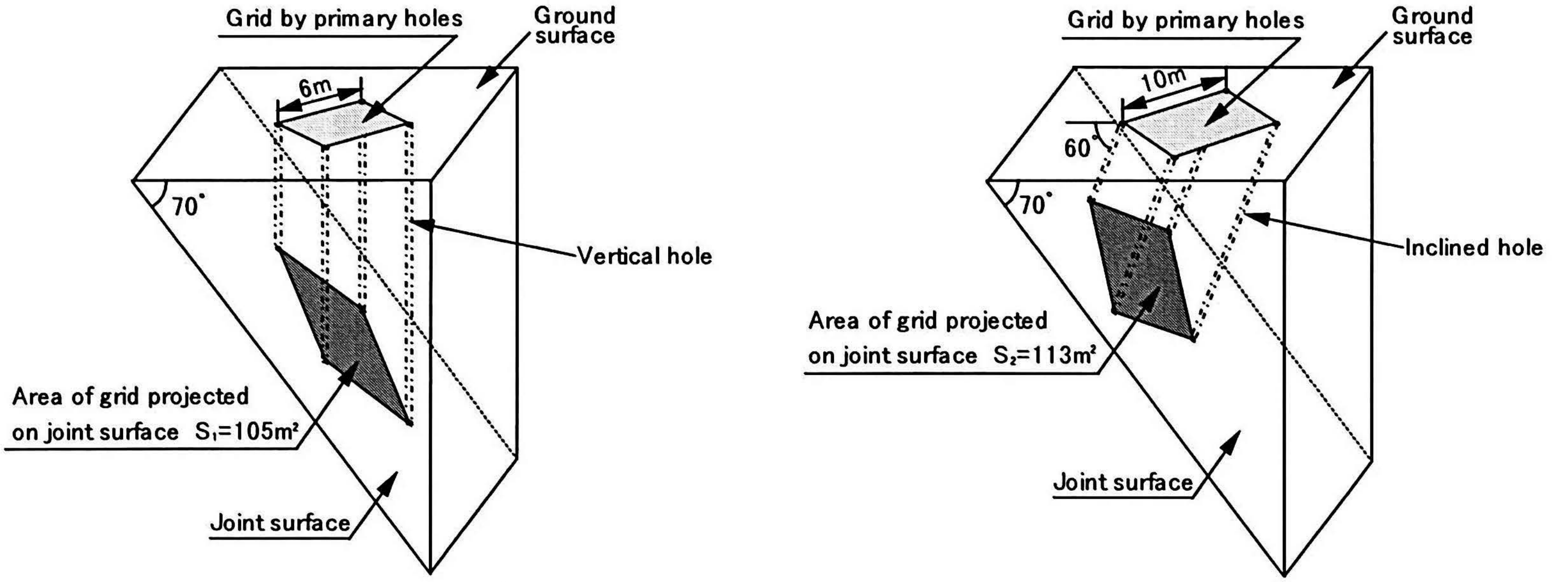

Fig. 5 Area of grid projected on a joint surface

easily. Considering these factors, the drilling direction of grouting holes was set so that the dip is 60° in the vertical plane of strike of N80° E.

With the use of inclined holes, primary hole spacing was increased from 6 m to 10 m. This spacing was determined so that the number of grouting holes per unit area on the plane that runs parallel to the predominant direction of the joint is almost the same as when vertical holes are used, i.e. the areas of grids projected on the joint surface in Fig. 5, S_1 and S_2 are almost the same. If this rule is followed, the relationship between the dip of grouting holes and primary hole spacing is as shown in Fig. 6.

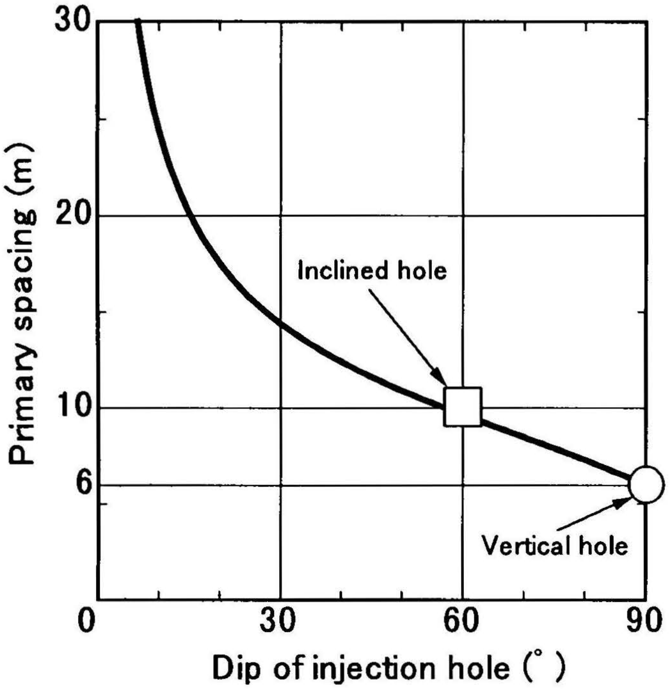

Fig. 6 Relationship between dip of injection hole and primary spacing

The drilling length of grouting holes was set to about 42 m (upper 27 m for overburden and lower 15 m for grouting section). The length of each stage was set to 5 m, and the grouting section was divided into stages 1, 2, and 3 from the top.

For other testing specifications, see Table 1.

TEST RESULTS

Figures 7 and 8 respectively show changes of probability of excess in the number of sequences of Lugeon value and cement take. Bar graphs showing their respective average value (value when probability of excess is 50%) are given in Figs. 9 and 10.

As far as primary holes are concerned, the permeability of the test site for inclined holes is statistically slightly higher than that for vertical holes. The greater joint density for inclined holes is one of the reasons for this. The tendency of permeability to decrease due to the grouting sequence was almost the same. As regards the cement take, no significant difference was noted for primary holes, but later, the test using inclined holes showed a more marked tendency to decrease as

Table 1 Specifications of grouting tests

<table>
<tr><th>Test cases</th><th>Vertical holes</th><th>Inclined holes</th></tr>
<tr><td>Method of grouting</td><td>Downstage grouting (5 m×4 stages)</td><td>Downstage grouting (5 m×3 stages)</td></tr>
<tr><td>Primary spacing on ground surface</td><td>6 m</td><td>10 m</td></tr>
<tr><td>Grout materials</td><td colspan="2">Normal Portland cement and water</td></tr>
<tr><td>Maximum injection pressure Pmax (kPa)</td><td>Primary hole: Pcr+98 or 49d
where Pcr (kPa) is critical pressure, and d (m) is upper-end depth of stage

After secondary hole,
<table>
<tr><th>Stage</th><th>1st</th><th>2nd</th><th>3rd</th><th>4th</th></tr>
<tr><td>Pmax</td><td>294</td><td>490</td><td>686</td><td>686</td></tr>
</table></td><td><table>
<tr><th>Stage</th><th>1st</th><th>2nd</th><th>3rd</th></tr>
<tr><td>Pmax</td><td>294</td><td>490</td><td>686</td></tr>
</table></td></tr>
<tr><td>Maximum injection rate</td><td>20 ℓ /min/st (4 ℓ /min/m)
10 ℓ /min/st when lifting of foundation reaches 0.1 mm</td><td>20 ℓ /min/st (4 ℓ /min/m)</td></tr>
<tr><td>Proportion changing standard</td><td><table>
<tr><th>W/C by weight</th><th>8</th><th>6</th><th>4</th><th>2</th><th>1</th><th>0.75</th></tr>
<tr><td>Grout take (ℓ)</td><td>400</td><td>400</td><td>400</td><td>400</td><td>1000</td><td>1000</td></tr>
<tr><td>Injection time (min)</td><td>40</td><td>40</td><td>40</td><td>40</td><td>40</td><td>40+ α</td></tr>
</table>Changed to the thicker one when grout take or injection time reaches the tabulated value.</td><td><table>
<tr><th rowspan="2">Lugeon value</th><th colspan="5">W/C by weight</th></tr>
<tr><th>8</th><th>6</th><th>4</th><th>2</th><th>1</th></tr>
<tr><td>Lu<10</td><td>400</td><td>400</td><td>400</td><td>400</td><td>600</td></tr>
<tr><td>10≦Lu<20</td><td>-</td><td>400</td><td>400</td><td>400</td><td>1000</td></tr>
<tr><td>20≦Lu</td><td>-</td><td>-</td><td>400</td><td>400</td><td>1400</td></tr>
</table>(ℓ)
Initial proportion is decided according to the permeability.</td></tr>
<tr><td>Completion criteria</td><td>Grout take with the rate of less than 1 ℓ /min/st continues for 20 minutes under maximum injection pressure.</td><td>Grout take with the rate of less than 1 ℓ /min/st continues for 30 minutes under maximum injection pressure.</td></tr>
<tr><td>Curing time</td><td>Over 12 hours</td><td>Over 6 hours</td></tr>
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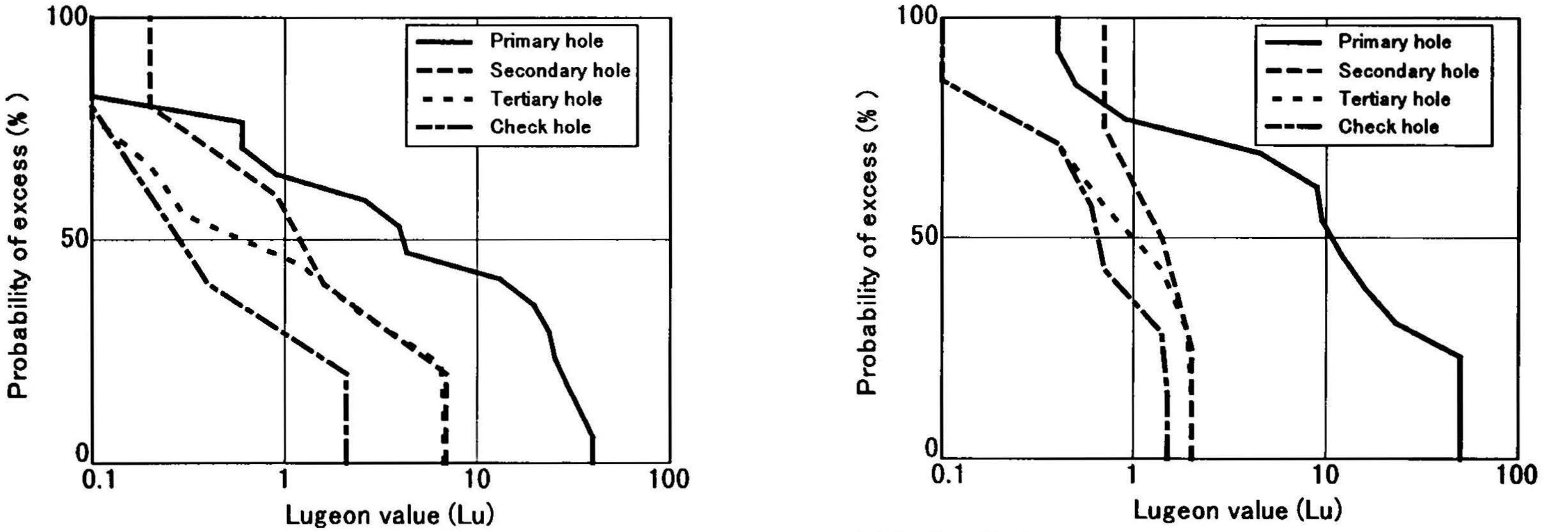
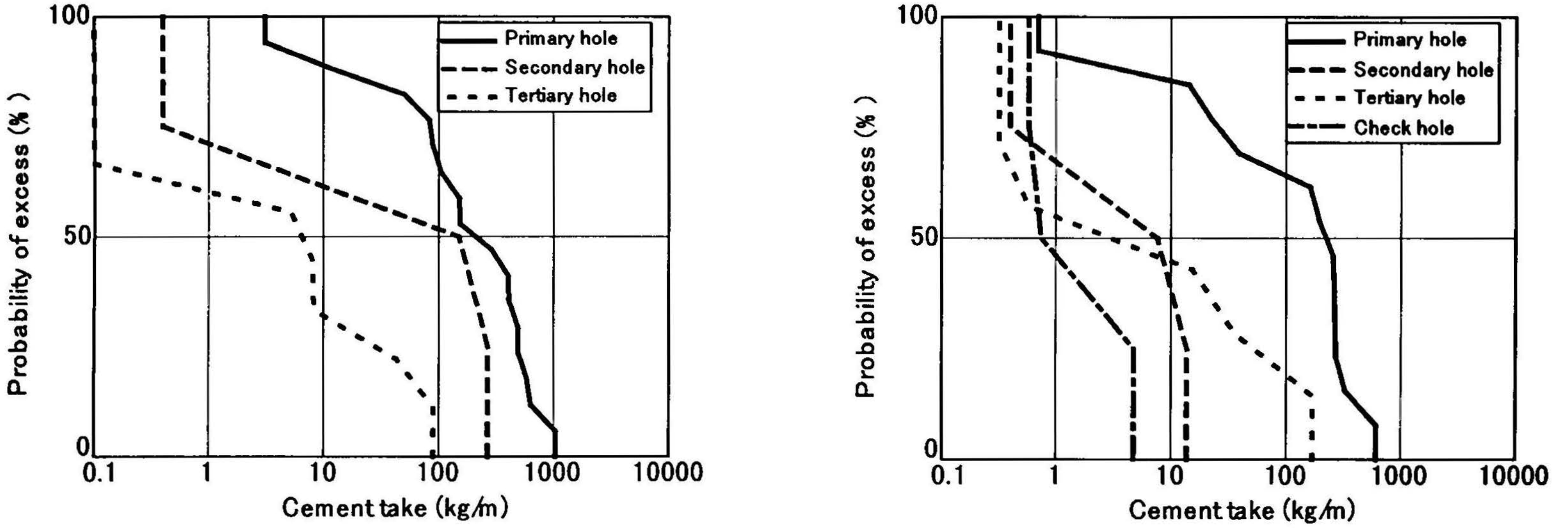


(a) Vertical holes

(b) Inclined holes

Fig. 7 Lugeon value



(a) Vertical holes

(b) Inclined holes

Fig. 8 Cement take

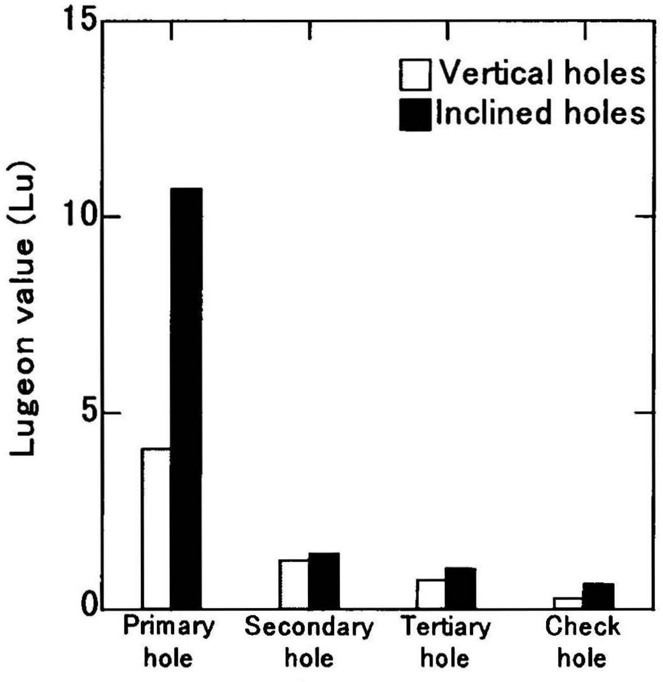


Fig. 9 Average Lugeon value

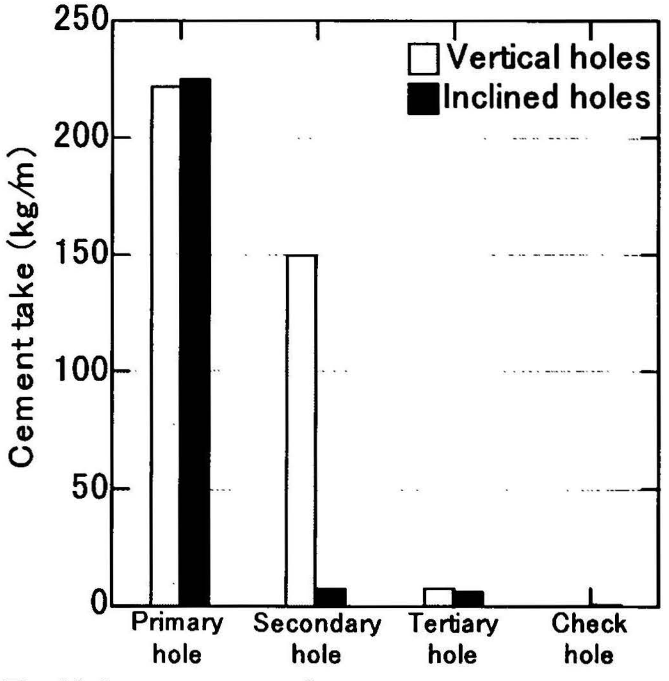


Fig. 10 Average cement take

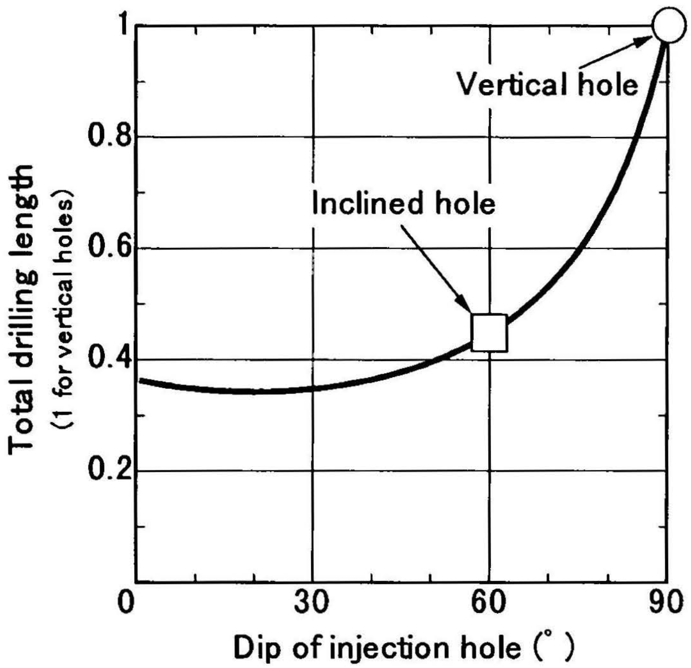


Fig. 11 Relationship between dip of injection hole and total drilling length

compared with the test using vertical holes. From these results, the test using inclined holes gave effective injection equivalent to or better than the test using vertical holes because the joint density of grouting holes increased, despite the fact that the primary hole spacing was increased from 6 m to 10 m.

The total length of grouting holes can be reduced if inclined holes with primary hole spacing of 10 m are used instead of vertical holes with primary hole spacing of 6 m. Figure 11 shows the relation between the dip of grouting holes and the total drilling length assuming that hole spacing is determined in the same manner as this test, and that the execution area, execution depth and the number of sequences for execution on the ground are the same. This figure indicates that the total drilling length can be reduced substantially just by inclining grouting holes for the rock mass in which the test was conducted. However, in actual blanket grouting, since the grouting area should be the one where the execution area on the ground is projected in the vertical direction in the rock mass, the execution area on the ground naturally increases as the dip of grouting holes decreases. Therefore, we cannot say unconditionally that the total drilling length of grouting holes can be reduced if inclined holes are used in the actual design, but we believe that for rock mass having properties similar to those of the rock mass we used in this test, it is worth conducting a grouting test using inclined holes and studying the efficiency of the method.

CONCLUSION

In this case study, we learned that grouting using inclined holes designed in consideration of the predominant direction of steep joints brought about an improvement equivalent to or better than grouting using vertical holes, despite the wider hole spacing, and thus the use of inclined holes results in efficient grouting.

As far as the lapilli tuff in which we conducted this test is concerned, the rock itself is practically non-permeable, and wide joints are thought to control the permeability of the rock mass. For this reason, watertightness can be easily improved by grouting as compared with soft rock, and injection is sufficiently effective even for grouting using vertical holes. In this test, however, the thick deposit on the foundation rock mass served as covering rock, controlled increases in critical pressure, decreases in leakage and lifting of rock mass and thus worked in favor of grouting. Actual grouting will be performed after such deposit is removed, and therefore there is a concern of a decrease in injection effects. The injection effects of grouting using inclined holes are thought to decline due to the removal of covering rock, but we consider that the smaller number of grouting holes will compensate for this decline in injection effects. In actual designing, however, we must carefully consider the possibility as a result of using inclined holes that 1) drilling cost per unit drilling length will increase, 2) the foundation treatment zone will expand horizontally, 3) structures such as the inspection gallery may turn out to be an obstacle to drilling, and 4) if the gradient of the slope and the dip of grouting holes are about similar to each other, the overburden will be thin, and harmful lifting or destructive damage to the foundation or leakage may frequently occur.

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