MODES OF GROUT TREATMENT ON GEOLOGICALLY INCOMPETENT ZONES, HSUEHSHAN TUNNEL

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ABSTRACT

The Hsuehshan Tunnel with a length of 12.9 km is the longest tunnel in the tunnel groups of the Taipei-Ilan Expressway. The Tunnel is situated within the Hsuehshan Range, and passes through formations of slightly metamorphosed sedimentary rocks. These rock formations were subjected to the collision of the Philippine Sea plate and the Eurasian plate, and formed many folds and were cut by faults that trended in northeast or northeast by east directions. As a result, geological conditions along the tunnel alignment are rather complicated. Also, there was a vast amount of groundwater along the tunnel route. Tunnel excavation frequently encountered influxes of large quantities of groundwater from the excavation face, and numerous collapses of excavation faces occurred causing serious mishaps. To curtail these incidents of groundwater influx, complete treatment through grouting to improve rock mass quality at these locations of geological incompetence was a prerequisite.

The paper takes the groundwater influx at Sta. 39K+074 in the Pilot Tunnel of the Hsuehshan Tunnel as an example, and explains the geologic characteristics of the incompetent zones and their treatment modes through grouting. Generally, large quantities of highly pressurized groundwater are intimately related to geologic discontinuous structures, such as faults and shear zones, and they are commonly recharged by ground surface sources. Treatment principles mostly take into consideration the lowering of the hydraulic pressure of the groundwater through draining. The watertightness of the rock mass is then enhanced by grouting that consolidates the rock mass, thus reinforcing the stability of the excavation face, and allowing safe excavation penetration. During grout treatment, care should be especially exercised in grout check feedbacks, and also flexible work operations should be practiced to cope with the highly variable geologic conditions, thus achieving good ground improvement.

Keywords: folds, faults, groundwater influx, modes of grouting treatment

INTRODUCTION

Taiwan is located on the suture line of the plate convergence between the Eurasian Plate and the Philippine Sea Plate; hence the island is covered with high mountains and precipitous valleys but very few plains. Due to compression and orogenic processes from these two tectonic plates, the resultant structural geologic conditions of the entire island are very complicated and highly variable. The topography of the central portion of the Island is a rapid uplift in a southeast-northwest direction, dividing the Island of Taiwan into an Eastern half and a Western half. The Western half of Taiwan is situated on the Eurasian Plate, thus the topographic expression is smoother. Most of the population of Taiwan and related economic activities are concentrated in the Western Plains, and in contrast, most of Eastern Taiwan is still lagging behind in terms of economic development due to this topographic barrier. In order to attain a well-balanced economic development for both the Eastern and Western halves of Taiwan, it becomes

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mandatory that fundamental infrastructures should pass through these high mountains. Because of this, tunnel engineering in Taiwan has enjoyed a healthy, rapid advancement in development in recent years. Establishing a communication and transportation thoroughfare between Eastern and Western Taiwan, and bringing better transportation to Eastern Taiwan, thus facilitating better, easier linking of Eastern Taiwan with metropolitan Taipei has been an important goal in most of these tunnel construction activities.

Besides the many folds and reverse faults that resulted from compressive plate-convergent tectonism and orogenic processes that highly complicated the structural geologic conditions of Northeastern Taiwan, the later spreading of the Ryu Kyu Arc overprinted extensional stresses on the original structural lineaments, thus further complicating the structural geological conditions, and making tunnel construction more difficult. At present, mountain tunnel construction projects are confronted by two major challenges in engineering geologic aspects: the very complicated and highly variable geologic conditions, and the tremendous groundwater influx into these tunnels. Among these, groundwater influx treatment proved to be the more difficult. For example, the extreme groundwater influx encountered in the Hsuehshan Tunnel of the Taipei-Ilan Expressway reached 750 l/s, and a groundwater influx of 1000 l/s was encountered in the Yungchun Tunnel in the Eastern Railway Improvement Project. The excavation faces collapsed due to these tremendous quantities of groundwater influx. This paper presents different aspects of the treatment of the rock mass at Sta. 39K+074 in the Pilot Tunnel of the Hsuehshan Tunnel as an example for explaining the geologic characteristics of rock mass with high water seepage and the principles of treatment for this type of ground. It is hoped that this paper will shed some light on the topic of groundwater influx in tunnels, and also serve as a reference in the consideration and planning of groundwater influx treatment.

GENERAL OUTLINE OF ENGINEERING PROJECT

The Engineering Project

The Hsuehshan Tunnel is 12.9 km in length, and is the longest tunnel in the National Expressway System. The entire tunnel system consists of two main tunnels and a pilot tunnel. The main tunnels are 10.8 m in diameter; the pilot tunnel is 4.8 m in diameter. This tunnel passes through the Hsuehshan Range. The maximum cap rock thickness is in excess of 700 m. Geologic settings along the tunnel alignment are highly complicated. The results of the surface geologic investigation and the data from the limited number of geologic boreholes were not adequate in affording an explicit understanding of this geologic complexity. Because of this, a pilot tunnel was excavated prior to construction of the main tunnels. The purpose of the pilot tunnel was to serve as exploration tunnel that would provide true information on geologic conditions along the tunnel alignment. It would also provide service access to spots where adverse geological conditions might call for emergency treatment of the rock mass. The pilot tunnel would also act as a drain to lower the groundwater. All of this would serve to assist in the construction of the main tunnels. When the construction was concluded, the pilot tunnel would serve as a service tunnel for regular maintenance works or for gaining emergency access to the main tunnels in case of fire.

Outline of Geologic Conditions

The Hsuehshan Tunnel is located in the Hsuehshan Range. The rock formations there have been subjected to plate collision effects, and were folded and truncated by many faults that trend in a northeast or northeast by east direction. Hence, geologic conditions along the tunnel alignment are highly complicated. Rock formations at the West Portal are younger Miocene Strata and transition to older Eocene Strata at the East Portal. In descending order from young to old, these rock formations are: the Fangchiao Formation, the Makang Formation, the Tatungshan Formation, the Tsuku Sandstone Formation, the Kankou Formation and the Szeleng Sandstone Formation. The tunnel alignment passes the Yingtzulai Syncline, the Taotiaotzu Syncline, the Shihtsao Fault, the Shihpai Fault, the Paling Fault, the Shanghsin Fault and the Chinying Fault. Figure 1 presents an outline of the geology along the tunnel alignment. The site of the present case study is the East Portal section of the Hsuehshan Tunnel, between the Shanghsin Fault and the Paling Fault. The rock formation at the site, the Eocene Szeleng Sandstone of Tertiary age, is a comparatively old rock formation in Taiwan. The rock strata in the Szeleng Sandstone is mainly comprised of gray to white, fine to medium-grained slightly metamorphosed quartz sandstone and argillite with intercalated dark gray beds and coaly shale seams. The quartz sandstone occurs in beds with intercalated argillite or coaly shale several

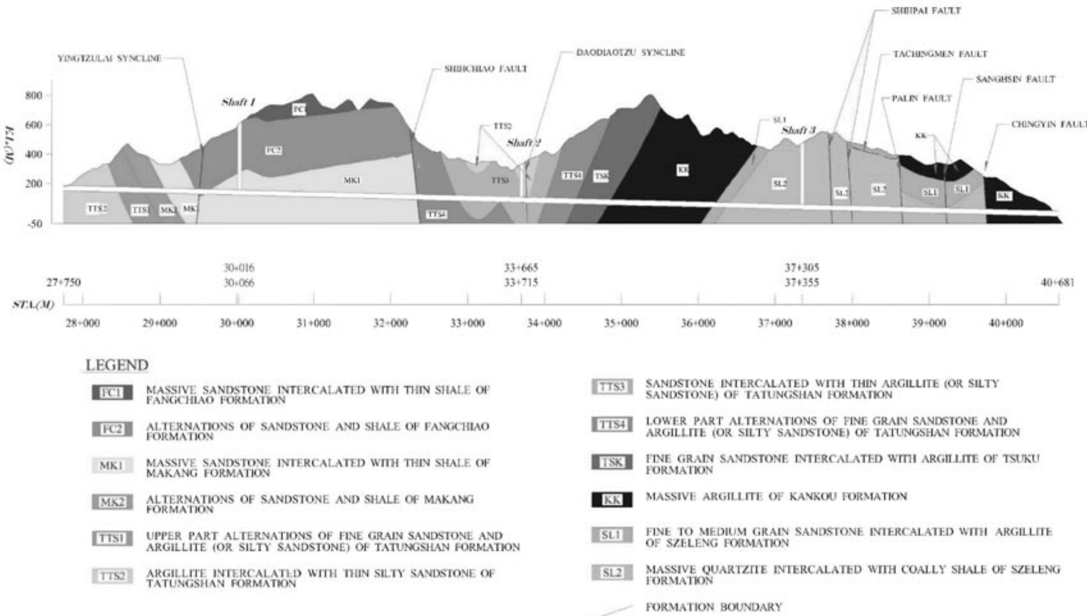

Figure 1. Geologic Profile along the Hsuehshan Tunnel

centimeters to several tens of centimeters thick. These intercalated beds are more plastic in their behavior. The quartz sandstone is mainly comprised of coarse to fine-grained quartz sand with minor amounts of feldspar. The rock is well cemented, and hard but brittle. Parts of these sandstone beds may contain as much as 90% quartz. This is very abrasive to cutter bits during borehole drilling. The Szeleng Sandstone in this section is hard and brittle. Also, five of the six faults traversed by the Hsuehshan Tunnel are clustered within the first 3 km section at the East Portal of the Hsuehshan Tunnel, forming a group of normal faults. In addition, the area is situated on the Northeast portion of the Hsuehshan Range, this location, in tectonics, is the intersection point of the plate collision and back-arc spreading, where numerous strike slip faults occur. The structural mode there is far more complicated than normal fault groups. Due to the frequent occurrence of faults, the rock formations in the East Portal section of the Hsuehshan Tunnel are intensely fractured. The quality of the rock mass there is mostly poor to very poor.

Excavation of the Pilot Tunnel revealed that as result of the compressive action from the orogenic processes and faulting, besides the group of normal faults, there also occurred numerous sizeable shear zones with clay seams in the Szeleng Sandstone within the area. Joints are well developed in these shear zones. These joints are densely clustered and may show three or four sets of joint planes. The spacing of the joints is from 5 to 10 cm, with some as closely spaced as 3 to 5 cm. The openings of these joints range from one to several mm. Joints in rock formations in the area are in essence systematic. There are three major sets of joints, and they all incline in high angles. The attitudes of these joint sets are: J1: north-south striking (including NNE to NNW); J2: northeast by east; and J3: northwest by west. All three sets of joints possess load relief fractures, and the joint planes are mostly clay coated. In all, joints are well developed in rocks of the Szeleng Sandstone Formation. These joints occur frequently and are densely clustered, rendering the rock mass quality rather poor, and hence the rock mass possesses strong water storing capacity, and yet the rock is highly permeable. Groundwater is often hidden behind fault planes or stored in intercalated beds sealed off by clay seams. These groundwater bodies erupted into the tunnel as sudden, pressurized surges, and presented great difficulty in tunnel excavation and construction. The shear zones that occur at Sta. 39K+079, Sta. 38K+998 and Sta. 38K+934 all possess water stopping properties. These shear zones showed aggravated geological conditions worse than those of the other shear zones, rendering more difficulty in construction control. Figure 2 below presents the plan map of the shear zone at Sta. 39K+079. This particular shear zone caused the bogging down of the TBM in the main tunnel, as well as causing considerable difficulty

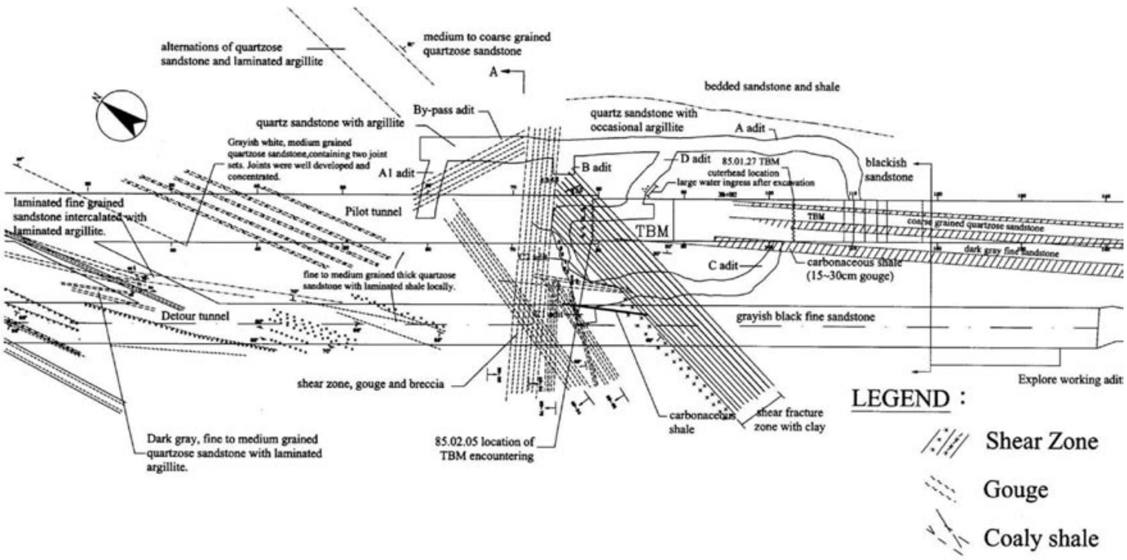

Figure 2. Plan View of the Geological Conditions around the 10th Stoppage of Pilot Tunnel TBM

in the drill and blast construction. This happened when the drill and blast excavation circumvented, through bypass adit, to the corresponding position in the main tunnel. Grout treatment had to be performed before the groundwater influx was effectively stopped.

The site for this present case study is midway between the Paling Fault and the Shanghsin Fault. The geologic conditions of these two faults, based on available geological information from the present construction stage and from the geological investigation stage, are presented briefly below.

Paling Fault: This fault is a normal fault located within the rocks of the Szeleng Sandstone Formation. The fault plane inclines to the east. Rock exposures on the surface of the ground indicated that the southeast side is the hanging wall, comprised of argillite of the Kankou Formation; the northwest side is the footwall, comprised of quartzose sandstone of the Szeleng Sandstone Formation. This fault intersects the tunnel alignment at Sta. 38K+680 in the Pilot Tunnel. Where this fault intersects the tunnel, the ground surface topographic expression is a depression, indicating that rocks in the footwall are fractured and weathered. The estimated width is 50 m.

The Shanghsin Fault: This fault is also a normal fault located within the rocks of the Szeleng Sandstone Formation. The fault strikes northeast, and inclines at a high angle towards the east. The Pilot Tunnel and the main tunnel intersect this fault at Sta. 39K+308 to Sta. 39K+320, respectively. Where exposed, the fault material is seen to be mainly fault breccias with occasional intercalations of fault gouge. This gouge is pulverized, and poorly cemented. The ground chips easily and has a poor stand up property.

OCCURRENCE AND CAUSE OF OCCURRENCE

Construction

In the original plan of the construction of the Hsuehshan Tunnel a section the length of 1 km in the eastern section of the tunnel would be constructed using the drill and blast method. This would then be followed by TBM excavation heading east. However, the Pilot Tunnel commenced excavation on July 1991, and in February 1996 the TBM excavation had completed 1,000 m of the Pilot Tunnel, but the TBM had been bogged down or trapped a total of ten times. All the advantages of using TBM excavation had been lost. In the ten times that the TBM was stopped, the geological conditions might not have been entirely similar, however, the last two times it was trapped happened as results of a sudden influx of a large quantity of pressurized groundwater into the tunnel followed by subsequent debris flow or mass flow. These influxes caused a prolonged trapping of the TBM, and operations to rescue the TBM became longer and more difficult. Following the tenth time the TBM was trapped, which happened at Sta. 39K+079, a new rescue measure was adopted to alleviate the situation. This measure called

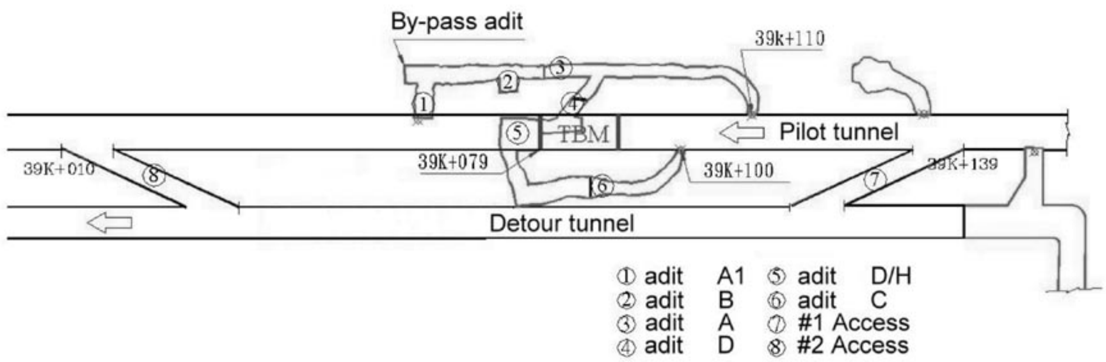

Figure 3. Plan for the 10th Stoppage of the Pilot Tunnel TBM

for excavating a bypass adit around the mired TBM to reach the front of the TBM.(Figure 3) And meanwhile, as the rescue works were in progress, tunnel excavation would proceed through the drill and blast method. This would be a flexible excavation method that would enable continuation of tunnel construction through the section underlain with Szeleng Sandstone and pressurized groundwater. It would also afford a chance to improve the adverse geological conditions of the ground. It was hoped that ground improvement would allow the safe passing of the main tunnel TBM and the freed pilot tunnel TBM, when these two machines reached this section later.

Discussion on the Cause of the Incident

The outcropping rock formations between Sta. 39K+120 and Sta. 39K+080 belong to the Szeleng Sandstone Formation of the Oligocene age. From the bottom towards the top, these consisted of grayish white quartzose sandstone with occasional intercalations of argillite or coaly shale and bedded sandstone with occasional intercalations of argillite that showed laminated coaly shale or bedding shear. There were no signs of groundwater seepage. The TBM excavation proceeded normally and smoothly. However, although the inclination of the rock formations between Sta. 39K+080 and Sta. 39K+060 was at a low angle, due to the effects of an obliquely intersecting shear zone, the rock formations were sheared and fractured with thick intercalations of shear clay that sealed off groundwater behind them, and thus caused no seepage. Over a tremendous span of time, an immense quantity of groundwater accumulated behind the shear zone. Thus as the TBM operation broke open the shear clay that acted as a water barrier, a large quantity of groundwater with rock fragments and clay rushed onto the TBM in the tunnel. After this first incident, considering the adverse geological situation at the site and the performance of the TBM, a detour tunnel running parallel to the Pilot Tunnel was excavated using the drill and blast method of excavation. However, as the excavation operation reached the outcrop of this same shear zone, an incident identical to the first one occurred again. A large quantity of pressurized water with rock debris and clay rushed into the tunnel. The influx was so strong that it was not possible to erect any steel support or shotcrete. Eventually, the ground had to be improved through consolidation grouting to stop the groundwater influx before excavation resumed.

During the construction of the Hsuehshan Tunnel, the main difficulty encountered was the sudden, abrupt influxes of large quantities of groundwater into the tunnel in the section of the tunnel alignment located in the Szeleng Sandstone Formation. The Pilot tunnel TBM was seriously impaired, and the construction operation severely delayed.

Before any review of the practical methods used for the treatment of pressurized groundwater stored in rock formations is attempted, an introduction to the hydrological model of the groundwater body in the rock formations of the Szeleng Sandstone is in order. Current geologic information obtained from the boreholes and the Pilot Tunnel excavation indicate that the rocks of the Szeleng Sandstone west of the Chinying Fault are chiefly comprised of quartzose sandstone with minor intercalations of argillite and coaly shale. The bedding inclination is small, and is almost horizontal. Joints are well developed and open, thus forming a continuous water storage body that is highly permeable with a high storage capacity. In addition, due to the dense

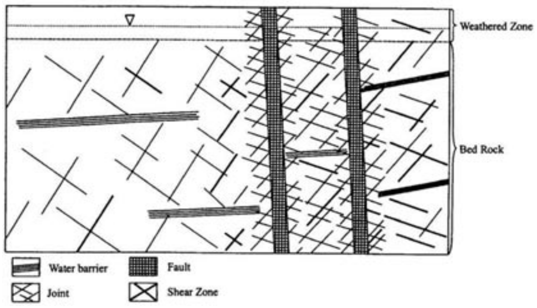

Figure 4. Schematic Illustration of the Rectangular Cell Groundwater Model

concentration of faults, shears are well developed; these fractures result in many vertical clay-bearing faults and shears zones that act as water barriers. On the other hand, argillite beds or coaly shale intercalated in the quartzose sandstone are comparatively low in permeability, and form semi-water-barriers in that they may be partially connected with the top or bottom beds. Under this configuration, groundwater in the Szeleng Sandstone Formation occurred stored in separated rectangular cells, as shown in Figure 4. The hydrogeological characteristics of the Szeleng Sandstone Formation, based on observations, are summarized as follows:

1. The hydraulic conductivity of the rocks of the Szeleng Sandstone Formation is estimated to range from 1 10-4 to 5 10-4m/sec; hence these rocks are highly permeable. This coincides well with the fact that previous deep borehole drilling showed no return water for holes sunk in these rocks.
2. The entire bulk of the Szeleng Sandstone Formation is well connected. Furthermore, Taiwan has abundant precipitation. Therefore there is a constant, widespread groundwater recharge. Groundwater influxes into the Pilot Tunnel maintained a persistent, steady flow of 180 l/sec. Such a bountiful supply of groundwater is a major difficulty in water-cut-off grouting.
3. There are frequent occurrences of large quantities of groundwater behind clay-bearing, high-angle fault or shear zones. Once tunnel excavation broke through any of these groundwater barriers, highly pressurized groundwater would rush into the tunnel. The strong groundwater flow carried with it the detrital materials that it collected from the brecciated fault or shear zones that it had eroded, and this mixture of water, rock debris, and clay formed a debris flow as it moved, causing large scale collapses in the tunnel.
4. Since the groundwater occurs stored in separate rectangular cells, reduction in water seepage or hydraulic pressure at the excavation face of the tunnel does not necessarily indicate that another highly pressurized groundwater body does not exist there. This increases the difficulty of predicting the occurrence of pressurized bodies of groundwater ahead of the excavation face.

MODES OF DRILL-AND-GROUT TREATMENT

Rocks outcropping into the section between the Pilot Tunnel Sta. 39K+120 and Sta. 39K+080 all belong to the Oligocene Szeleng Sandstone Formation. In a bottom to top ascending order, these rocks are grayish white quartzose sandstone with occasional intercalations of argillite or coaly shale, and bedded sandstone with occasional intercalated laminated carbonaceous argillite that sometimes showed bedding shears. There were no signs of groundwater seepage. Nor there were any unusual signs when the TBM excavation reached this location. However, although the inclination of the rock formations between Sta. 39K+080 and Sta. 39K+060 was at low angles, due to the effects of an obliquely intersecting shear zone, the rock formations were sheared and fractured with thick intercalations of shear clay that sealed off groundwater behind them, and thus there was no seepage. Over a tremendous span of time, an immense body of groundwater accumulated behind the shear zone. Thus when the TBM operation broke open the shear clay that acted as water barrier, a large quantity of groundwater with rock fragments and clay rushed onto the TBM in the tunnel. After this first incident, considering the adverse geological situation at the site and the performance of the TBM, a detour tunnel running parallel to the Pilot Tunnel was excavated using the drill and blast method of excavation. However, as the excavation operation reached the outcrop of this same shear zone, another incident identical to the first one occurred. A large quantity of pressurized water with rock debris and clay rushed into the tunnel. The influx was so strong that it was not possible to erect any steel supports or shotcrete. Eventually the ground had to be improved through consolidation grouting to stop the groundwater influx before excavation could resume.

In tunnel construction, when a collapse occurred as result of debris flow or mud flow triggered by an influx of pressurized groundwater as excavation was passing through a fault zone or a shear fractured rock mass, it was common practice to construct a detour tunnel, or to attempt draining to lower the hydraulic pressure. In Japan, construction of the A-Bo Tunnel was penetrating Quaternary volcaniclastic deposits when the excavation operation encountered a serious cave-in as a result of an influx of a large quantity of groundwater into the tunnel. The incident was resolved by lowering the hydraulic pressure through draining. However, a lengthy period might be required for this same type of treatment to become effective when groundwater recharge is highly effective. In cases where a low discharge rate at the exhaust drain hole is causing poor pressure-lowering results or the recharge area for the groundwater body is excessive, forced consolidation grouting may be used as the treatment method. One example is the pilot tunnel of the Seikan Tunnel in Japan. A cave-in occurred during excavation in a fault zone, and the ground was improved through the use of triple-cone squeezed grouting. The improved ground enabled the safe passage of the tunnel excavation.

The shear zone and the pressurized groundwater influx encountered in the detour tunnel at Pilot Tunnel Sta. 39K+074 was from the same geologic structure that caused the 10th trapping of the TBM in the Pilot Tunnel. A measurement was made on the groundwater seepage following the stoppage of the operation consequent to the 10th TBM stoppage. The measurement showed that the total amount of groundwater seepage stood at 100 to 150 l/sec. Another measurement made at a horizontal investigation hole at Sta. 39K+119~Sta.39K+019 showed hydraulic pressure of 18 kg/cm2, indicating very effective recharge of the groundwater within the area. Hence, although the excavation operation had to revert to the drill and blast method, it seemed impossible that, within a short time, lowering the water pressure through draining measures and keeping excavation resumed The hydrogeological characteristics of the Szeleng Sandstone Formation are rather peculiar. The rock formation is capable of storing a large quantity of groundwater, the rock is highly permeable, there are numerous faults and shears densely distributed within the formation, and the highly pressurized groundwater occurs in separated cells. Because of this, it was anticipated that incidents of this type would be encountered again in future operations. Examining all past experiences, it was then concluded that draining and grouting would be the proper ground treatment measures that would allow smooth continuous excavation operations in the future.

Selecting Grouting Materials

The materials commonly used in consolidation grouting are cement, bentonite and ultra-fine cement. For chemical grouting the materials are selected from the "water-glass" series, the silicate series or PUIF. Selecting the proper materials can determine success or failure in a grouting project. Ideal grouting materials should be able to meet the following demands:

(1) The grout should be stable, it will not undergo any chemical reaction when stored over a long period of time

(2) Low viscosity, flows freely, excellent grouting properties

(3) Setting time for chemical grout should be adjustable for effective control of grout coverage,

(4) Non-toxic, odorless, non-corrosive, harmless to human beings and low pollution to the environment,

(5) Grouting equipment, piping and wiring should be easy to clean,

(6) When a grout sets, the shrinking should be low, and possesses adequate bondage with the rock mass,

(7) High resistance to compressive stress,

(8) Low cost, readily available,

(9) Easy to mix and operate without need for special equipment or apparatus.

The site of the present case study is located within the rocks of the Szeleng Sandstone Formation. Rocks of the Szeleng Sandstone showed good continuity, and are high in water permeability. Geological boring results indicated that there was a possibility of a large influx of pressurized groundwater. The purpose of the present grouting operation was to achieve water cut-off through consolidation grouting of the rock mass. Hence, with reference to past experience, L.W. grout fluid (a mixture of cement and water-glass) was selected for use. Grouting with L.W. grout fluid would effectively achieve the purpose of stopping water, while a variation of the mixing ratio would achieve the purpose of grout coverage. Further, considering that part of the consolidated rock mass would eventually be removed in tunnel excavation, the consolidation effect of the grouting did not need to be that of attaining a higher strength for the rock mass. Referring to experience from the 10th stoppage of the TBM, a B.C. (bentonite-cement) mix would achieve the desired effect of water stopping and consolidation. Ingredients for both the

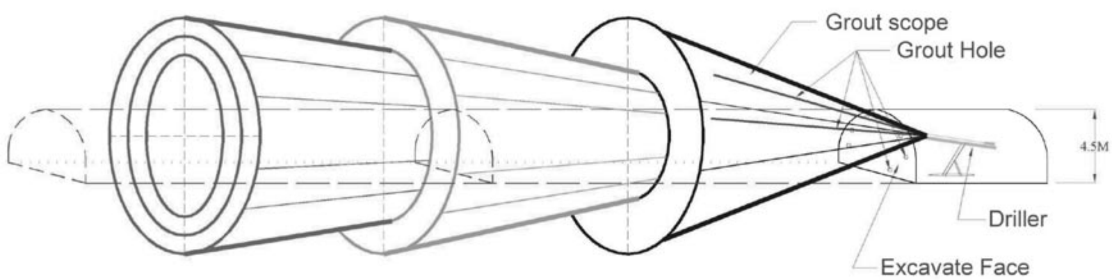

Figure 5. Schematic Illustration of Conical Grouting

L.W. and B.C. mixes were easy to acquire. These mixes were easy to mix and simple to use without requiring any specific equipment. Hence, in this case, L.W. and B.C. grout fluids were used. In addition, some of the holes were grouted with pure cement, in accordance with the locations of these holes.

Planning Treatment Principles

The treatment principles for grouting Sta.39K+074 in the detour tunnel followed the conical grouting treatment principles used in pilot tunnel of the Seikan Tunnel in Japan (Figure 5). Grout hole arrangement adopted the more conservative three-ring configuration. In this treatment, the 33 m of ground immediately ahead was treated for water-cut-off and consolidation. Then, depending on the result of this treatment as well as the actual conditions, drain holes were drilled to drain the groundwater. This was followed by excavation for 25 m with the expectation that the adverse ground might have been cleared. The grout fluids were L.W., B.C., or pure cement, adjusted in accordance with the grouting site or the groundwater influx conditions. The principles for grout hole layout and grout operation for geological treatment are as follows:

(1) The grouting scope, which is outward from the excavation cross section, shall cover an area at least 1 diameter of the tunnel.

(2) The distance between grout holes at the bottom of these holes shall not exceed 2 m.

(3) The purpose of the outer cone is water cut off, L.W. grout fluid shall be used; the inner cone is for the purpose of consolidation, B.C. and pure cement grout fluid shall be used.

(4) Drill and grout in stage-down manner, maximum length of grouting in one grout hole shall not exceed 15 m. If water seepage during drilling of grout hole is in excess of 2 l/sec or considerable hydraulic pressure is detected, drilling shall stop and grouting shall commence.

(5) In grouting using L.W. fluid, the setting time is set at 2 minutes; this shall be adjusted in accordance with water flow. In grouting using B.C. or pure cement, mixing of grout fluid shall be from lean to thick, and shall be adjusted in accordance with grout take.

(6) Pressure for grouting shall be controlled to within 3 times the hydraulic pressure of the groundwater, and shall not exceed 50 kg/cm2.

(7) Upon conclusion of grout operation, the grout hole used for consolidation grouting shall be drilled, again, to as deep as the groundwater influx location, for use as a water draining hole. In accordance with requirements, drill 38 mm φ drain hole (L=3 ~ 6 m) during excavation.

Result of Ground Treatment

A long distance horizontal borehole drilled at Sta. 39K+119.24 revealed that there was a great abundance of groundwater approximately 15 m in front of the excavation face. The rock mass was fine to medium-grained quartzite, well jointed and fractured, hence a highly permeable rock mass but also an excellent water reservoir. The Pilot Tunnel encountered fault and shear zones here, and the great quantity of groundwater influxing with the heavy load of rock debris and clay trapped the TBM. In view of this, a conservative treatment measure was adopted. Three rings of grout holes were grouted in 2 stages. Grouting was conducted in a stage down manner whenever water was encountered. First stage grout holes were about 21 m in depth; second stage grout holes were 30 m in depth, holes were arranged in alternation, and were grouted from the outside towards the inside in every other hole in sequence to facilitate checking on adjacent

Table 1. Quantitative Data of Grout Treatment at Sta.39K+074

Grouting Quantity / Item — Hole No., Stage, Date			L.W.						B.C.					NOTE
			cement (bag)	water (L)	water glass (L)	water (L)	volume (M^3)	pressure (kg/cm^2)	cement (bag)	bentonite (kg)	water (L)	volume (M^3)	pressure (kg/cm^2)	
D1	1st (0~23.0m)	1997/08/06	6.0	654	525	225	1.50	50	-	-	-	-	-	OK
D2	1st (0~23.0m)	1997/08/23	168.3	16,804	9,750	9,750	38.98	50	-	-	-	-	-	OK
D3	1st (0~22.5 m)	1997/08/10	32.0	3,488	1,200	2,800	8.00	50	-	-	-	-	-	OK
D4	1st (0~21.5 m)	1997/08/09	293.0	22,085	13,750	13,000	53.49	50	-	-	-	-	-	OK
D5	1st (0~21.5 m)	1997/08/13	22.0	2,398	825	1,925	5.50	50	-	-	-	-	-	OK
D6	1st (0~24.0m)	1997/08/20	177.0	22,577	12,275	12,958	50.62	50	-	-	-	-	-	OK
D7	1st (0~23.0m)	1997/08/27	29.5	4,278	2,475	2,275	9.50	50	-	-	-	-	-	OK
D8	1st (0~22.0m)	1997/08/10	54.0	5,886	3,825	2,925	13.49	50	-	-	-	-	-	OK
D9	1st (0~22.0m)	1997/08/13	14.0	1,526	525	1,225	3.50	50	-	-	-	-	-	OK
D10	1st (0~22.0m)	1997/08/16	31.0	3,379	1,487	2,387	7.75	50	-	-	-	-	-	OK
D11	1st (0~21.5 m)	1997/08/15	20.4	2,424	925	1,825	5.50	50	-	-	-	-	-	OK
D12	1st (0~21.5 m)	1997/08/06	4.0	436	350	150	1.00	50	-	-	-	-	-	OK
D13	1st (0~22.0m)	1997/08/17	6.0	1,155	625	625	2.50	50	-	-	-	-	-	OK
D14	1st (0~22.0m)	1997/08/18	6.0	1,155	625	625	2.50	50	-	-	-	-	-	OK
Subtotal of hole D			863.2	88,245	49,162	52,695	203.80		-	-	-	-		
A1	1st (0~20.5 m)	1997/09/06	-	-	-	-	-		8.0	60.0	852	1.00	50	OK
	2nd (0~28.5 m)	1997/09/21	-	-	-	-	-		44.0		4,686	5.52	50	OK
A2	1st (0~20.5 m)	1997/09/04	-	-	-	-	-		6.0	45.0	639	0.75	50	OK
	2nd (0~28.5 m)	1997/09/19	49.4	8,702	4,750	4,750	18.99	50	-	-	-	-		OK
A3	1st (0~20.5 m)	1997/08/25	-	-	-	-	-		86.0	645.0	9,159	10.78	50	OK
	2nd (0~28.5 m)	1997/09/18	6.5	1,145	625	625	2.50	50	-	-	-	-	50	OK
A4	1st (0~20.5 m)	1997/08/28	-	-	-	-	-		52.0	390.0	5,538	6.52	50	OK
	2nd (0~28.5 m)	1997/09/14	25.0	4,404	2,404	2,404	9.61	50	-	-	-	-		OK
A5	1st (0~21 m)	1997/09/05	-	-	-	-	-		62.0	465.0	6,603	7.77	50	OK
	2nd (0~28.6 m)	1997/09/17	68.0	8,662	4,875	4,875	19.50	50	-	-	-	-		OK
A6	1st (0~21 m)	1997/09/01	-	-	-	-	-		72.0	540.0	7,668	9.03	50	OK
	2nd (0~29 m)	1997/09/20	68.1	11,486	6,292	6,292	25.16	50	-	-	-	-		OK
A7	1st (0~21 m)	1997/09/01	-	-	-	-	-		22.0	165.0	2,343	2.76	50	OK
	2nd (0~29 m)	1997/09/23	-	-	-	-	-		36.0	195.0	3,105	3.76	65	OK
A8	1st (0~21 m)	1997/08/28	-	-	-	-	-		42.0	315.0	4,473	5.27	50	OK
	2nd (0~29 m)	1997/09/23	-	-	-	-	-		70.0	525.0	7,455	8.78	50	OK
A9	1st (0~22 m)	1997/09/01	27.0	3,649	2,085	2,085	8.25	20	116.0	870.0	12,354	14.54	50	OK
	2nd (0~29 m)	1997/09/21	-	-	-	-	-		34.0	255.0	3,621	4.26	50	OK
A10	1st (0~22 m)	1997/09/06	-	-	-	-	-		104.0	780.0	11,076	13.04	50	OK
	2nd (0~29 m)	1997/09/22	-	-	-	-	-		23.0	172.5	2,450	2.88	50	OK
A11	1st (0~21 m)	1997/09/04	-	-	-	-	-		30.0	225.0	3,195	3.76	50	OK
	2nd (0~28.5 m)	1997/09/20	11.7	2,061	1,125	1,125	4.50	50	-	-	-	-		OK
A12	1st (0~20.5 m)	1997/09/05	-	-	-	-	-		14.0	105.0	1,491	1.76	50	OK
	2nd (0~28.5 m)	1997/09/18	13.0	2,290	1,250	1,250	5.00		-	-	-	-	50	OK
A13	1st (0~20.5 m)	1997/08/21	-	-	-	-	-		32.0	240.0	3,408	4.01	50	OK
	2nd (0~28.5 m)	1997/09/01	34.0	5,454	3,000	3,000	12.00	50	-	-	-	-		OK
A14	1st (0~20.5 m)	1997/08/30	-	-	-	-	-		10.0	75.0	1,065	1.25	50	OK
	2nd (0~28.5 m)	1997/09/01	22.0	3,946	2,154	2,154	8.61	50	-	-	-	-		OK
Subtotal of hole A			324.7	51,799	28,560	28,560	114.07		863.0	6,397.5	91,181	107.34	-	
B1	1st (0~20.5 m)	1997/09/08							22.0	165.0	2,343	2.76	50	OK
	2nd (20.5~33 m)	1997/09/23							52.0	215.0	3,837	4.75	50	OK
B2	1st (0~21m)	1997/09/12							10.0	75.0	1,065	1.25	50	OK
	2nd (0~28 m)	1997/09/25							66.0	220.0	4,356	5.50	50	OK
B3	1st (0~20.5 m)	1997/09/09							234.0	1,755.0	24,921	29.34	50	OK
	2nd (20.5~33 m)	1997/09/26							6.0	20.0	396	0.50	50	OK
B4	1st (0~21m)	1997/09/07							12.0	90.0	1,278	1.50	50	OK
	2nd (20.5~33 m)	1997/09/26							9.0	30.0	594	0.75	50	OK
B5	1st (0~20.5 m)	1997/09/08							12.0	90.0	1,278	1.50	50	OK
	2nd (0~28.5 m)	1997/09/26							36.0	120.0	2,376	3.00	50	OK
B6	1st (0~20.5 m)	1997/09/12							58.0	435.0	6,177	7.27	50	OK
	2nd (0~28 m)	1997/09/25							33.0	110.0	2,178	2.75	50	OK
B7	1st (0~20.5 m)	1997/09/14							16.0	120.0	1,704	2.01	50	OK
	2nd (0~28 m)	1997/09/26							18.0	60.0	1,188	1.50	50	OK
B8	1st (0~20.5 m)	1997/09/07							122.0	915.0	12,993	15.30	50	OK
	2nd (20.5~33 m)	1997/09/24							39.0	130.0	2,574	3.25	50	OK
Subtotal of hole B			-	-	-	-	-		745.0	4,550.0	69,258	82.83		
Total			1,187.9	140,044	77,722	81,255	317.88	-	1,608.0	10,947.5	160,439	190.17	-	

grout holes and correct holes with less than desirable grout results. Grout holes on the outside ring mainly serve the purpose of water cut off and in controlling the scope of grout. L.W. fluid was the main grout. The setting time of the L.W. grout fluid was adjusted in accordance with the grout hole conditions, water flow, and hydraulic pressures, in order to achieve the purpose of water cut off and controlling of grout scope. First stage grouting of outer ring grout holes totaled 204 m3 of L.W. The Second stage grouting totaled 131 m3. The water cut off result was successfully achieved, and water seepage in the inner ring holes was reduced, and thus work time was reduced. The main purposes for the inner ring holes were to consolidate the rock mass to allow safe excavation operation, and to guarantee that the tunnel construction would pass through this section safely. To achieve these purposes, B.C. or pure cement grout fluid was used. The first stage grouting of the inner ring grout holes totaled 155 m3 of grout. The second stage grouting totaled only 22 m3 of grout.

Problems encountered during grouting operation were mainly the difficulties in grout hole drilling. In the present grouting operation, 2 rotary KH-120 drill rigs were used simultaneously to reduce work time. However, the highly fractured rock mass with abundant groundwater proved to be very difficult to drill, jamming or breaking drill rods and causing cave-ins. Drilling as well as grouting was seriously affected. In extreme cases, it would take two days to complete one drill and grout operation. Work advance was very slow, and the present grouting ground treatment operation took 69 days to finish. Quantitative data on the present ground treatment operation are presented in Table 1.

When the present grout treatment in the detour tunnel of the pilot tunnel was completed, many drain holes were drilled in the detour tunnel for the purpose of re-draining the Eastbound tube of the main tunnel, and for lowering hydraulic pressure in the groundwater body ahead. Through the locations of water seepage, it would then be possible to estimate the effective margin of the grout scope for the grout cone. It would also be possible to judge the effective grout take scope in the well-jointed Szeleng Sandstone Formation through this grouting operation. Observation results indicated the achieved effective grout scope might approximately reach 4 to 6 m from the grout holes. The observed result showed that the actual grouting corresponded well with the expected result in the operation principles.

Establishing Ground Treatment Mode

Experience gained from the present ground treatment at Sta. 39K+074 in the detour tunnel of the pilot tunnel indicated that, in general, an influx of a large quantity of pressurized groundwater is commonly linked to geologic discontinuities such as faults and shear zones, and the groundwater body usually possesses a good ability to recharge from an extensive ground surface or immense groundwater replenishing source. The groundwater influx characteristics are different than those of smaller secluded formational cognate water from deposition of the strata. Lowering the groundwater through draining would be ineffective.

Consequently, after acquiring the present precious experience, the construction work team began an attempt to establish the operational ground improvement treatment principles applicable to rock mass of the Szeleng Sandstone Formation. Thus, in the ground treatment grouting operations that followed, a review was made on grout hole layout in an attempt to reduce the number of grout holes that needed to be drilled. However, the pressure of the groundwater was too high, and the fractured zone too extensive, and so under consideration of safety, the grout hole layout remained in the two-ring layout. Check holes were drilled between the two rings of the grout holes when a grouting operation was concluded in order to verify the grout result. Finally, drain holes were drilled.

The number of drain holes, and the locations of these drain holes, cannot be pre-determined based on theoretical calculation. These drain holes are usually decided at the site, and adjusted according to the site conditions. Following review and study, the principles for their adjustment are as follows. When drilling drain holes, the total groundwater seepage shall be measured following the completion of each addition drain hole. When the total water seepage does not show a conspicuous increase with the increase in the number of drain holes, an upper limit on the effect of additional drain holes has been reached, and drain hole drilling shall be stopped.

Following much review and discussion, a flow chart for geologic investigation and ground treatment procedures has been formulated (Figure 6). The flow chart is the culmination of years of site experience. Past experiences on drill and grout operations were also reviewed, and this resulted in the synthesis of the best timing for drilling and grouting and the best form for grout hole layouts. The synthesis consists of three types of grouting methods (Figure 7). The construction site followed these grouting

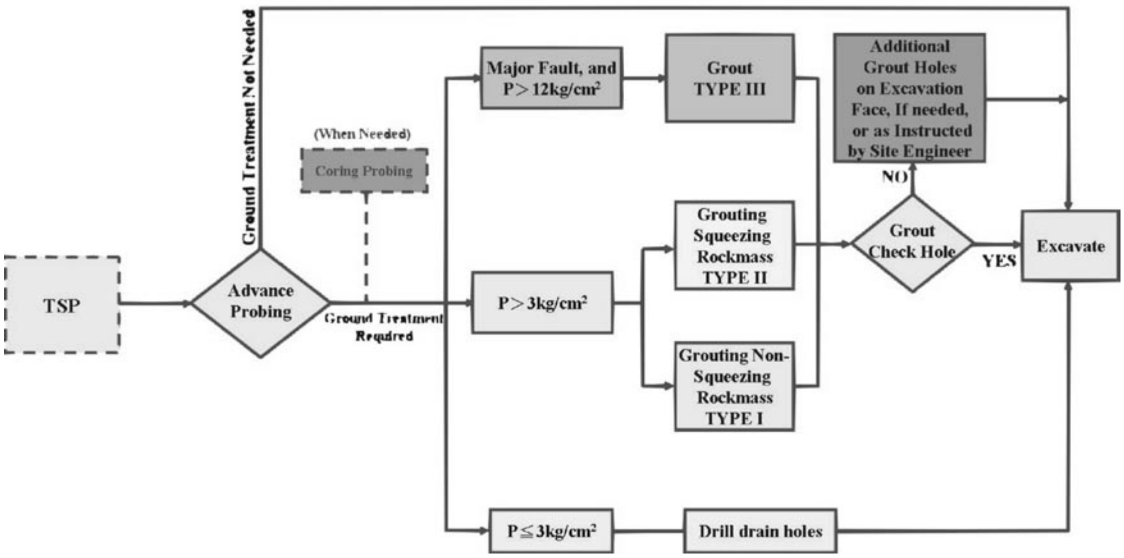

Figure 6. Procedures for Geological Investigation and Grouting

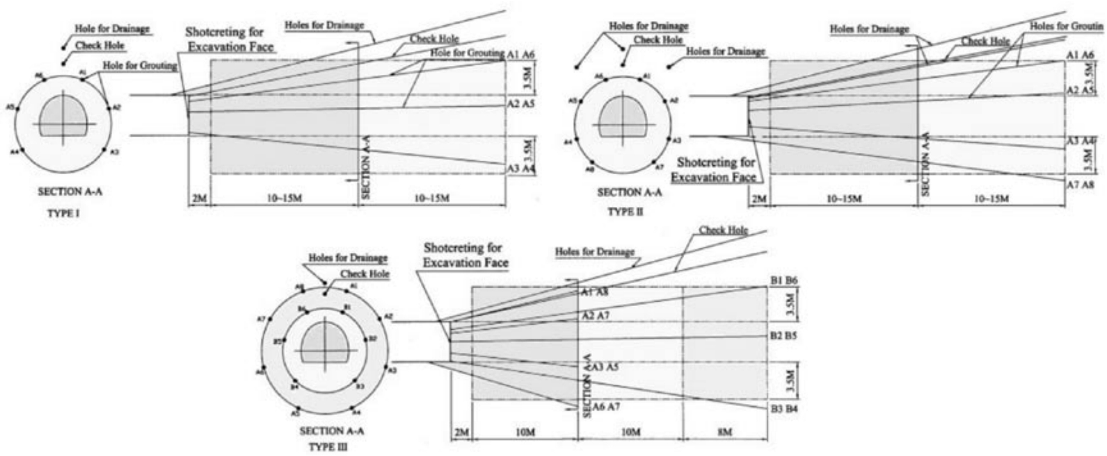

Figure 7. Layout for Grouting and Draining Holes

modes, and was successful in accomplishing the desired results, greatly reducing the time required for ground treating through grouting. The time required to improve each 23 m long section has been reduced to one week, with ground improvement results within reasonable expectations, and the improved ground suitable for safe excavation. These principles will be of assistance in safely passing sections of adverse geological conditions in future tunnel excavations.

CONCLUSIONS AND RECOMMENDATIONS

As a case study, this paper presents a synopsis of the ground improvement grouting methods and the installation of draining facilities performed during the 11 stoppages of the TBM in both the Pilot Tunnel and the detour tunnel of the Hsuehshan Tunnel when adverse geological conditions were encountered.

The conclusions are as the follows:

1. An influx of a large quantity of pressurized groundwater is intimately linked to the geologic discontinuities, such as faults and shear zones, and the groundwater body usually possesses a good recharge from an extensive ground surface area or an immense groundwater replenishing source. In these

areas, fractured rock masses with abundant fissures provide excellent storage space for groundwater. The faults act as recharging passageways and the shear zones form good water barriers. These then combine to form hidden hazards in construction operations. For these reasons, adequate geologic and hydrologic investigations should be preformed prior to tunnel excavation.

2. When confronted by special geological conditions during tunnel excavation, plans for ground improvement should be formulated, taking into consideration the issues of rock mass characteristics, hydrogeological conditions, engineering requirements, environment protection demands, construction equipment, and construction materials. The plan should be put into use, and gradual modifications to it should be conducted in accordance with the actual situation encountered.

3. When encountering large quantities of groundwater influxes in rock formations like the thick, high capping Szeleng Sandstone Formation, draining measures would be too time consuming and difficult to realize the expected results. Instead, when within immediate reach of the site, grouting should be performed as the chief measure, and it should be supplemented with draining from a long distance away.

4. When encountering adverse geologic conditions that cause large quantities of groundwater influxes in rock formation like the thick, high capping Szeleng Sandstone Formation, grouting results are directly related to grout operation planning. The two major factors are grouting pressures and grout quantities.

5. The total fissure rate of a rock mass is the major factor determining the grout quantity for a rock mass. The fissure rate is proportional to the number of fissure sets and the widths of the fissures, but inversely proportional to fissure spacing.

6. Adequate ingredients and appropriate grout ratios, grouting apparatuses and equipment, and the grouting work team are important keys to successful ground improvement operations.

7. When excavating in such complex ground, regardless of the mode of excavation being used, geological investigation shall be viewed as a routine operation, and shall not be omitted under any pretext. All appropriate investigatory methods befitting the specific geological conditions at site shall be adopted. In addition, it is recommended that advance probing should be increased in terms of the probing frequency, the number of holes and the length of the probe holes. Such advance probing will serve as an early warning prior to occurrence of a water influx.

8. The purpose of grouting lies in consolidating the rock mass and thus increasing the watertightness of the rock mass so that it will enable greater stability in the excavation face. However, in application, intensifying the grout density simply for the sake of grouting shall be refrained from. Proper attention should be directed at the checking and the feedback of the ground improvement operation and its results. Sufficient information that can help increase an understanding of the rock mass characteristics in the water influx section should be acquired. The mode of operation shall be adjusted with due reference to time and site factors, so that even under the most changeable geological conditions, the most effective ground improvement will be attained.

9. For groundwater influxes, the treatment principles are consolidation grouting to stop the water flow and lower the hydraulic pressure to drain down the water. These concepts can be combined in use to enhance the effect. However, operational procedures should be properly planned to assure expected results.

10. In general, a rock mass that demands ground treatment is a rock mass of inferior quality. It will cause difficulty in drilling grout holes and this will result in lost time. For this reason, a drill rig is an important tool in the success of a grouting operation. The contractor should look upon his drill rigs as an investment, and he shall use the best assembly of machinery in achieving the best treatment results.

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