STUDY OF HYDRAULIC CONDUCTIVITY OF THE FRACTURE ZONES, DERIVED FROM INFLOW MEASUREMENTS IN THE HSUEHSHAN TUNNEL

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ABSTRACT

As a geological exploratory tunnel, the 12.9 km long Pilot Tunnel of the Hsuehshan Tunnel was begun in July, 1991 and completed in October, 2003. During tunneling with the TBM, there were 13 cave-ins. Of the 13 cave-ins, the 3rd to 6th and the 11th to the 13th were mainly due to extremely poor rock conditions, resulting in cave-ins of the face and rock debris falling into the cutter head and the shield, without water. However the 1st, 2nd, and 7th to 10th cave-ins were mainly caused by large water inflows. This study collected the data from the water inflows including the magnitude of the water-bearing zones, the altitudes, the widths, the water heads when bursting out, the initial transient maximum water inflows and the attenuation curves. With the data collected, the study utilized the image method and superposition principal to transfer the finite domain to the infinite domain, followed by using the convolution-deconvolution method to transfer the time-variant inflow into the constant inflow. With the above-mentioned method, a semi-analytical equation was derived from the function of the water inflow during tunneling, the water head, the width and the hydraulic conductivity of the fracture zones. The study indicated that the hydraulic conductivity of the water-bearing zones was in the range of 6.38 x 10-5 to 7.88 x 10-4 m/s, which is about 100 times greater than the hydraulic conductivity of rock (7.83 x 10-7 to 3.62 x 10-6 m/s). For the cave-ins in the Kankou Formation and Chinyin Fault, the prominent variable percolation coefficient implies that the hydro-geological properties of "water pockets" encountered during tunneling are quite site-dependent. However, the 8th to the 10th cave-ins occurred in the Szeleng Sandstone, showing quite uniform hydraulic conductivity between 2.25x10-4 and 3.82x10-4 m/s. It can be inferred that the hydro-geological characteristics of the sheared zones and fractured zones in Szeleng Sandstone are similar to each other.

Keywords: water-bearing zone, hydraulic conductivity, water pocket.

INTRODUCTION

As a geological exploratory tunnel, the 12.9 km long Pilot Tunnel of the Hsuehshan Tunnel was begun in July, 1991 and completed in October, 2003. During tunneling with the TBM, there were 13 cave-ins. Of the 13 cave-ins, the 3rd to 6th and the 11th to the 13th were mainly due to extremely poor rock conditions, resulting in cave-ins of the face and rock debris falling into the cutter head and the shield, without water. However the 1st, 2nd, and 7th to 10th cave-ins were mainly caused by large water inflows. With the data collected from the water inflows, the study utilized the groundwater hydraulics to calculate the hydraulic conductivity of the water-bearing zones:

CALCULATING PROCEDURE

Collecting the Data of Water Inflow

The data from the water inflows includes the magnitude of the water-bearing zones, the altitudes, widths, the

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water head when bursting out, the initial transient maximum water inflows and the attenuation curves. (Table 1 and Fig. 1)

Setting Up the Conceptual Model

The conceptual model, which is the foundation of the numerical model, was set up based on the data from water inflow. Two kinds of groundwater inflow conceptual models were simulated using the data from the water inflow:

(1) Conceptual Model I

Assumes that the water-bearing zone, which the pilot tunnel passed through, extends relatively wide and can be regarded as infinite (at least at the initial stage of water inflow, as illustrated on fig. 2).

(2) Conceptual Model II

Assuming the stratum, which the pilot tunnel passed through, is impermeable, but intersected by one high-angled fractured zone forming a groundwater storage space and permeable route for groundwater (illustrated on fig. 3). The fractured zone is assumed to extend limitedly upwards and infinitely downwards. When calculating, therefore, the upper boundary condition has to be taken into account.

Conducting the Formula Calculations

With the conceptual model mentioned above as the basis, the study utilized the groundwater hydraulics to develop several semi-analytical calculation formulas corresponding to some of the current hydrogeological configurations mentioned previously.

The quantity of groundwater inflow into the tunnel is an unknown element and time-variable. The drawdown in the portal of the tunnel, whose radius is equal to r0, is a constant:

$$D = h_0 - z_0 \quad (1)$$

Where D is the drawdown in the portal of the tunnel, h0 is the initial hydraulic head and z0 is the elevation of tunnel. The study utilized the image method to transfer the tunnel from finite space into several (maybe infinite) tunnels in infinite space, and sum up the groundwater inflow by the superposition principal (Bear, 1972). The image method and superposition principal have transferred the finite domain into the infinite domain. It is a solution of the time-variant groundwater inflow by using the convolution-deconvolution method to transfer the time-variant inflow into the constant inflow (Sneddon, 1976). A recursion formula is derived with the function of the groundwater inflow during excavation, the water head, the width and hydraulic conductivity of the fractured zones. The formula has the form:

$$Q(t_i) = Q(t_{i-1}) + \frac{D - \sum_{j=1}^{i-1}\left[Q(t_j) - Q(t_{j-1})\right] \times F(P, r0, \Delta t_{ij})}{F(P, r0, \Delta t_{ii})} \quad (2)$$

Where

Q: the quantity of groundwater inflow in the excavation face ([L3] [T-1]) or in the lateral walls per unit of tunnel length ([L3] [T-1] [L-1]).

tij: ti-tj-1(tii=ti-ti-1)

F: a mathematical function of hydraulic conductivity, storage coefficiency, thickness of aquifer, distance from boundary, distance from sink source and the time since excavation. F is several expressions corresponding to some current hydrogeological configurations.

Composing the Computer Program

Efforts have been made to program the above-mentioned mathematic model as a means of the following mathematical calculations and trial and error procedures. The study used the Turbo C ++ programming language developed by Borland® Company.

Feed-back Calculating of Hydraulic Conductivities

During tunneling with the TBM, there were 13 cave-ins. Of the 13 cave-ins, the 3rd to 6th and the 11th to the 13th resulted from rock debris falling into the cutter head and the shield, without water. The records of the groundwater inflow in the portal of the pilot tunnel indicated the quantity of inflow was decreasing (fig. 4). So these cave-ins were mainly due to extremely poor rock conditions, shear zones comprised of fractured rocks and gouge, and resulted in the cave-ins of the face and rock debris falling into the cutter head and the shield. So our study only analyzed the hydraulic conductivities of fractured zones that resulted in the 1st, 2nd, and 7th to 10th cave-ins.

There are some parameters of the 1st, 2nd, and 7th to 10th cave-ins in Table 2. These parameters indicate that the 1st, 2nd, and 7th cave-ins are in the argillite of the Kankou Formation, and the maximum groundwater inflow is only about 42 L/sec. The rapid decrease of groundwater inflow indicated poor capacity and hydraulic conductivity of Kankou Formation. However, the lithology in the 8th to 10th cave-ins was quartzite intercalated with thin argillite and carbonaceous shale. And the increase of the groundwater inflow indicated that the fractured zones in Szeleng Sandstone extended for a considerable range. The fractured zones show not only quite high hydraulic conductivity, but also a high ability to gather groundwater from the vicinity.

In addition to hydraulic conductivity, we needed to know the specific storage (Ss) of the rock in the calculation formula. This parameter could be obtained from the porosity and compressibility of the rocks. The formula is in the form:

$$S_s = \rho_w g\ (\beta_b + n\beta_w) \qquad (3)$$

Where β_b and β_w are the compressibility of rocks and fluid, respectively, ρw is the density of water and n is porosity of rocks. The compressibility of fractured rocks ranges from 3.3 10-10 to 6.9 10-10 m2/N. The compressibility of water at 25 C is 4.8 10-10 m2/N (Domenico, 1990). The specific storage of Szeleng Sandstone derived from the previous formula ranges from 3.44 10-6 to 7.48 10-6 m-1. The average specific storage, 5.46 10-6 m-1, is used in following calculation.

According to the annual preliminary reports of engineering geological investigations in the Hsuehshan Pilot Tunnel, the hydrogeological configurations of the 1st, 2nd, and 7th to 10th cave-ins, analyzed in this study, are suitable for the above-mentioned conceptual model II. With the parameters and the data collected from groundwater inflows, the study matches the calculated quantity of groundwater inflow with the measured one by adjusting the hydraulic conductivity of water-bearing zones.

CALCULATING RESULTS

The results of the calculations of the hydraulic conductivity of the water-bearing zones of the 1st, 2nd, and 7th to 10th cave-ins are listed in Table 3. The calculated quantity of groundwater inflow and the measured ones are shown in Fig 5 to Fig 10.

The study indicates that the hydraulic conductivity of the water-bearing zones is in the range of 6.38 10^{-5} to 7.88 10^{-4} m/s, which is about 100 times greater than the hydraulic conductivity of rock (7.83 10^{-7} to 3.62 10^{-6} m/s). For the cave-ins in the Kankou Formation and Chinyin Fault that is the 1st, 2nd, and 7th cave-ins, the prominent variable percolation coefficient implies that the hydro-geological properties of "water pockets" encountered during tunneling are quite site-dependent. However, the 8th to the 10th cave-ins that occurred in the Szeleng Sandstone, showed quite uniform hydraulic conductivity between 2.25 10-4 to 3.82 10-4 m/s. It can be inferred that the hydro-geological characteristics of the sheared zones and fractured zones in Szeleng Sandstone are similar to each other.

DISCUSSION

The calculated quantity of groundwater inflows is very close to the measured ones in the initial stage. Nevertheless, the calculated quantity of groundwater inflows became larger than the measured ones as time went by. This error was considered to have mainly resulted from the movement of the boundary of the real water-bearing zones and from the sealing grouting, which caused the rapid decrease of groundwater inflow, in the few days following the groundwater inflow bursting out.

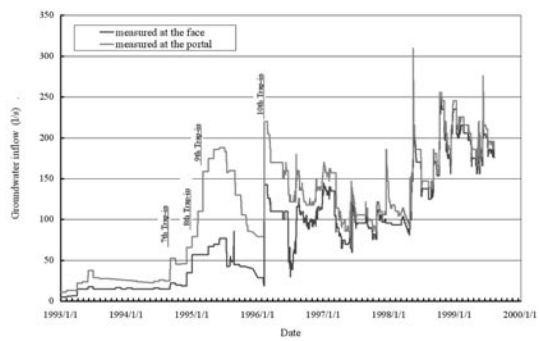

Fig. 1 Historic Curves for the Groundwater Inflow of Hsuehshan Pilot Tunnel and Face

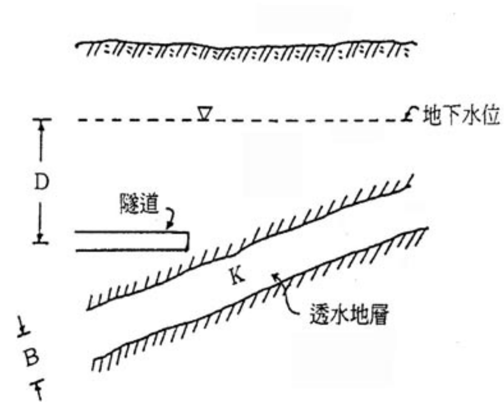

Fig. 2 Sketch Map of Conceptual Model I

Table 1 The Reasons for the 13 Cave-ins in the Hsuehshan Pilot Tunnel

Incident #	Date	Chainage	The reason for cave-ins	Geological conditions
1	1993.02.02 ~ 1993.04.24	40K+138.5	cave-ins of the face and groundwater inflow(32 L/sec)	shear zone of argillite
2	1993.05.24 ~ 1993.07.15	40K+083	cave-ins of the face and groundwater inflow on 82.05.26(40 L/sec)	argillite intercalated with tuff
3	1993.08.29 ~ 1993.10.3	40K+075	cave-ins of the face	shear zone of argillite
4	1993.10.22 ~ 1993.12.20	40K+040.74	cave-ins of the face	shear zone of argillite
5	1994.02.22 ~ 1994.04.07	39K+972.4	cave-ins of the face	shear zone of argillite
6	1994.05.25 ~ 1994.6.30	39K+841.9	cave-ins of the face	gouge of Kingying Fault
7	1994.07.07 ~ 1994.09.19	39K+816.04	cave-ins of the face and a small amount of groundwater inflow	disturbed area of Kingying Fault
8	1994.11.07 ~ 1994.12.23	39K+529.11	extremely large amount of groundwater inflow (185 L/sec)	fractured quartzite of Szeleng Sandstone
9	1995.02.18 ~ 1995.12.04	39K+168.7	cave-ins of the face and a small amount of groundwater inflow (150 L/sec in the initial stage)	fractured quartzite of Szeleng Sandstone
10	1996.02.05 ~ 1996.09.13	39K+079.4	cave-ins of the face and a small amount of groundwater inflow (150 L/sec)	fractured quartzite of Szeleng Sandstone
11	2001.04.10 ~ 2001.08.15	37K+431	extremely poor rock conditions, resulting in the cave-ins of the face and rock debris falling into the cutter head	fractured quartzite of Szeleng Sandstone, intercalated with thin argillite
12	2001.08.27 ~ 2001.11.10	37K+366	extremely poor rock conditions, resulting in the cave-ins of the face and rock debris falling into the cutter head and the shield	fractured quartzite of Szeleng Sandstone, intercalated with thin argillite, a small amount of groundwater inflow
13	2003.06.07 ~ 2003.09.17	34K+989.65	extremely poor rock conditions, resulting in the cave-ins of the face and rock debris falling into the cutter head and the shield	grey to black fine grain sandstone of Tatoshan Formation, a small amount of groundwater inflow

(Ministry of Transportation and Communications, Taiwan Area National Expressway Engineering Bureau, 2004)

1st, 2nd, and 7th to 10th Cave-ins

Incident # (Chainage) Date	The maximum quantity of groundwater inflow in initial stage (l/s)	Water-bearing zones		The hydraulic head
		Attitude	Width(m)	
1st (sta.40+138.5) 1993.1.22-1993.4.24	32	N48ºW/80ºS	0.3-0.6	*(5 kg/cm^2)
2nd (sta.40+083.0) 1993.5.25-1993.7.15	40	N50ºW/25ºS	0.2-0.6	*(5 kg/cm^2)
7th (sta.39+816.0) 1994.7.10-1994.9.19	30	N10ºE/76ºS N40ºE/80ºS	5	7-8 kg/cm^2
8th (sta.39+530.0) 1994.11.8-1994.12.23	185	-	2.5-6	*(10 kg/cm^2)
9th (sta.39+168.7) 1995.2.18-1995.12.5	150	N40-50ºE/70ºN	4-5	*(10 kg/cm^2)
10th (sta.39+079.0) 1996.2.5-1996.09.13	150	N11ºE- 25ºW/80ºS N11ºW/50-70ºS	primary : 5-7 secondary : 8-12	*(10 kg/cm^2)

*(The hydraulic head in brackets indicates it is estimated)
(Ministry of Transportation and Communications, Taiwan Area National Expressway Engineering Bureau, 1997)

Table 3 The Results of Hydraulic Conductivities of the 1st, 2nd, and 7th to 10th Cave-ins

Incident # (Chainage) Date	The maximum quantity of groundwater inflow in initial stage (l/s)	Geological conditions	The hydraulic conductivity of the water-bearing zone (m/s)
1st (sta.40+138.5) 1993.1.22-1993.4.24	11-32	grey to black argillite of Kankou Formation	7.88×10^{-4}
2nd (sta.40+083.0) 1993.5.25-1993.7.15	20-40	grey to black argillite of Kankou Formation	6.38×10^{-5}
7th (sta.39+816.0) 1994.7.10-1994.9.19	25-30	grey to black argillite of Chinyin Fault	1.20×10^{-4}
8th (sta.39+530.0) 1994.11.8-1994.12.23	185	quartzite intercalated with argillite of Szeleng Sandstone	3.70×10^{-4}
9th (sta.39+168.7) 1995.2.18-1995.12.5	150	quartzite intercalated with argillite of Szeleng Sandstone	3.82×10^{-4}
10th (sta.39+079.0) 1996.2.5-1996.09.13	150	quartzite intercalated with argillite of Szeleng Sandstone	2.25×10^{-4}

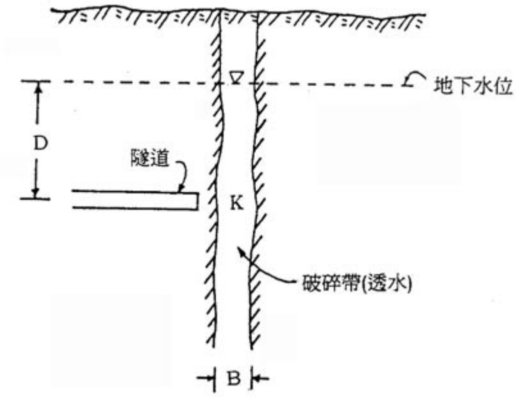

Fig. 3 Sketch Map of Conceptual Model II

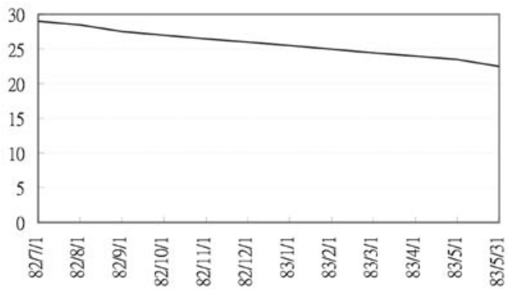

Fig. 4 Historic Curves for the 3rd to 6th Cave-ins Groundwater Inflow Recorded in Portal of Pilot Tunnel

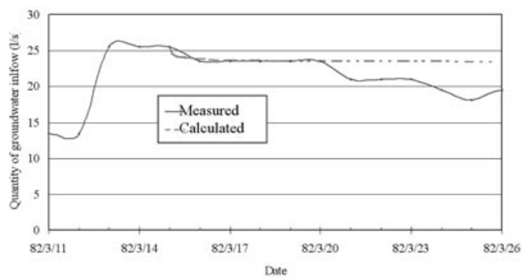

Fig. 5 Historic Curves for Calculated and Measured Groundwater Inflow of the 1st Cave-in

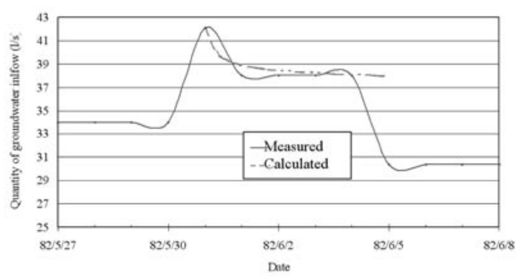

Fig. 6 Historic Curves for Calculated and Measured Groundwater Inflow of the 2nd Cave-in

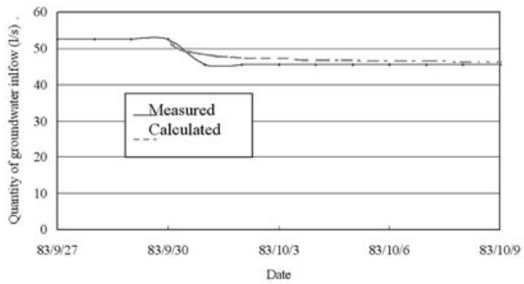

Fig. 7 Historic Curves for Calculated and Measured Groundwater Inflow of the 7th Cave-in

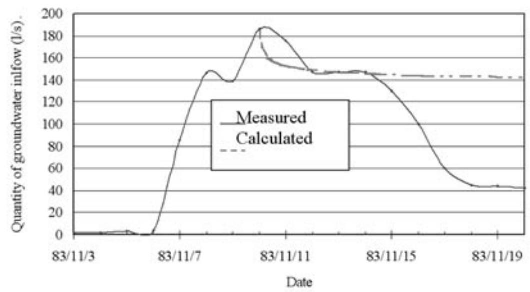

Fig. 8 Historic Curves for Calculated and Measured Groundwater Inflow of the 8th Cave-in

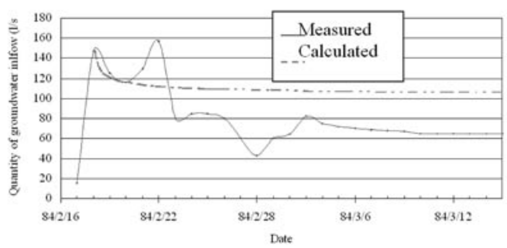

Fig. 9 Historic Curves for Calculated and Measured Groundwater Inflow of the 9th

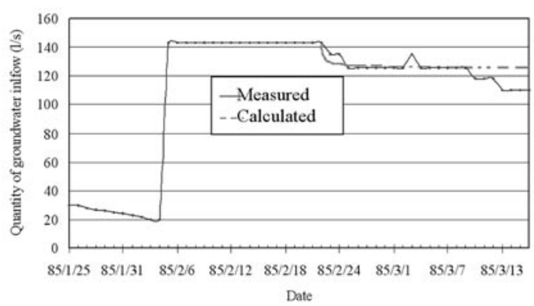

Fig. 10 Historic Curves for Calculated and Measured Groundwater Inflow of the 10th Cave-in

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