THE RAISE BORE CONSTRUCTION METHOD USED IN SHAFT NO. 1 OF THE HSUEHSHAN TUNNEL

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ABSTRACT

The Hsuehshan Tunnel is about 12.9 km long. It is the longest tunnel of the Taipei-Ilan Expressway. There are three sets of vertical ventilation shafts in the tunnel, each set having two shafts separated from each other by 50 m, one for fresh air and the other for exhaust air. Shaft No. 1 is 6.0 m in diameter and about 510 m in depth. The raise bore and bench down excavation methods were selected because the shaft is deep and the pilot tunnel had already passed under the proposed location of the shaft and it could be used for mucking. Because Shaft No. 1 is located on a monocline of the South limb of the Yingtzulai Syncline which is associated with adverse geological conditions, grouting was done to pre-treat the weak rock formations in advance of the raise boring of the pilot hole, the reaming of the hole, and the bench down excavation.

The adverse rock formations were pre-treated by bentonite-cement (B/C) grouting in the long-stage because of the tight construction schedule and the need to use the raise bore method. There were 4 deep grouting holes drilled; three of them were drilled by a high-capacity drilling machine, while the last one utilized the pilot hole drilled for the raise bore construction.

First, a pilot-hole of 31 cm in diameter was drilled from the surface of the ground to the bottom of the shaft for the raise boring method. Then, the drill bit was changed to a reaming head to ream the pilot hole upward toward the surface of the ground. Finally, the drill & blast method was used for the benching-down excavation to enlarge the hole to its full size of 7 m in diameter.

After the pilot hole drilling and the reaming of the hole were finished, the benching down excavation proceeded in Shaft No.1. Generally, there would be a 1%~2% offset of the pilot hole, which is equivalent to a 5~10 m offset on a 500 m deep shaft. However, in the case of Shaft No.1, there was only a 72 cm offset in the exhaust-air shaft and a 14 cm offset in the fresh-air shaft, resulting from the pre-treatment of the bentonite-cement grouting and use of the DDS (directional drilling system) for the pilot hole drilling. In this paper we discuss the practice of the grouting treatments for shaft excavation and the procedures of the raise bore method for future reference in similar construction.

Keywords: **raise-boring method, RBM, bentonite-cement grouting method, B/C grouting, syncline, reaming head, directional drilling system, DDS**

INTRODUCTION

The Hsuehshan Tunnel that connects Pinglin , Taipei County with Toucheng, Ilan County on the Taipei-Ilan Expressway is about 12.9 km long. It is the longest tunnel of the Taipei-Ilan Expressway. It is also the 5th longest tunnel in the world. The Hsuehshan Tunnel consists of two main tunnels each in one direction, a 4.8 m diameter pilot tunnel situated directly below the two main tunnels and three sets of vertical ventilation shafts.

The Hsuehshan Tunnel employs a longitudinal reinforced ventilation system. Each set of vertical shafts is composed of a fresh air intake shaft and an exhaust

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shaft; these shafts are spaced 50 m apart. At the base of the vertical shaft there is a ventilation machine room that is situated flush with the tunnel invert and connects the two tubes of the tunnel. At each of the machine rooms there are three sets of ventilation relay stations. Together these form 8 independent ventilation circuits, thus guaranteeing air quality in the tunnel.

The vertical ventilation shafts of the Hsuehshan Tunnel are located on sites with complicated geological conditions within the geologic province of the Hsuehshan Range. The deepest shaft reaches 501 m below the surface of the ground, and these shafts are situated within a water source conservancy area. This means that planning the construction methods used for these vertical shafts would have to take into consideration the diameters of the shafts, the depths, the engineering geological conditions, construction time, construction costs, construction sites and accessibility and environmental protection issues. Consideration was also given to whether the horizontal tunnel at the bottom of the vertical shaft is passing through, and treatment methods for construction at geologically weak grounds as well as feasibility of construction technology. The work team, comprised of personnel from the Taiwan Area National Expressway Engineering Bureau, Sinotech Engineering Consultants, Ltd., and the Retired Soldiers Engineering Association, worked hand in hand to overcome this seemingly insurmountably, difficult project. The three sets of vertical shafts were completed in October 2004. This paper presents a case study on the construction methods used in these vertical shafts. It is hoped that this will serve as a future reference for the planning and design of projects of a similar nature.

GENERAL DESCRIPTION OF CONSTRUCTION METHODS FOR VERTICAL SHAFT EXCAVATION AND CONSTRUCTION METHOD PLANNING

General Description of Vertical Shaft Construction Method

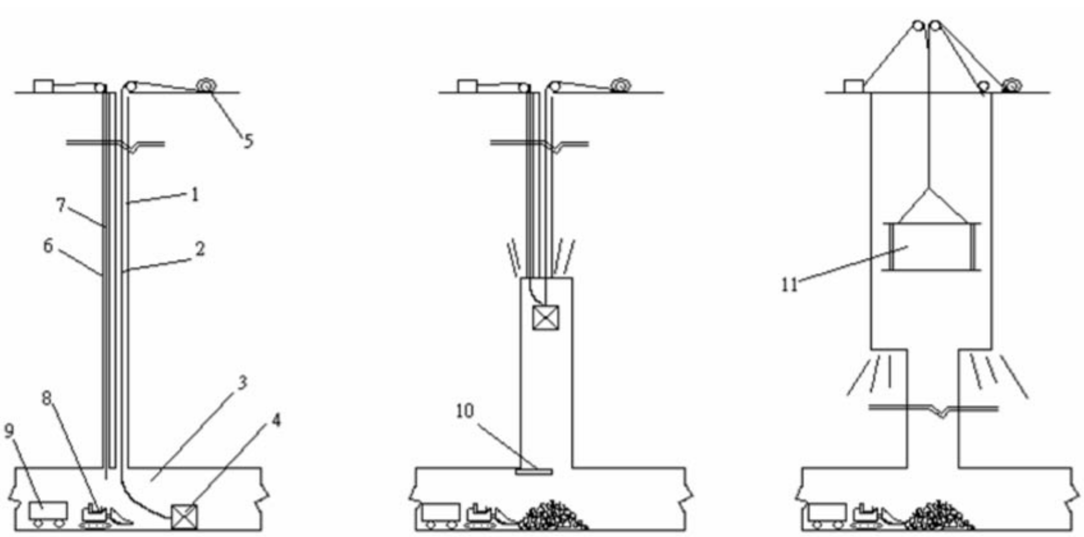
There are many construction methods used for the excavation of vertical shafts. Four distinct methods may be recognised if construction advance is the main consideration. They are as follows:

The Conventional Vertical Shaft Excavation Method

In reference to the direction of the advance of the excavation, conventional methods for vertical shaft excavation may be differentiated into downward methods and upward methods. In general, downward excavation is the more commonly used.

The Cage Method

In this method, major construction procedures are: (1)



1.Cable hole 2. Cable 3. Tunnel below 4. Cage 5. Winch 6. Auxiliary hole 7. Piping 8. Muck loader 9. Mucking truck 10. Guard plate 11. Workbench

Figure 1. Excavation Construction through Cage Method

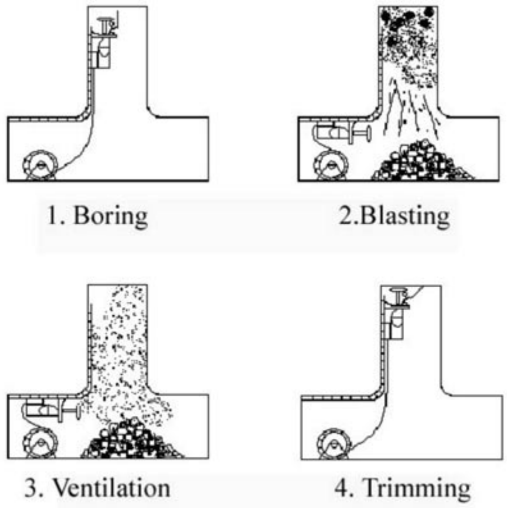


Figure 2 Sequential Steps in the Climbing Method of Shaft Excavation

At the center of the vertical shaft, a vertical hole is bored from the top down to the invert of the tunnel, an auxiliary hole is also drilled from the top down to the invert of the tunnel. (2) A cable, which is attached to a winch located on the top of the vertical shaft, is inserted through the vertical hole that was drilled. A work cage situated on the invert of the tunnel is then attached to the cable. (3) The vertical shaft excavation work then proceeds from the bottom of the bored hole, in small cross sections, up towards the top of the vertical shaft. The cage hanging down from the cable serves as workbench for construction workers. The cage is raised and lowered by the winch. (4) Reaming to enlarge the vertical shaft and the final lining of the vertical shaft are also done from the cage in both up and down directions. (Figure 1)

Figure 1. Excavation Construction through Cage Method

The Climbing Method

Equipment used in the climbing method of vertical shaft excavation is mainly differentiated into Alimak and Jara. In essence, excavation of the shaft in this construction method proceeds from the bottom of the vertical shaft towards the top. Figure 2 shows the major steps in the climbing method.

The Raise Bore Method

In the raise bore method of vertical shaft excavation a pilot hole is drilled by the raise borer at a designated location to a horizontal tunnel at the bottom of the vertical shaft. The pilot hole is then reamed to a larger diameter using a reamer. The cross section of the enlarged hole is checked to see if it meets the design specifications for the cross section. If the designed diameter of the vertical shaft is larger than the enlarged hole, the hole is further enlarged. Figure 3 shows the sequential steps in raise boring method.

Planning for Vertical Shaft Excavation

The main elements in the planning of vertical shaft construction methods are mostly similar to the engineering construction of tunnels. These elements include diameter of the shaft, depth, engineering geological conditions, construction technology, construction duration, construction costs, safety, environmental protection measures and auxiliary construction methods. In opting to use the raise bore

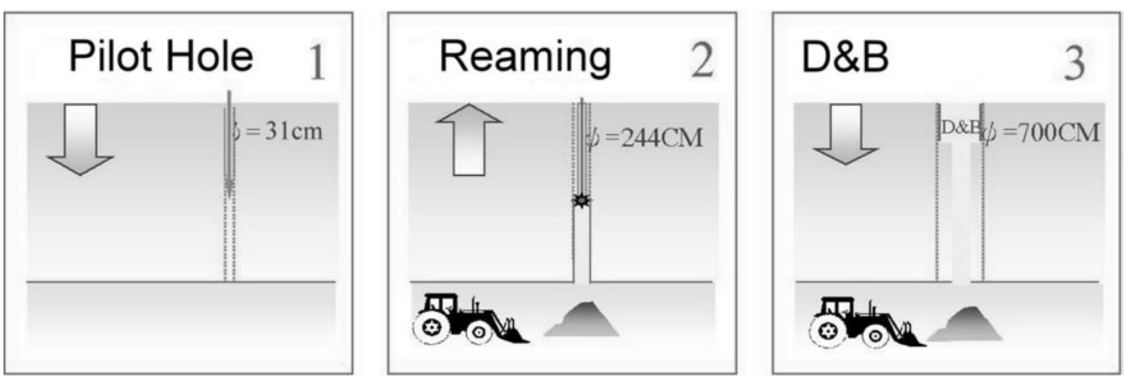


Figure 3 Sequential steps in vertical shaft excavation through raise boring method

Table 1 Main Elements in Vertical Shaft Excavation Planning

METHOD / MAJOR ELEMENT	SINKING METHOD	CAGE METHOD	CLIMBING METHOD	RAISE BORING METHOD
Horizontal Tunnel passing through	Not limited	Necessary	Necessary	Necessary
Geologic suitability	Not limited	Good	Slightly better	Slightly better
Depth of Shaft	Not limited	<100m	<150m	>100m
Shaft Diameter	Not limited	Diam=2m	Diam 2m~4m	Diam>3.5m
Work Condition	Fair	Poor	Poor	Good
Cost	Low	Low	High	Highest
Construction Period	Long	Short	Short	Shortest
Construction Technique	Not limited	High	High	High
Safety	Safe	Poor	Poor	Safe

method as the construction method, then the timing of a horizontal tunnel at the bottom of the vertical shaft passing through would also have to be considered. Ventilation shafts are frequently located in hilly or mountainous sites, hence the construction site and the access to it are issues that have a higher degree of difficulty than the actual tunnel construction, and thus more care should be exercised. Whether construction of a vertical shaft can be completed in the best suitable and economic manner depends largely on whether the vertical shaft construction is correct. Table 1 presents a synopsis of these elements.

CASE STUDY ON THE RAISE BORE METHOD: USING SHAFT NO. 1

General Description of the Construction of Shaft No. 1

In the original design, Shaft No. 1 was located in the center of a tea farm in Tahuwei, Pinglin Hsien, Taipei County. Local tea planters thought exhaust air from the ventilation shaft would be a source of pollution that would affect the quality of tea and tea production, thus they expressed strong objections. These resident tea farmers even went so far as to take action by interrupting the construction of the vertical shafts. They wanted the ventilation shafts relocated. Following several years of failed negotiation and construction delay, the ventilation shafts were moved to a location 405 m from the originally designated location. A horizontal tunnel 328 m in length connected the ventilation shafts, and through this horizontal tunnel, the exhaust air was expelled behind a ridge. The depth of the vertical shaft changed from 345 m to 500 m due to the shift in location. This shift in location also meant that new soil and water conservancy plans and environmental impact assessment proposals had to be submitted once again for the new shafts. Following approval of the new site, the land was purchased, and construction commenced in June 2000. By that time, the pilot tunnel of the Hsuehshan Tunnel had already advanced to the bottom of the shaft, thus construction of the vertical shaft employed both the sinking method and the raise bore method, in order to avoid mucking from great height through the mountainous area.

General Description on Geological Conditions at the Site of Vertical Shaft No. 1

Vertical Shaft No. 1 of the Hsuehshan Tunnel is located on a monocline on the Southeastern limb of the Yingtsulai Syncline. Near the ground surface, rocks of the monocline are fragmented as the result of load relief and weathering. There are intercalated clay seams in the beds. The lithologies of the rock formation are sandstone and shale at the lower part of the Miocene Fangchiao Formation and thick-bedded sandstone with occasional shale of the Makang Formation.

Ground Treatment Methods at the Fresh Air and Exhaust Shafts of Ventilation Shaft No. 1

In tunnel engineering, when incompetent ground is encountered, the measures taken for the safe penetration of such ground are to change the excavation methods as well as the support methods. Besides these measures, the ground or the sheared or fractured geologically incompetent rock mass can be subject to pre-treating in order to attain a ground or rock mass adequate for tunnel excavation. Ground pre-treatment and improvement methods include grouting, ground freezing, or draining of the groundwater. For Ventilation Shaft No. 1 of the Hsuehshan Tunnel the pilot tunnel beneath the vertical shaft had already advanced to the site, and it was possible to employ a mixed sinking excavation method with the raise bore method of excavation in the construction of the vertical shafts. Data from the geologic borehole sunk for subsurface geological investigation indicated the rock formation at 78 m below ground surface was fractured and contained abundant groundwater. There was also a shear fracture zone 45 m in width with and inclination of 65o. It was decided that bentonite cement should be used to perform the grouting. Using bentonite cement to improve the ground and to form a waterproof curtain would facilitate the operation of the raise borer in the drilling of the pilot hole and in the reaming of the hole. Using bentonite cement would also help avoid possible detrimental effects on the local hydrogeological settings of the site and possible adverse effects to the West Portal construction work progress through groundwater seepage. Using the exhaust shaft as an example, the grouting operation consisted of four holes, in which, grouting of the third hole was done using bentonite cement through the deep hole. The fourth hole was operated in conjunction with raise bore method; the pilot hole in the raise bore method was used as the fourth grouting hole, thus guaranteeing that bentonite cement pre-grouting would reach the entire depth.

General Description of the Raise Boring Excavation of Ventilation Shaft No. 1

The fresh air shaft for Ventilation Shaft No. 1 is 489 m deep, the exhaust shaft is 501 m deep, and the two shafts both have inner diameters of 6 m, and are spaced 50 m apart. At the time of construction, the pilot tunnel of the Hsuehshan Tunnel had already passed the site; construction using the raise bore method commenced following ground improvement by bentonite cement grouting.

In the present raise bore method a pilot hole with a diameter of 31 cm was drilled to the machine room at the bottom of the vertical shaft. A 244 cm diameter reaming bit was then placed on the pilot hole drill rod, and the pilot hole was reamed from the bottom towards the top. The enlarged hole was then excavated from the top down by means of drill and blast excavation method. Waste material from excavation was trucked out from the bottom of the shaft through the tunnel.

In most cases, pilot hole drilling in vertical shaft construction through the raise bore method would show an offset on the order of 2%~3%, equivalent to 5 to 10 m in a vertical shaft with depth of 501 m. The present operation made use of a new precision directional drilling system (DDS), plus the ground was pre-treated with bentonite grouting. The combined effect of the new drill and the grouting resulted in an offset that was only 72 cm in the exhaust shaft (equivalent to an offset rate of 0.0014%), and 14 cm in the fresh air shaft (equivalent to an offset rate of 0.0003%). This was a world record in high precision. The highest single day advance for the pilot hole boring was 44.5 m, and the highest single-day advance for reaming was 54 m, both of these are records not frequently seen in this country (Table 2). Upon completion of the reaming, water seepage was measured at the bottom of the exhaust shaft, and the measurement showed seepages of 0.81 and 0.27l/s, indicating that there were positive effects from the grouting treatment.

Following the completion of the reaming of the shafts in Ventilation Shaft No. 1, the assembly of hoisting equipment and a winch at the collard of the shaft commenced immediately. This hoisting assembly would serve as a work platform for the downward expanding excavation to the depth of 500 m. The most stringent safety requirements were carefully applied in setting up this equipment.

The downward excavation to enlarge the vertical shaft was done round by round through the drill and blast excavation method. The enlarged pilot hole with a 244 cm diameter was used to dump waste rocks down to the bottom of the shaft; these waste rocks were then trucked out of the tunnel. Upon completion of each round of excavation, the shaft was immediately lined. In this sinking excavation, the construction draining was also done by way of the pilot hole. The water was treated in the wastewater treatment facility in the horizontal tunnel and then discharged out of the tunnel. Using this construction method avoided having to muck through the hoisting up of waste materials through the collard of the shaft and trucking them away by access road. Also through using this method, construction draining did not depend on a forced pumping system that would have required the installation of an additional wastewater treatment facility. Because of this, the time and money that usually would have been spent on mucking and water treatment when using other construction methods were saved.

During the downward excavation of this vertical shaft an overbreak as large as 3 m occurred in a reaming section within a shear fracture zone. This overbreak was the culminated result of the weathering of the unsupported excavation face, the load relief and the impact from falling waste rocks. The wall of the affected pilot hole showed irregular forms of collapse. Following inspection, emergent measures aiming at curtailing the aggravation of the situation were taken. These measures included the installation of reinforced supports by means of forepoling steel pipe and wire mesh, face sealing by shotcrete, and the backfilling of collapsed spots. The section with the adverse geological conditions was eventually overcome. The vertical shaft was completed in October 2004. The maximum single-month excavation for the vertical shaft had reached 95.3 m, which was the national record. Photos 1~4 show some of the construction under progress.

The present vertical shaft is currently undergoing lining installation. The excellent effect of the grout treatment made the lining installation go smoothly without any threat from groundwater seepage. Consequently, the maximum excavation had reached 126 m/month, also the best record in the country.

CONCLUSIONS

1. In most cases, the offset in pilot hole drilling in raise bore shaft excavation comes to around 1% to 2%. For a 500 m vertical shaft which this would be an off-set of 5 m to 10 m. In Ventilation Shaft No. 1of the Hsuehshan Tunnel, the pilot hole drilled at the fresh air shaft was 500 m deep. The offset was only 14 cm because a precise directional drilling system (DDS) was used.
2. The bore holes for the grouting with the bentonite cement for the treatment of the incompetent ground were drilled with drill rods with an inner diameter of 10 cm. Although an inclinometer was used, the drill rod offset was as high as 1.5%, causing a lot of time to be spent on hole trimming.
3. The thorough understanding of the geological conditions of the rock mass is a prerequisite. Incompetent shear zones should be pre-treated. This will preclude drill rod jamming or excessive waste when drilling the pilot hole or reaming.
4. When the depth of a shaft is in excess of 350 m, raise bore excavation becomes highly difficult, and the best kind equipment should be used and it should be in tiptop shape. The work team should be comprised of experienced personnel.
5. Raise bore shaft excavation is commonly done at sites with less than ideal environmental settings. In selecting construction methods, planning construction schedules, picking equipment and construction workers, a high priority should be given to work safety and adhering to sanitation and environmental protection regulations.
6. There have been very few cases of raise bore construction in Taiwan in the past. Raise bore machines, hoisting equipment and the relevant supporting machinery were mostly assembled in a "makeshift" manner. Whether such equipment will still meet the stricter present day requirements is a point to be considered in equipment planning for future projects.
7. In terms of construction and geologic conditions, construction of Ventilation Shaft No. 1 of the Hsuehshan Tunnel will serve as an excellent case history for future reference

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Table 2. Statistics on Raise Boring Construction, Ventilation Shaft No. 1					
Raise Boring Construction for Exhaust Shaft					
Pilot Hole, Raise Boring			Reaming, Raise Boring		
Date	Advance (m)	Accum. Depth (m)	Date	Advance (m)	Accum. Depth (m)
2002 09 23	9	9	2003 02 09	24.4	24.4
2002 09 24	1.5	10.5	2003 02 10	44	68.4
2002 09 28	2.3	12.8	2003 02 11	33.5	101.9
2002 09 29	1.5	14.3	2003 02 12	1.5	103.4
2002 09 30	1.7	16	2003 02 13	4.4	107.8
2002 10 01	1.5	17.5	2003 02 14	28.9	136.7
2002 10 02	2.5	20	2003 02 15	18.1	154.8
2002 10 03	2	22	2003 02 16	38	192.8
2002 10 04	1.6	23.6	2003 02 17	24.3	217.1
2002 10 05	2	25.6	2003 02 18	34.9	252
2002 10 06	1.9	27.5	2003 02 19	28.8	280.8
2002 10 07	2.2	29.7	2003 02 20	43.9	324.7
2002 10 15	20.1	49.8	2003 02 21	4.5	329.2
2002 10 16	3.3	53.1	2003 02 22	50.2	379.4
2002 10 19	16.1	69.2	2003 02 23	37.8	417.2
2002 10 19	15.9	85.1	2003 02 24	51.7	468.9
2002 10 24	31.8	116.9	2003 02 25	32.04	500.94
2002 10 25	30.3	147.2	Completed 2003 02 26 08:00		
2002 10 26	2.8	150	Total	500.94	
2002 10 28	7.8	157.8			
2002 10 29	27.4	185.2			
2002 10 30	10.6	195.8			
2002 11 05	9	204.8			
2002 11 06	28.8	233.6			
2002 11 07	27.3	260.9			
2002 11 08	27.4	288.3			
2002 11 14	33.3	321.6			
2002 11 15	30.3	351.9			
2002 11 16	30.4	382.3			
2002 11 17	7.7	390			
2002 11 20	19.5	409.5			
2002 11 21	4.7	414.2			
2003 01 06	2.8	417			
2003 01 21	9.3	426.3			
2003 01 22	15.1	441.4			
2003 01 23	16.7	458.1			
2003 01 24	16.8	474.9			
2003 02 04	5.4	480.3			
2003 02 05	20.1	500.4			
2003 02 06	0.54	500.94			
Total	500.94				

Table 2 (cont'd). Statistics on Raise Boring Construction, Ventilation Shaft No. 1					
Raise Boring Construction for Fresh Air Shaft					
Pilot Hole, Raise Boring			Reaming, Raise Boring		
Date	Advance (m)	Accum. Depth (m)	Date	Advance (m)	Accum. Depth (m)
2003 03 06	10	10	2003 04 21	47.8	47.8
2003 03 07	13.9	23.9	2003 04 22	36.5	84.3
2003 03 08	12.1	36	2003 04 23	42.4	126.7
2003 03 11	44.5	80.5	2003 04 24	41	167.7
2003 03 12	17.2	97.7	2003 04 25	48.5	216.2
2003 03 13	20.7	118.4	2003 04 26	27.3	243.5
2003 03 14	28.8	147.2	2003 04 27	34.9	278.4
2003 03 15	13.7	160.9	2003 04 28	38.1	316.5
2003 03 16	34.9	195.8	2003 04 29	50	366.5
2003 03 17	36.4	232.2	2003 04 30	47	413.5
2003 03 18	27.4	259.6	2003 05 01	7.7	421.2
2003 03 19	19.8	279.4	2003 05 02	54	475.2
2003 04 07	21.2	300.6	2003 05 03	5.02	480.22
2003 04 08	30.3	330.9	Total	480.22	
2003 04 09	28.9	359.8			
2003 04 10	34.1	393.9			
2003 04 11	28	421.9			
2003 04 12	28.9	450.8			
2003 04 13	24.7	475.5			
2003 04 14	4.72	480.22			
Total	480.22				

Photo 1. Directional Drilling System for pilot hole drilling, Raise boring method

Photo 2. Drill bit for reaming, raise boring construction method

Photo 3. Mucking during reaming operation, raise boring method

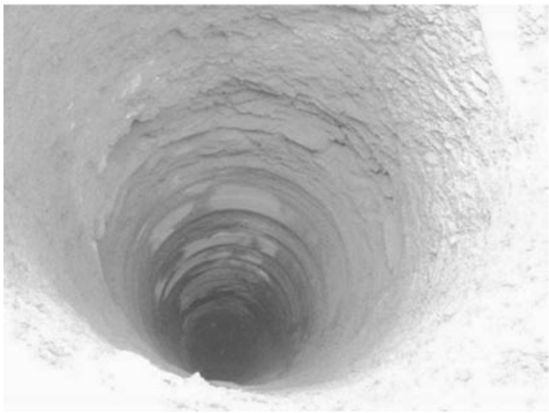

Photo 4. Upward reaming completed, raise boring method