

## PLANNING AND DESIGN OF THE HSUEHSHAN TUNNEL

Mou-Sheng Tsai, Tieh-Bin Lu, Yeou-Herng Lee, Fang-Sen Lu

### ABSTRACT

**The Hsuehshan Tunnel is a 12.9km long tunnel that penetrates through the Hsuehshan Range. The deepest overburden is as much as 720 m. Geological conditions along the tunnel alignment are very complicated. Rock formations traversed by the tunnel are highly fractured and contain huge reserve of groundwater, rendering engineering operation a very difficult task. Since commencement of construction in 1991, there had been many serious accidents resulting in much delay to the projected progress. Under great effort from all concerned, these seemingly insurmountable difficulties were overcome, and the pilot tunnel was broken through on October 2003, and construction of the two main tunnels will be concluded at the end of 2005. In this paper, the original design principles and issues of emphasises are presented together with considerations and recommendations. It is hoped that this short paper will serve as reference to similar major infrastructural projects in the future.**

### 1. INTRODUCTION

In consideration on development of the eastern Taiwan Lanyan plains, and in turn, for faster development of eastern Taiwan, it is mandatory that the distance between Taipei and the Lanyan Plain be effectively reduced. Construction of an expressway linking Taipei and the eastern Taiwan area was deemed the sole solution to this social-economic issue. The Taipei-Ilan Expressway thus was proposed and became a prime government policy. The alignment of the Taipei-Ilan expressway at the eastern end starts from metropolitan Taipei, and runs in a due southeast direction to the towns of Shihting and Pinglin, from Pinglin a series of long tunnels are used to penetrate through the Hsuehshan Range. Upon leaving the Hsuehshan Range at Toucheng, the expressway runs on the Lanyan plain to Ilan, the ultimate destiny of the 31-kilometer long expressway. Five tunnels of various lengths are located along the expressway; the culminated total length of these tunnels is 20.1 km. All tunnels are twin-tube two-direction in design. The Hsuehshan tunnel that cuts through the northern branch of the Hsuehshan Range is 12.9 km long, and constitutes the critical-path item to the entire expressway project. A tunnel boring machine (TBM) was specially brought into Taiwan for the first time to undertake tunnel driving in this unique, but highly challenging engineering project.

During investigation, state-of-the-art techniques were employed, so as to achieve the most reliable results. These investigations included remote sensing and aerial photo interpretation for geological reconnaissance works; hydraulic fracturing for measuring in-situ stresses. For high speed TBM boring, lining and support of the tunnel was by means of pre-cast concrete segments and high tensile steel rebars with  $F_y=5,000$  kg/cm<sup>2</sup>. In addition Value Engineering Study as well as using Professional Construction Management were introduced for management of this project.

### 2. PLANNING AND DESIGN

Ten years went by since the first completion of the "Feasibility Study on a Tunnel Highway between Nankang and Toucheng", during this decade 19 investigative works related to planning and design studies were performed, these are tabulated in Table 1. They included route selection, route alignment planning, engineering layout, function design and selecting the construction method. All of these works were granted to qualified, experienced engineering consulting firms. Assistance from experts was also sought, the aim was to realize technical transfer from these international firms and experts to local, domestic engineering consulting firms, thus up-grading and improving the engineering technological level in Taiwan area.

Table 1 Summary of works performed during planning and design stages

Work Item No.	Nature or Title of Work	Performed by	Time Period
1	Feasibility study on Tunnel Highway between Nankang and Toucheng	China Engineering Consultants, Inc.	1982.01~1982.12
2	Geologic Evaluation along Tunnel Highway between Nankang and Toucheng	Sinotech Engineering Consultants, Inc.	1984.02~1985.02
3	Feasibility Study on the Nankang-Ilan Highway	De Leuw Cather International Ltd.	1985.07~1988.04
4	Remote-sensing and aerial photo geologic study along the alignment during route selection stage	Industrial Technology Research Institute.	1989.10~1989.12
5	Geologic investigation and study, section between Lanyan Plain and section between Nankang-Pinglin, route selection stage	Moh and Associates, Inc.	1989.10~1990.05
6	Basic controlled surveying and 1/1000 scale topographic map aerial surveying	Chinese Society of Photogrammetry and Remote Sensing	1989.11~1990.08
7	Services for environmental impact assessment study	C.T.C.I	1989.11~1990.10
8	Geologic investigation for the Hsuehshan Tunnel section, route selection stage	Sinotech Engineering Consultants, Inc.	1989.12~1990.05
9	Services for route selection	De Leuw Cather International Ltd.	1989.12~1990.04
10	Transportation planning and analyses for the Taipei-Ilan Expressway (inclusive of Suao Extension)	Asian Technical Consultants, Inc.	1990.06~1990.12
11	Supplementary surveying for Basic Design Stage, National Taipei-Ilan Expressway	Chu – Kung Engineering Company, Inc.	1990.07~1990.09
12	Services for Basic Design	Asian Expressway Consultants (A consortium consisting of Parsons Brickerhoff of U.S., Electrowatt of Switzerland and Sinotech of ROC)	1990.06~1991.05
13	Geological Investigation, Section between Nankang and Pinglin for Basic Design	Moh and Associates, Inc.	1990.08~1991.01
14	Geological Investigation, Section between Pinglin and Toucheng for Basic Design	Sinotech Engineering Consultants, Inc.	1990.08~1991.03
15	Evaluation of Value Engineering on Basic Design	CLW INC. Consulting Engineers	1990.09~1991.03
16	Advisory Board Meeting	Taiwan Area National Expressway Engineering Bureau	1990.03~1991.01
17	Services for Detailed Design	Sinotech Engineering Consultants, Inc.	1992.02~1993.11
18	Services for Detail Design of Traffic Control Engineering	China Engineering Consultants, Inc.	1993.10~1995.10
19	Detail Design of Pilot Tunnel	Retired Soldier Engineering Agency	1991.07~1992.03

A summary of works performed during the various stages is presented as follows:

#### 1. Feasibility Study for the Nankang-Ilan Highway

The feasibility study for the Nankang-Ilan highway was awarded to a number of consulting firms by the Institute of Transportation Studies, Ministry of Transportation and Communications, in 1987. The engineering consulting firms comprised of De Leuw Cather of USA, Geoconsult of Austria, and China Engineering Consultant, Inc. of ROC.

#### 2. Route Evaluation and Selection

Result of the feasibility study was submitted to the Executive Yuan for approval. Following further geological evaluation and environment impact assessment, a better route was selected from candidate Routes 2 and 3. The Nankang-Ilan highway provisional office, Taiwan Area National Expressway Engineering Bureau, was given the authority to oversee the project. Following a review of the reports, the provisional office submitted a proposal awarding the services to a consortium comprising the domestic engineering consultants Sinotech Engineering Consultants, Inc., and two foreign consulting firms, De Leuw Cather, and Geoconsult. The major aim of the services was evaluating the candidate routes, and selection of a route. Candidate route 3 was recommended. However, with consideration on extension and connecting possibilities, the location of the eastern portal was shifted, and route 2A was chosen as the candidate route. This proposal was approved, and the service contract was awarded.

#### 3. Basic Design Study, Taipei-Ilan Expressway

In 1990, following open competition, the consortium made up of Parsons Brinckerhoff International, Inc. (PBI) of USA, Electrowatt Engineering Services, Ltd. (EWI) of Switzerland, and Sinotech Engineering Consultants, Inc. (Sinotech) of ROC, won a contract to undertake basic design of the project. Scope of work included tunnel, ventilation shafts, cross tunnels, portal arrangements, ventilation, illumination, fire fighting, emergency escape and evacuation, communication, monitoring facilities, maintenances, emergency power supply system, as well as study and design on other pertinent necessary functionalities for Hsuehshan Tunnel. Seeing that for the needs to conduct geological surveying and to serve maintenance and repair requirements during operation of the expressway and the long tunnel, most

experts and consulting firms unanimously voiced their recommendation that a pilot tunnel be integrated in the overall design of the Hsuehshan Tunnel. They also recommended that the pilot tunnel should be excavated by means of a TBM at an early date. In December 1990, basing on results of the Basic Design Study, a call for tender to bid was made. The contractor shall perform detailed design as he sees fit in accordance with construction requirements. In line with international practice, a copy of geological design summary report (GDSR) was furnished as reference to tendering parties

#### 4. Detailed Design

In 1991 the Taiwan Area National Expressway Engineering Bureau (TANEEB), Ministry of Transportation and Communications (MOTC) entrusted the detailed design study to Sinotech Engineering Consultants, Ltd. Detailed Design Study was based on the basic design study framework, and in accordance with the various tender documents. During detailed design Study foreign experts were also invited to act as short term consultants or advisors. It can thus be said that the strictness that went into the past four study stages was at least as stringent as American or European practices, if not more. The four stages of study rendered to the designing and planning of the Hsuehshan Tunnel were conducted following a strict procedure, and were planned by the most experienced consulting firms and experts from the United States or Europe, and were joined by the best consulting firms and expert in the domestic market, it would not be exaggerating if one were to say that the best of east and west congregated and joined forces in working on the Hsuehshan tunnel project.

#### 5. Value Engineering Study and Analysis

To keep construction cost for the Hsuehshan tunnel under control, value engineering study and analysis was performed in two phases during basic design study stage. The first phase of this study and analysis was entrusted by TANEEB to Century Engineering Consulting Company in October to November of 1990; right after basic design works on tunnel cross section layout, construction method evaluation, and ventilation were concluded. Century solicited expert in this field, over-seas and domestic alike, and formed a work team. This work team was further sub-divided into small groups, and worked and analyzed "Highway Bridges" and

"Tunnel Engineering", two topics of entirely different attributes. The work team drafted up 13 recommendations in the report it submitted to TANEED. Among these recommendations, the one specifically recommended reducing the diameter of the tunnel was accepted by TANEED following evaluation. Upon submittal of the first draft of the preliminary report for basic design, estimated construction cost was NT\$ 62.96 billion. This amount exceeded the original tabulated budget of NT\$ 60.1 billion by a wide margin. In order that the construction cost is controlled within the budgeted sum, TANEED requested that the consulting firms set up a cost appraising group to conduct "review on saving construction funds". The consulting firms were to re-evaluate the result and propose recommendation relevant to design adjustments that were arranged in order of priority for eventual execution. The construction cost was controlled within the budgeted NT\$ 60.1 billion.

### 3. GEOLOGIC INVESTIGATIONS

The Hsuehshan Tunnel is 12.9 km long, greatest thickness in overburden is nearly 720 m. The tunnel cuts through the Hsuehshan Range, and this area is one with very complex geological structures. In every study stage, from the onset of planning and design stages up to construction, geological investigation and study was performed in accordance with the

precision demanded by the nature of the stage. In Table 2, the works of geological investigations are presented. In Figure 1, the geologic sectional profile along the alignment of the Hsuehshan Tunnel is presented. The geologic sectional profile was the most important piece of result from geological investigation conducted during the planning and design stage. The major geologic elements are Eocene, Oligocene and minor Miocene folded sedimentary rock formations. In terms of order of exposure of these rock formations along the alignment of the tunnel, Tertiary Miocene rocks are exposed at the west portal, and then gradually changed to older, Tertiary Eocene rock formations. They are represented by rocks of the Fangchiao formation, the Makang formation, the Tatungshan formation, the Kangkou formation, and the Szeleng Sandstone. Major geologic structures encountered along the tunnel alignment are mainly fold structures; these are the Yingtzelai syncline and the Taotiaotze syncline. There are six major faults, they are: the Shihtsao fault, the Shihpai Fault, the Tachingmian fault, the Paling fault, the Shanghsin fault and the Chingying fault.

#### 1. Feasibility Study on the Nankang-Toucheng Tunnel Highway

This was the earliest of the study stages conducted for the Taipei-Ilan expressway. This was a geological evaluation and study along the alignment of the feasible route. This geological investigation and evaluation work was entrusted to Sinotech Engineering Consultants, Inc. in 1984. This followed closely the

Table 2 Major Geological Investigation Work Items during Various Study Stages

Work Item	Remarks
1. Remote sensing study and aerial interpretation	Understanding regional geological setting. For Detailed Design reference
2. Field geological investigation	In-depth understanding on engineering geology along tunnel alignment
3. Seismic refraction survey	Unraveling geological structures and rock formations within 50 m beneath tunnel alignment
4. Subsurface investigation through boring	Details on geological structures, rock formations and relevant engineering geological features at sites of vertical shafts
5. Exploration by trenching	Details on fault locations and relevant geologic features
6. Exploration through adits	Actual geological condition at portal of tunnels, and rock mass behavior after excavation exposure
7. In-situ tests	Understanding site behavior of rock mass, rock mechanical behavior of geologic structures, and in-situ stresses
8. Laboratory tests	Understand and obtain rock mechanical parameters for design references

feasibility study on the Nankang-Toucheng tunnel highway entrusted to China Engineering Consultants, Inc. by the Provincial Highways Bureau in 1982.

## 2. Feasibility Study on the Nankang-Ilan Highway

The Institute of Transportation Studies, MOTC, entrusted a consortium of engineering consulting firms to conduct feasibility study on the Nankang-Ilan highway. The consortium comprised De Leuw Cather International of United States, Geoconsult-Consulting Engineers of Austria, and China Engineering Consultants, Inc. of the Republic of China. The study selected three candidate highway corridors on the stretch of land between Pinglin and the Ilan plain. A comparison of these route corridors was made following geologic investigation and corridor inspection and checking in keeping with information and engineering elements on hydrology, topography, and tunnel length.

## 3. Route Evaluation and Selection for the Nankang-Ilan Expressway

The major concern of this study was to conduct geological investigation on the more viable candidate route between corridors 2 and 3, basing on results from the feasibility study, so as the final route can be opted from these two candidate routes. Included in this geological investigation works was remote-sensing and aerial studies along the extent of the candidate corridors. Geological investigation that checked the result of remote-sensing and aerial photo studies, and seismic survey, boring investigation with relevant tests will also be performed. All works performed will be such an extent that they covered an area that extended 2 km on either side from the central lines of the candidate corridors. A reconnaissance survey would be conducted in the region between Pinglin-Chiaohsi and Toucheng, the purpose was to establish a geological structural model of the area under consideration. Through this preliminary geological structural model, the geological structure and potential geological hazards would be mastered. Geological hazards to be accessed included portal stability, locations of major fault zones, and fractured zones, area under influence of hot springs, landslides, locations of high groundwater pressure. These are the major factors detrimental to safety of the tunnel. In addition, a preliminary study on applicability of TBM to the Hsuehshan Tunnel was also conducted. This took into consideration the manufacturing of the TBM, the type of TBM for use, the construction

procedure, engineering costs, and the possible hazards that the TBM might encounter, and the counter measures to adapt, and all were carefully evaluated.

## 4. Basic Design Study Stage

In keeping with progress of basic design study, geological investigation for the section between Pinglin and Toucheng was entrusted to Sinotech Engineering Consultants, Inc. Major task for geological investigation for this stage was detail engineering geological investigation along the alignment of route 3, the best route alignment. Emphasis of geological investigation lied in the tunnel alignment, road works, locations where major structures were situated, such as portals, and sites of vertical shafts. Further investigation concentrated on locations where the tunnel might cross a fault zone, as well as on the geologic engineering characteristics of the fault zone. In this geological investigation, the coverage extended to 600 m from either sides of the tunnel central line. Means of geological investigation included surficial investigation, and geological boring investigation. These were supplemented with detailed aerial photo interpretation, seismic refraction survey, and an adit driven at 150 m near the east portal for verification of colluvial deposits at the portal. Relevant tests performed included rock and soil tests to obtain parameters in-situ stresses, strength of rocks, as well as information on the deformation modulus and shear strength. Faults were inspected through trenching to evaluate their activity. The three vertical ventilation shafts were all investigated with full length bore holes that penetrated the entire designated depth to check the geological conditions and to conduct in-situ stress measurement in deep bore holes.

## 5. Supplementary Geological Investigation, Detailed Design Stage

Geological investigation for this stage constituted a follow up on the recommendations made on results of the detailed investigation performed during the previous study stage. Hence, investigation was mainly on sites where there might be potential geologic hazards, and sites where the geologic conditions remained to be unraveled, such as the group of normal faults at the eastern half of the tunnel alignment, the brittle but high-strength Szeleng quartzite, locations where the tunnel encounters fault zones, folded strata, or fractured rock masses,

groundwater surge, potential threat from hot spring, and portal stability. In addition, extra effort went into supplementary geological investigation to secure design parameters needed in the design of tunnel, slopes at the portals and tunnel foundations. Boring of ventilation shaft No. 3 was also included in geological investigation of this stage. During the preceding stage, this deep hole was bored down to 344.5 m when highly fractured quartzite refused to yield and forced a stoppage following loss of drill rods in the hole. In this stage, a new location, slightly shy of the old location was selected, and the hole was drilled and completed to depth of 490 m. Lugeon tests were conducted through out drilling to master the permeability of the rock mass.

#### 6. Construction Stage

Owing to methodology and technical limitations, there is always a certain degree of uncertainty when geological investigation is performed for the purpose of tunnel construction. In this stage, to further exert a strong grip on the geological conditions following tunnel excavation, some geological investigative works were planned in a hope that the risk could be effectively reduced. These investigative items included geological recording and mapping of the excavated surfaces, monitoring after excavation, in-situ stresses tests, laboratory tests, drilling of advance probe holes. These advance bore holes were to gain knowledge of the ground in advance prior to TBM excavation. This information will be basic reference in construction operation.

Aside from the more traditional means of geological investigation through field geological investigation, seismic investigation, and subsurface investigation through bore holes, systematic remote sensing and aerial investigation had also been applied. These were employed in order that a regional engineering geological scenario could be established. Furthermore, hydraulic fracturing method of investigating the in-situ stress conditions of the rock mass was also introduced to examine of the rock mass along the alignment of the Hsuehshan Tunnel, the data obtained were the basis in tunnel support analysis and design. In terms of total cost spent on geological investigation, NT\$ 100 million was spent on conducting the geological investigation in the design and planning stage, and NT\$ 85 million was budgeted for geological investigation during construction. The sum total of fund allocated for geological investigation was then roughly one percent

of the total engineering cost, this reflects a viable size of geological investigation that should be performed for any major tunnel construction project.

## 4. TUNNEL DESIGN CONCEPT

### 1. Tunnel Alignment Design

The route of the Hsuehshan tunnel was finalized following the feasibility study, route selection, and basic design stages. This alignment starts from the right bank of the Peishihhsi river at the town of Pinglin in the west, and enters into the Ilan plain in the east end. This alignment was 'fine-tuned' in the basic design stage to shorten the distance at best possible, as well as to adjust the curvature in such a way as to totally avoid any possible fatigue to the driver through sight fixation. Consideration was also given to the very strong glare at the east end as the tunnel opens towards the Pacific ocean. The safe sight distance also demanded that the exit portion of the tunnel should have a minimum curvature of 600 m in diameter. In gradient, the tunnel descends steadily from elevation 208 m at the west end at Pinglin, at a downhill rate of 1.25%, to elevation 44 m at Toucheng at the east end. Normal camber for the road surface in the tunnel is 2%; the maximum clearance is 3.4%.

### 2. Tunnel Layout

Main structures of the tunnel included two main tunnel tubes and a pilot tunnel. Ventilation is through an enhanced longitudinal system comprised of three sets of vertical shafts precisely assigned along the alignment of the tunnel. Each vertical shaft included one fresh air shaft and one exhaust air shaft. At the bottom of each set of vertical shafts there is an underground ventilation machine room. Between two adjacent ventilation machine rooms there is an interchange station that serves the purpose of diluting the polluted air and thus improves the quality of air in the tunnel. There are three interchange stations along the entire length of the tunnel. The fresh air shaft of the interchange station is spaced 50 m from the exhaust air interchange station. Table 3 presents the summary data of the vertical shafts. At a distance of 350 m along the entire length of the tunnel, there is a cross connection that joins the east-bound tube of the tunnel with the west-bound tube. There are 28 cross connections along the tunnel. For traffics, cross connections are assigned at distance of 1.4 km along the tunnel. The total number of traffic cross connection is eight, they serve the purpose of

Table 3. Inner Diameter and Depth of Ventilation Shafts

Vertical Ventilation Shaft	No. 1 Vertical Shaft		No. 2 Vertical Shaft		No. 3 Vertical Shaft	
	Fresh Air Shaft	Exhaust Air Shaft	Fresh Air Shaft	Exhaust Air Shaft	Fresh Air Shaft	Exhaust Air Shaft
Inner Diameter(m)	6.00	6.00	6.50	6.50	6.00	6.00
Depth(m)	480	501	238	249	438	459

evacuating vehicles in case of an emergency. Where each vehicle cross connection connects with the main tunnel, there is an emergency parking bay. During construction of the main tunnel, the exact locations of the cross connections may be adjusted according to the geological conditions at the site. Figure 2 presents a perspective view of the Hsuehshan tunnel and the ventilation shafts.

The distance between the two tubes of the two main tunnels, from center to center, is 60 m; this was determined in accordance with diameter of the tunnels, about 12 m for the Hsuehshan tunnel, and rock mechanical analytical results. The major concern was that after tunnel excavation, stress redistribution will occur, with the determined figure of 60 m, it was expected that convergence will achieve the initial stress conditions prior to tunnel excavation. At the portals, however, for reason of reduction on land use, this distance was reduced down to 42 m.

### 3. Layout of Tunnel Cross Section

Both the east-bound and the west-bound tubes of the main tunnel are one-direction-twin-lane design. Net clearance is 4.6 m, total width of the road surface is 7.6 m, it includes two traffic lanes, with each lane at width of 3.5 m; the road-shoulder is 0.3 m wide; the pedestrian walks at both sides are 1 m wide with net clearance of 2 m, allowing walking during emergency evacuation or maintenance work; the curb is 15 cm high allowing immediate door opening in case of emergency or when the vehicle stalled. Excavation cross sections of the tunnel varied with regard to the methods of excavation adopted. The cross sections of the portions of the tunnel excavated by TBM are circular in shape with an outer diameter of 11.8 m. Preliminary lining is mainly precast concrete segments. Cross sections for tunnel portions excavated through drill and blast are horse-shoe-shaped. Beneath the tarmac road

surface, there is an up-arched gallery cover; the space between the gallery cover and the invert segment is the invert gallery. Pipeline, wire and cable systems used for electric power supply, communication and fire-fighting are installed in this invert gallery. The invert gallery also doubles as conduit in transmission of fresh air to cross connections and underground ventilation machine rooms. The jet fans for tunnel ventilation are installed at the apex of the tunnel clearance. Traffic signs, notice boards and monitoring equipment are all set on the tunnel side walls.

Tunnel draining system consists of draining for polluted water from the road surface, and draining of groundwater. In the original design, road surface was elastic, in this design a treated asphalt sub-layer was laid on a sub-grade of crushed stone, the asphalt sub-layer was followed by an asphalt-concrete surface layer and an abrasive surface layer.

### 4. Safety Equipment

In the Hsuehshan tunnel the cross connections for traffics would allow traffics to go from one tube of the tunnel to the other tube in an emergency for evacuation. In an emergency, personnel in the tunnel could also use the vehicular cross connections to escape as well as evacuate to the Pilot Tunnel. The emergent parking bays provide emergent parking of stalled vehicles, or it will serve as emergent parking or for diverting traffic jam at the spot. Pedestrian cross connections will also provide passages for personnel in a vehicle to escape or evacuate to the site of emergency or for escape to the Pilot Tunnel. Fire-fighting hydrants are installed at spacing of 50 m. An emergency telephone is installed at distance of 175 m. Within the tunnel there are also equipment for safety control, illumination, ventilation, road and driving condition monitoring facilities, fire-fighting equipment and instruction and directions for emergency evacuation.

## 5. Pilot Tunnel

A pilot tunnel was excavated along the entire 12.9 km length of the Hsuehshan tunnel. This pilot tunnel is situated just below the center of the two main tubes. Its diameter is 4.88 m. The pilot tunnel was excavated before works on the main tunnel started, thus, the pilot tunnel will serve as a prospecting tunnel for geology along the length of the tunnel, and will also perform pre-draining of the tunnel. Any treatment to the main tunnel could be performed through the pilot tunnel, and thus would lower the risk in subsequent construction of the main tunnel. The pilot tunnel would serve also as supplement transportation route. Following completion of the Hsuehshan main tunnel the pilot tunnel would have road surface 3.0 m wide with net clearance of 2.9 m, single way traffic with parking bays spaced at 350 m. Stairs are installed to facilitate connection to the pedestrian cross connections and the vehicular cross connections. However, the major role is in providing additional emergency access for personnel and traffics, ambulances to and from operation and ventilation rooms, independent of the main tunnel, to perform maintenance and operation jobs. Figure 3 presents the relationship between the pilot tunnel and the main tunnel.

## 6. Support Design

Tunnel excavation operation methods vary in accordance with the cross section of the tunnel. When a tunnel boring machine (TBM) is used to perform excavation, the cross section is circular in shape; whereas when the tunnel is excavated through drill and blasting, the cross section of the tunnel is horse-shoe-shaped. Furthermore, it is also a well known fact that tunnel support is intimately related to the excavation method adopted. In a tunnel section that is excavated by TBM, reinforced concrete pre-cast segments are the only means of support, simply because of the fact that TBM excavates in a very rapid advance rate. Once the geologic weak zone or the fault brecciated zone is treated, regardless of the rock mass quality, only one type of support is used, just for reason of simplicity. In drill and blast excavation, in contrast, excavation support can use rock bolts, shotcrete, and steel braces, etc., depending on the characteristic of rock mass being excavated. In both of these excavation methods cast-at-site concrete is used as inner lining. Waterproof membrane is installed between the inner

and the outer linings, this will guarantee that the tunnel is free of groundwater intrusion, and the tunnel will remain dry.

Support design for the drill and blast section is through use of empirical calculation. The rock mass is divided into six types, following the geotechnical parameters taken into consideration by Bieniawski in his RMR system and Barton's Q-System. Consequently, six types of corresponding tunnel supports are selected, as shown in Figure 4. Where the tunnels intersect, or where there is a depressed notch, tunnel support was still designed according to the above-mentioned criteria, however, rock mass rating or classification is then given an appropriate reduction in keeping with evaluated situation. Furthermore, strengthening is also conducted for safety reasons. Finally, as a re-checking on the safety of supporting, numerical back calculation is performed for analysis and evaluation. All cross connections, workrooms, enlarged excavation, section, recesses for electrical purposes, and vertical shafts are excavated through drill and blast method with semi-rigid supports such as shotcrete, wire mesh, rock bolts, and steel sets. Selection on actual supporting for use depends on geological conditions and construction progress. When needed, forepoling, steel laggings, and temporary shotcrete and rock bolts for excavation face can be applied to strengthen the ground and ensure safety.

In section excavated by TBM, pre-cast reinforced concrete segments that were specially designed for TBM supporting purposes are used as support. Segments for the pilot tunnel measure 1.2 m wide and 18 cm thick, ribbed steel bars are used. Four segments constituted a full ring. For the main tunnel, each supporting ring is constituted of six segments; each segment is 1.5 m wide, 35 cm thick. It is estimated that the daily need for segments is about 312 slabs per day, the required quantity is quite demanding. To meet this requirement, steel bar cages that can be assembled through automatic welding are used in concrete segment manufacturing. For consideration on speeding up concrete segment production and cutting down costs, high tensile strength wire with  $f_y=5,000$  kg/cm<sup>2</sup> are used in conjunction with bar cages.

## 5. TUNNEL CONSTRUCTION METHOD EVALUATION

### 1. Excavation Method Evaluation

The 12.9 km long Hsuehshan tunnel is the critical path projects in the Taipei-Ilan expressway



construction project. Detailed, exhaustive studies on the construction methods for this long tunnel had been performed in every study stages. World famous experts in this field had been consulted. After considering the geological background, the environment, cost and construction duration requirements, the recommendation suggested that TBM construction be the method adopted. During construction, well-known experts and experienced consulting firms also had been invited to study and evaluate on the adopted construction. Selecting TBM construction is considered the appropriate choice.

#### (1) Feasibility Study

The consulting firm for the feasibility study tended to favor construction by means of drill and blast method.

#### (2) Route Selection Stage

During this study stage, feasibility studies on the various layout combinations for the Pilot Tunnel and the main tunnel, and whether the drill and blast method of construction or by TBM had been performed. It was recommended that the Pilot Tunnel could be bored by TBM. Method of construction of the main tunnel should be upheld temporarily, and awaits geological information to be amassed. The construction method for the main tunnel could then be decided.

#### (3) First Board Meeting of Consultants

Members of the 1st board of consultants made site inspection and examined geological background information analyzed construction progress, costs and technique. In their evaluation report, the board of consultants considered it feasible to construct the Hsuehshan tunnel using TBM. The board of consultants also placed emphasis on the importance of construction experience and construction management. During the pursuant design and planning processes, similar board meetings of consultants were held to verify the consulting firm's recommended construction methods. Board meetings of consultants had also been held during construction stage for consultation on construction technique and construction management. Total of seven board meetings had been held. The use of TBM in construction of the Hsuehshan Tunnel had been a correct choice constitutes the unanimous comment through out all seven board meetings.

#### (4) Basic Design Stage

The consulting firm for the basic design study performed a detailed comparison on the conventional drill and blast method of tunnel construction and tunnel construction using TBM. The comparison result indicated that the use of TBM in the Hsuehshan tunnel is superior to construction by drill and blast. TBM construction was thus recommended.

#### (5) Detailed Design Stage

In this stage, all recommended construction methods were synthesized for evaluation, and the construction method selected, engineering design then commenced. To cope with the possibility that a number of faults would be encountered, for avoiding rock fall and miry ground that might cause injury to workers and machine alike, the double shield type of TBM used in excavating the channel tunnel was selected for construction.

In a retrospective synthesis, major elements used in evaluating and selecting the construction method lied in elements concerning geological structures, the length of the tunnel and cross section, construction progress, engineering costs, safety, labor requirement, environment protection, and improvement of technology. Following these points of consideration, the pros and cons of construction methods were assessed first based on these elements. The relevant inferiority or superiority was then assessed, and a better construction method realized. The tunnel cuts through the Hsuehshan mountain range, the cap rock is very thick, further, it crosses the Taipei water reservation and protection area there is no addition land to afford setting up additional work faces aside from the work areas at both portals. An additional work face at the middle of the tunnel would mean a work adit 2.0 km long with longitudinal gradient of 8%; mucking and ventilation are problematic. It was also anticipated that during construction of the tunnel, other major construction projects would be in progress, these are the second freeway, the Metro System of Taipei, and transbasin diversion project for water resources, the labor resources would be a real problem. A drill and blast construction method would be in the order of 20 years to complete. Following these evaluations, construction by TBM seemed to hold an edge over conventional drill and blast construction method.

Employing mechanized construction method can shorten work period by a lot, and is the world trend in the field of tunnel construction. At the time of method appraisal, there was an outlook that in the major construction projects pending, there are a number of long tunnels awaiting construction operation. Due to this aspect, a special clause was entered into the contract of the Hsuehshan Tunnel, specifying that the contractor would have the obligation to perform technology transfer to personnel in Taiwan. This will achieve the aim that the technology of tunnelling in Taiwan would be improved through construction to this tunnel by TBM.

Upon completion of synthesized evaluation during the planning stage, a decision was reached: the main tunnel would be excavated by two 11.7 m diameter TBM, and the pilot tunnel by one TBM 4.8 m in diameter. During manufacturing of the TBM, one year at the fastest, tunnel construction at the east end from Toucheng to Pinglin by drill and blast method, to go past the section of inferior geological conditions, thus reducing geological hazards. Figure 5 shows a scene during advancing of TBM in the main tunnel of Hsuehshan tunnel.

## 2. Evaluation on Vertical Shaft Construction Methods

Vertical ventilation shafts along the Hsuehshan tunnel may be as deep as over 400 m. Geological investigation revealed that a number of fractured zones occurred in the depth, and groundwater is bountiful. Thus, an evaluation on the construction methods for these vertical shafts was conducted. The conventional construction for vertical shaft excavation is the sinking method that excavation starts from the ground surface and descends layer by layer down. Occasion deep shafts had been constructed by the raise boring method that employed a pilot shaft bored by raise borer. The raise boring vertical shaft construction method is illustrated in Figure 6.

The conventional "sinking method" of vertical shaft construction is started from the top on the ground surface down. In this method, mucking is by buckets hoisted up for disposal. Once large quantity of groundwater ingress occurred there is no possible chance of retreating from the work site. In the raise boring method, construction would await completion of the main tunnel, and then a reamer would bore in an upward direction for a

mucking hole. When the muck hole is completed, drill and blast construction will expand the hole to designed cross section size. At this time, the tunnel below had been completed; mucks from excavation can fall on to the invert of the horizontal tunnel for transporting out of the tunnel for disposal. Groundwater is naturally drained by gravity through pilot hole for disposal. The whole process is fast and straight forward.

Ventilation shaft construction for the Hsuehshan tunnel took into consideration these two methods, and appraised the pros and cons of these methods as well as their characteristics, with due reference to geological conditions. The conclusion was that raise boring has advantage over the conventional sinking method. However, when consideration was also given to the expertise of the construction contractor, the actual geological conditions after excavation, and the fact the arrival of the tunnel to the exact site of shaft boring is still pending, therefore, it was decided that selecting a construction method for vertical shaft excavation would be the contractor's responsibility.

## 6. TENDER STRATEGY

The Taipei-Ilan Expressway project began with planning and design studies in July 1989. It was originally slated to be open for traffic at the end of 1999. That would mean completion in ten and half years. The main project was divided into 5 civil engineering lots, in addition, there are E/M, architecture and traffic control lots. Among which, contract lot IV was the main Hsuehshan tunnel and road works, Toucheng section, and Lot V, the pilot tunnel. In view of the fact that the project is huge and exceptionally difficult, TANEED concentrated consideration on maximum overall interest in deciding tendered strategy. Whether an international tender, or direct negotiation with local contractor RSEA would achieve the goal on achieving best benefit to the nation. Under consideration to avail of an opportunity to build an chance on the job, and gaining transfer of technology, as well as achieving completion project within planned schedule, TANEED recommended to PCC, Executive Yuan, direct negotiation with RSEA.

The Taipei-Ilan expressway was an important national project. At time of contracting, RSEA was the most technically manpowered organization, with complete line of rich engineering experiences, and fruitful practical record, RSEA was the best contractor in Taiwan to undertake the task. And also in view of the urgency

of national construction and development, as well as achieving scheduled completion, quality and national honor, local construction market condition and full utilization of national resources, it was then decided to grant the contract to RSEA. This was deemed the best-there-could-be in terms of meeting national interest.

### **7. INFLUENCE ON SIMILAR ENGINEERING PROJECTS IN THE FUTURE**

The Hsuehshan tunnel plays a very important role in the field of civil engineering. The application of geotechnical technology during planning, design and construction stages is the essential issues. During the planning and design stages, mastering geological understanding is a condition that predicts whether the project will succeed or not. It also dictates if the project could be controlled within the budget as well as the time schedule.

Concerning the drill and blast section, once main tunnel excavation started, conspicuous influences are shown in rock mass around the pilot tunnel and on the tunnel lining. This is a clear manifestation that for multi-tunnel construction, simultaneous excavation in several tunnels will exert a strong interaction. This interactive behavior should be a phenomenon that the designer as well as the constructor should attempt to fully understand, and endeavor to seek an effective solution.

Regarding TBM constructed portion of the tunnel. It might be that due to limitation imposed by current technology, geological investigation would not achieve the goal of total mastering of the geological information desired, especially in groundwater quantity, its pressure and source that matter much the failure or success of a project. Nevertheless, through detailed planning, geological investigation conducted during planning, design, and construction stages, when supplemented by geophysical exploration, would still yield a realistic picture of the conditions of the ground ahead of the excavation site. This is helpful for drafting countermeasures in case of prospective hazards ahead, and minimizes the construction risks. For almost all long tunnel projects, the construction period is frequently an issue that draws much criticism, and also much focus of engineering dispute and claims. For these reasons, if the engineer is able to exercise his professionalism, experience, and conscience in drafting up a reasonable engineering schedule time table, then a clear and definitive first step in returning leadership to

the hands of the proper personnel would have been trot on firm ground.

Future prospect in tunnelling in Taiwan shows that the size, length and number of tunnels will all exceed the present expectation. What is more, most, if not all, of these tunnels would cut through much grounds with difficult geological conditions hereto not seen or heard of before that the engineers would be facing new challenge every day of his working career. The east coast expressway, the central cross island expressway, and the southern cross island expressway, all under active planning, are three examples. All of these prospective areas are precipitous and rugged, virtually inaccessible. The thickest cap rock could easily be in excess of 1,000 m or even 1,700 m. Along the alignments, hot springs, high geothermal gradients and highly variable geological conditions are the normal settings. To say that future tunnelling is a challenging is an understatement that would blur the true picture of the future.

The Hsuehshan pilot tunnel is constructed by the first TBM introduced into this country for hard rock excavation. Although over ten years it took from its launching to breaking through, and we seemed not to see too fantastic result it offers, nonetheless the launching of this first TBM launched a good number of other TBM used in Taiwan. The successful Taiwan Power Hsinwuchieh Project is not just one of the cases, but one that broke the records when it achieved an advance rate of 400 m.

The Taipei-Ilan expressway project creates a modern expressway in the mountains. For a long time to come, this is a reference to many more similar projects in the future. It serves also as a weathercock in future planning and construction of the circum-island highway network, the central cross island expressway, and the southern cross Island expressway. Policy and execution method used in the past for this project will sure serve as valuable reference for these new, future projects.

### **8. CONCLUDING REMARKS**

The Taipei-Ilan expressway engineering project is both complicated and difficult. It includes expertise in various fields of engineering. From the early stages of project planning professional construction management system was applied to enhance all operations, schedule-controlled, man-power saving and to raise production quality. Throughout the over ten years of design and

planning of the Hsuehshan tunnel project, world stand technology and methodology were used. The accumulated experience and technology in geological investigation, design and planning programs, either by the government or civilian consulting firms, were immense and far beyond description. However, as we stand and face the more difficult projects of long tunnels set beneath excessively thick cap rocks in the near future, and intense competition from WTO, we fellows of Taiwan tunnelling venture to say that there are still rooms for improvement in development of soft and hard wares in tunnel engineering. This paper serves both as a short note of praise and short note to the glorious moment celebrating concluding through of the Hsuehsham tunnel, the very first tunnel in Taiwan designed for, and constructed by tunnel boring machine, TBM.

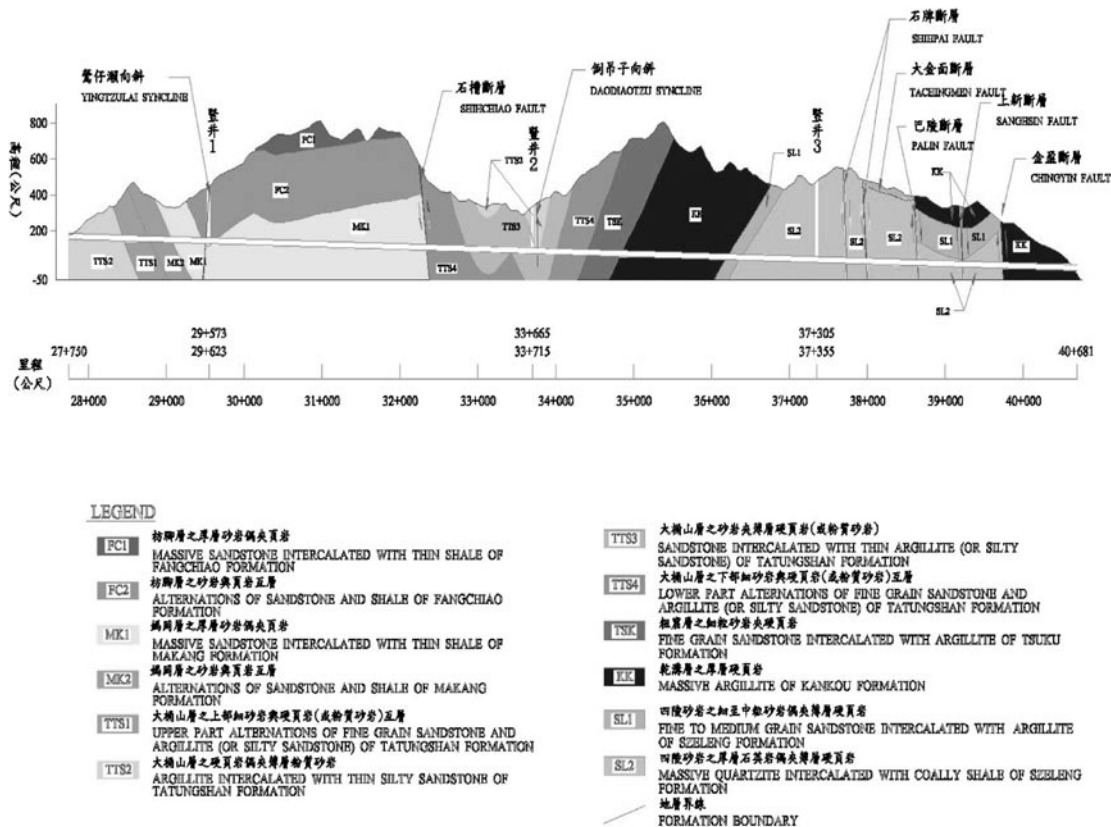


Figure 1 Geological Profile of Hsuehshan Tunnel



Figure 2 Ventilation System of Hsuehshan Tunnel

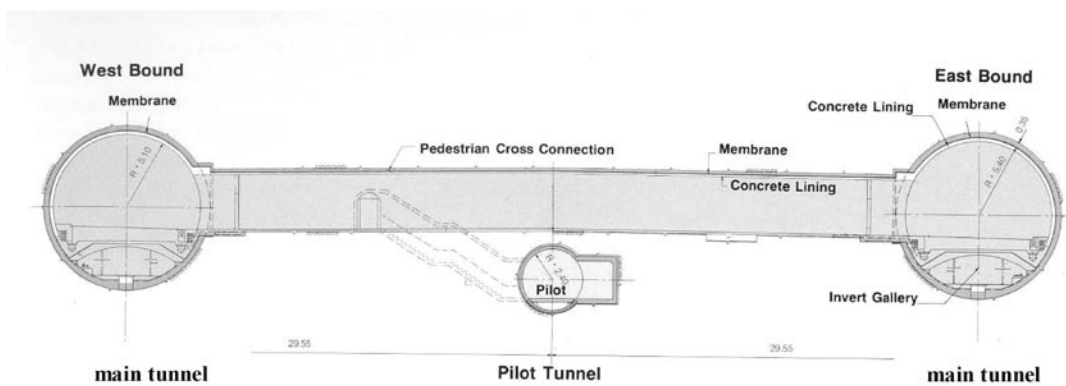
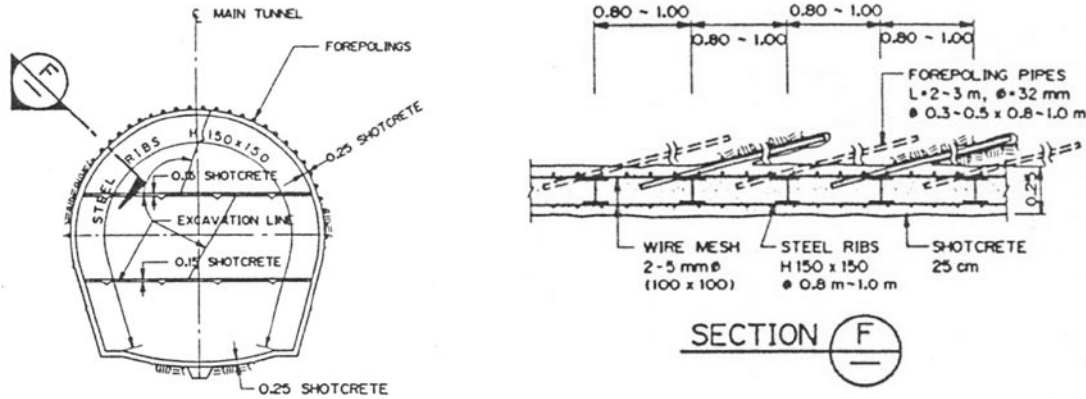


Figure 3 The Relationship of Hsuehshan Tunnel and Pilot Tunnel



ITEM	DESCRIPTION	AMOUNT / m
EXCAVATION	5 STEPS, IF REQUIRED	142.1 m <sup>3</sup>
ADVANCE	0.8 ~ 1.0 m	—
SHOTCRETE	C & W : 25 cm	32.7 m <sup>2</sup>
	F & B : 15 CM, IF REQUIRED	—
WIRE MESH	C, W, I : 2 - 5 mm $\phi$ (100 x 100)	85.0 m <sup>2</sup>
	F & B : 1 - 5 mm $\phi$ (100 x 100) IF REQUIRED	—
STEEL RIBS	H 150 x 150 mm, $\phi$ 0.8 ~ 1.0 m	1144 kg
FOREPOLINGS	C : PIPES, L = 2 ~ 3 m, $\phi = 32$ mm $\phi = 0.3 ~ 0.5 \times 0.8 ~ 1.0$ m	72.6 m
INVERT	SHOTCRETE : 25 cm CLOSE INVERT WITHIN 15 DAYS, OR DIRECTED BY THE ENGINEER	9.8 m <sup>2</sup>
PROTECTION OF FACE	SHOTCRETE 5 ~ 10 cm LOCALLY, IF REQUIRED	—

## CLASS VI

Figure 4 Hsuehshan Tunnel D & B Method Typical Ground Support (Class VI)

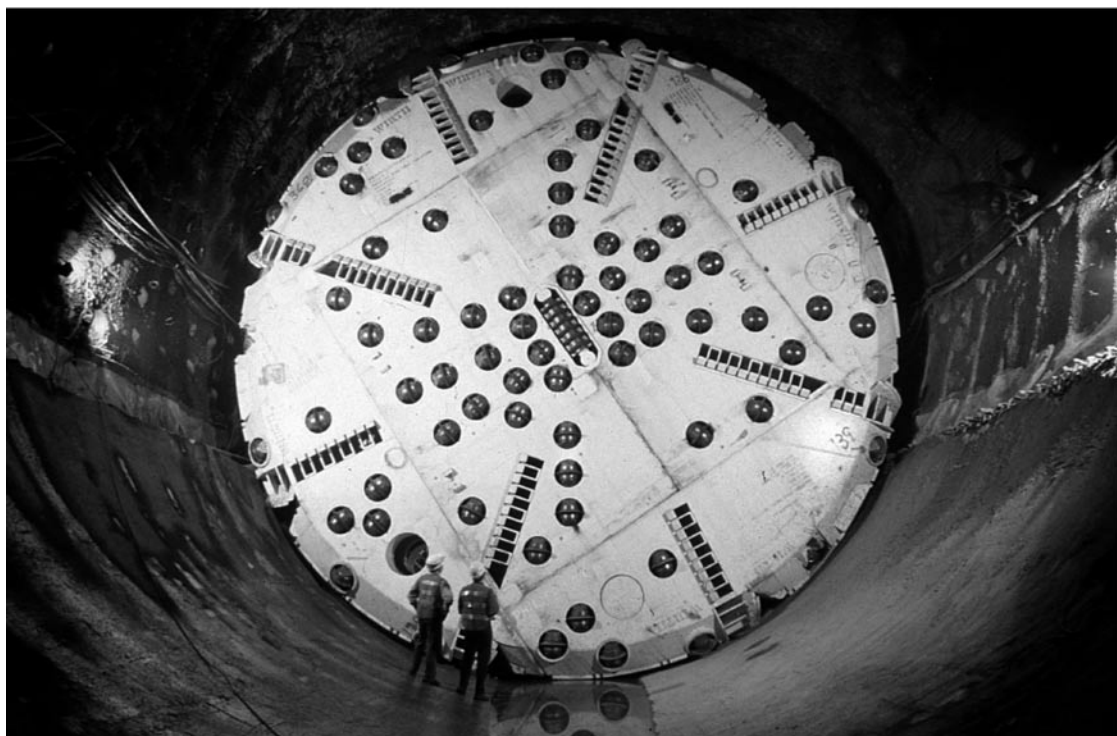


Figure 5 Hsuehshan Main Tunnel TBM Launching

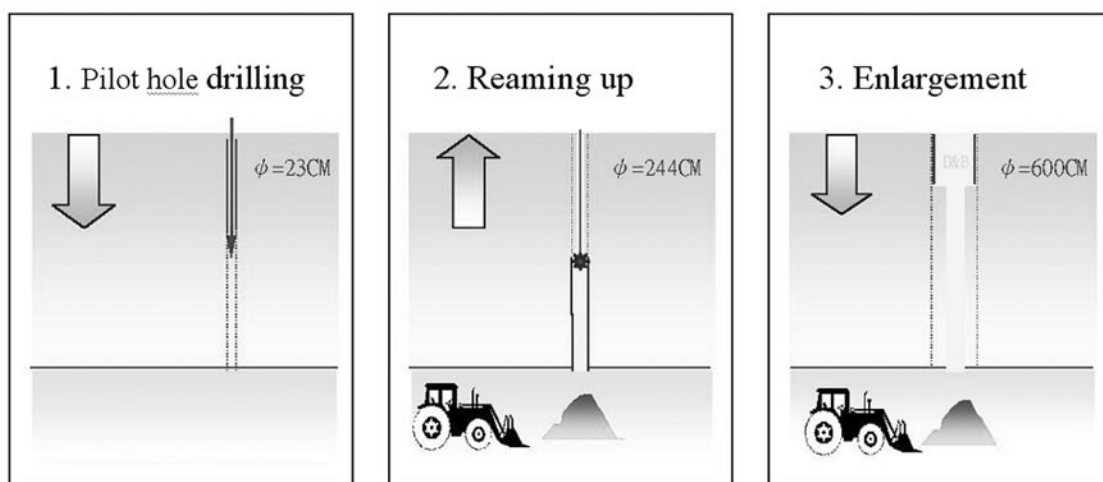


Figure 6 Procedures of Raise Boring Method for Shaft Excavation

