APPLICATIONS OF THREE DIMENSIONAL GEOLOGICALAL MODELS TO THE CONSTRUCTION OF THE HSUEHSHAN TUNNEL

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ABSTRACT

The geological data at the excavation faces were collected on a routine basis during the construction of the Hsuehshan Tunnel. The computer module GeoMAP was developed to retrieve appropriate data from the data pool for making required geological maps or predicting unknown geological conditions ahead. GeoMAP can automatically produce the tunnel unrolled geological map and 3D geological block diagram in a tunnel section. The pole densities of major weak planes can be analyzed and used to survey the existence of potentially unstable key blocks, perform stability analysis, and plan the rock bolt design. All the results can be exported into a VRML97 format, and displayed in the computer as in a virtual reality world. Example cases are shown in this paper.

Keyword : geological data pool, 3D geological block, virtual reality

INTRODUCTION

One purpose in constructing the Hsuehshan Pilot tunnel was to investigate and foresee the geological conditions ahead of the main tunnel. Therefore, in parallel with some horizontal prospecting drilling, the geological data at the excavation faces were collected round by round during the tunnel construction stage. Normally, these data were mainly prepared for routine reporting, and geological interpretations, if required, were made periodically when tunnel length recorded accumulated to certain extent.

The interpretation works including the production of the tunnel unrolled geological map, constructing the geological map of main tunnel, and making statistics of pole densities of major weak planes in order to locate unstable wedges. All these works help the site geologists to foresee inferior geological conditions ahead of the working face and to some extent to ensure the tunnel safety.

It was found that after several years of routine works, large amounts of data were accumulated and they became very difficult to handle. Therefore an automatic data managing system was called for to solve the problem effectively and would be helpful to store the data for future utilization.

The plan was to digitize the collected geological data and then store the data in an electronic data pool for further processing. It was desirable to have a system that could automatically produce the tunnel unrolled geological map and 3D geological block diagram only using geological data collected from the tunnel excavation face. The pole densities of major weak planes can also be analyzed and used to survey the existence of potentially unstable key blocks, perform stability analysis, and plan the rock bolt design. In this paper the author wishes to introduce a computer system which contains many functional modules and was developed to retrieve appropriate data from the above-mentioned data pool for making required geological maps or predicting unknown geological conditions ahead. Example cases are presented in this paper.

COLLECTION OF GEOLOGICAL DATA

Data Collection

The site geologists recorded the geological data from the excavation faces immediately after they were exposed. Data were collected on a daily basis during the construction of the Hsuehshan Tunnel. In the sections where the drilling and blasting method was used, the data collection was easy to make and geological data were clear and easy to interpret. However where the TBM was used, this work could not be done with high quality since the shield machine could not provide enough room for observation. The processes of data

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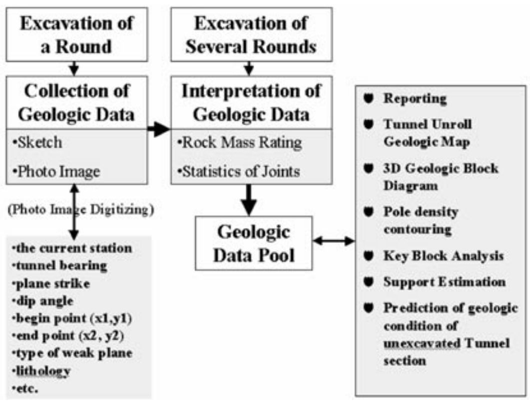


Fig.1 Process for Data Collection and Reporting

collection and the reporting are shown in Fig.1 and Fig.2.

The data as recorded in Fig.2 are mainly those of the location and orientation of weak planes within a tunnel advancing face at a station, and contain detailed descriptions of joint condition of these planes. This information is very important in characterizing the rock mass condition or deciding the rock mass rating and corresponding support requirements. At the right hand side of Fig.2 are the hand-drawings of the geological outcrop at the face. It is always beneficial to have a clear scenario of the tunnel geological conditions for engineering judgment, but sometimes the quality of the sketches depends too much on the geologists who drew them. Taking photos of a tunnel excavation face is regarded as a preferable alternative in case the visualization conditions are good.

DATA PROCESSIN AND DISPLAY

Tunnel Unrolled Geological Map By TUNLOG

In the early years of the Hsuehshan Tunnel excavation, reconstruction of the tunnel unrolled geological map was carried out after every 50 meters of excavation and the results were compiled in the annual report of geological investigation work of the pilot tunnel using TUNLOG. TUNLOG is a program developed by Sinotech Engineering Consultants, Inc. (Lok 1993). The program uses dBase IV for data input and editing, Microsoft

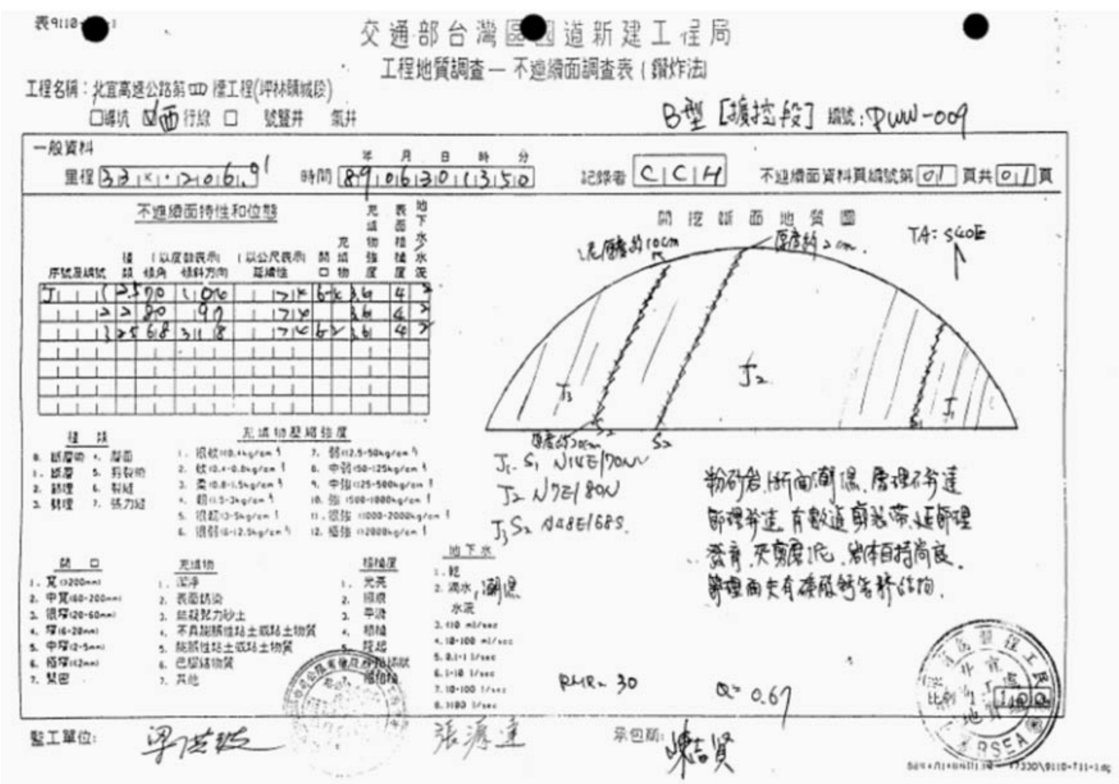


Fig.2 Reporting of Geological Data for a Round

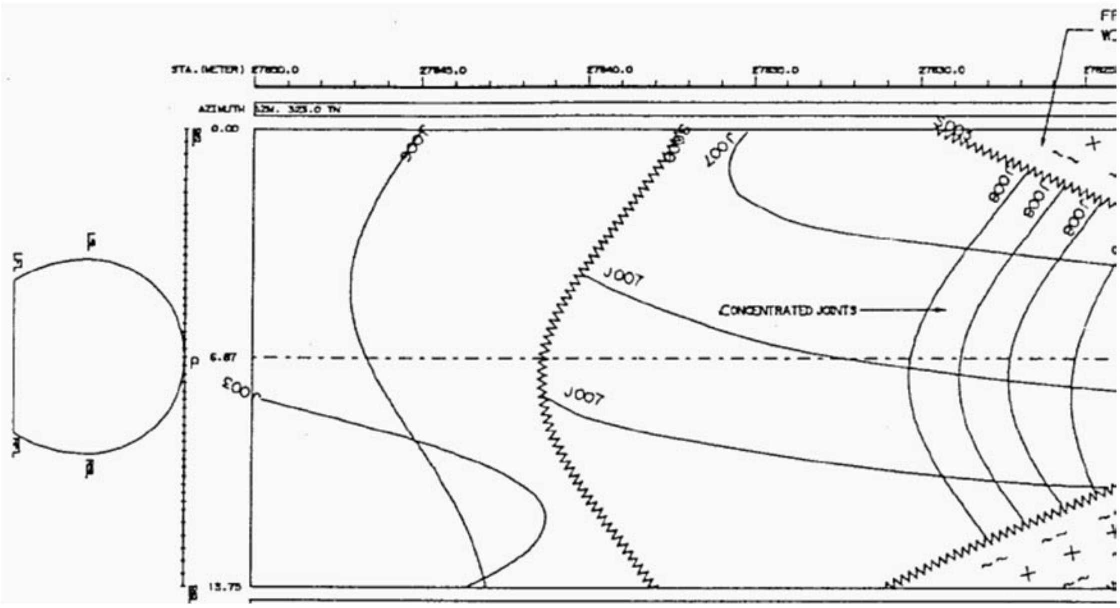


Fig.3 Reporting of Geological Data within a Certain Length Using TUNLOG

Fortran to process data, and Micro Station to do the graphic output. It was found to be too inconvenient to use and abandoned later. Fig.3 shows the typical results of the tunnel unrolled geological map produced by TUNLOG.

Due to the fast development of computer technology, a high performance PC can be used and colorful displays of 3-D computer graphics are much easier to use in the data processing of tunneling. The author proposes a new, fully Microsoft windows compatible program to replace the TUNLOG for the site engineer in handling the geological data. A computer program using the Visual Basic (version 6.0) was developed and named GeoMap. GeoMap was mainly based ideas that used the geological data and photo images collected at the excavation face, and associated data restored by digitizing the major discontinuities from images and making geological interpretations. Keeping the photo images of each excavation face is tedious but also very useful when enhanced geological data interpretations are called for in a later time. In the current version, GeoMap also provides many tools for reconstruction of the tunnel unrolled geological map or 3D geological block diagram, finding key blocks, simulating tunnel geological conditions in a virtual reality world, etc.

Photo Image Digitizing

Fig. 4(a) shows the photo image of a tunnel excavation face. Fig. 4(b) shows the comparable results after digitizing and data interpretation. The acquired data are stored in a data pool using the *.mdb format of Microsoft Access database program. For each weak plane, the data contains the tunnel station, tunnel bearing, plane strike and dip angle, begin point (x1, y1) and end point (x2, y2) of discontinuity trace, type of discontinuity, lithology etc. It is noted that the persistency of a bedding plane is continuous while a joint is limited. In the data processing, the bedding plane or the joint should be identified to make the results more sophisticated. The scale effect of joint at a plane outcrop can be considered using the method proposed by Yu (1999).

Tunnel Unrolled Geological Map

With collected data for one round or many rounds as a whole, GeoMap can import the associated weak plane data stored in a mdb file and then create a tunnel unrolled geological map automatically. Fig.5 shows the results of an example case.

3D Geological Block Diagram

3-D geological block diagrams can be particularly helpful in communicating geological information to

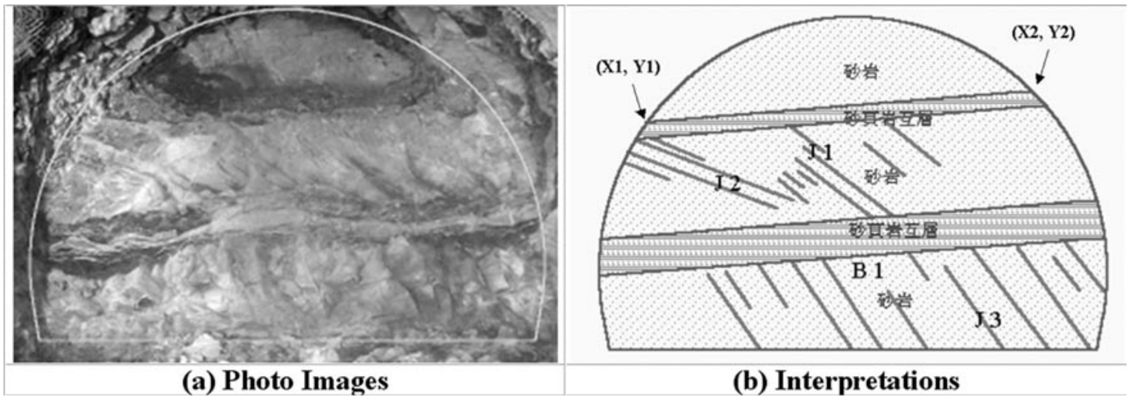


Fig.4 Geological Data Interpretation for Each Round

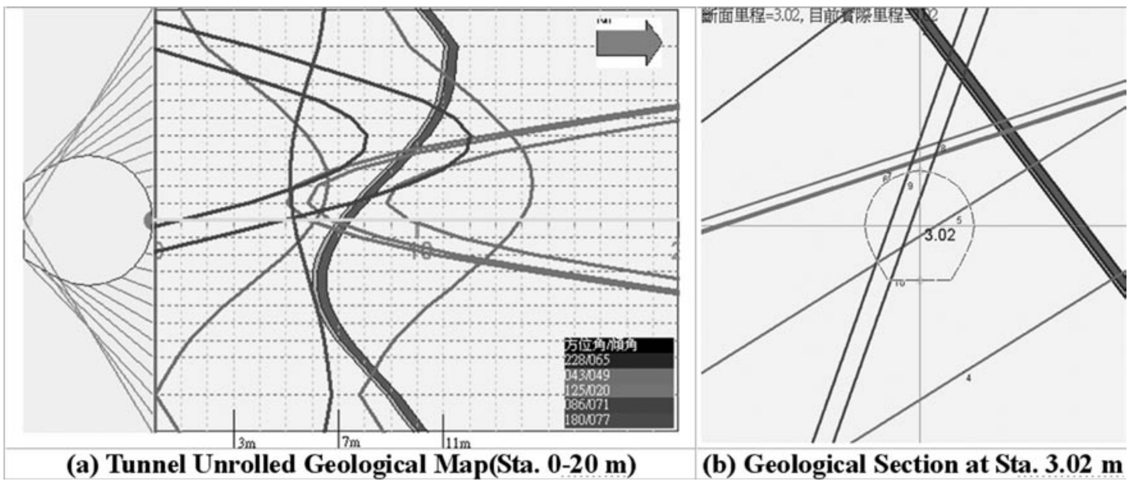


Fig.5 Tunnel Unrolled Geological Map Constructed by GeoMAP

non- geologists. Since the data collected are associated with a 3-D spatial nature, they can be translated to show the geological block diagram surrounding the tunnel area. Fig. 6 illustrates the 3-D block diagram of an example case.

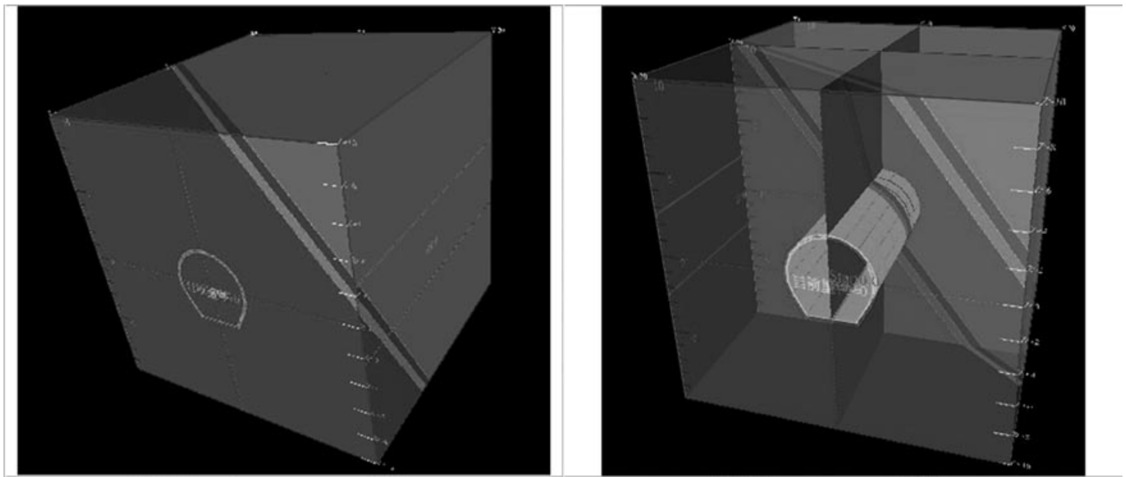
Virtual Reality (VR) Visioning

The output data associated with the tunnel unrolled geological map and the 3D geological block diagram can all be translated to the Virtual Reality Modeling Language (VRML 2 or VRML 97) format (Ames, et. al, 1997). With the aid of an installed VR software plug-in (i.e. Cosmo Player) and a web browser anyone with a qualified PC can see and explore the tunnel image in 3D manner. This can be very convenient when remote communication is necessary. Fig. 7 shows the tunnel in a VR world of an example case.

KEYBLOCK ANALYSIS

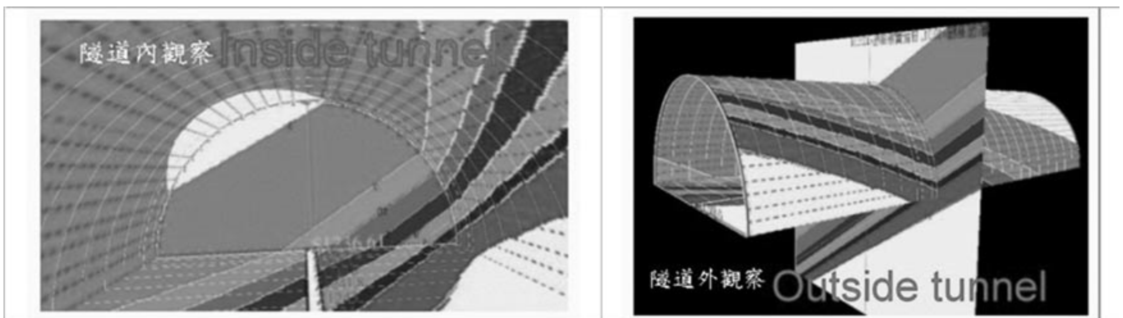
The failure of tunnel sections by progressive cave-ins induced by unstable key blocks is quite common. Fig. 8 shows how an example case occurred in a rock tunnel recently constructed in Northern Taiwan. To prevent this kind of failure, careful reviews of geological data, especially those of preferred orientation of major rock discontinuities are required. The pole densities of major weak planes can be analyzed and used to survey the existence of potentially unstable key blocks, perform stability analysis, and plan the rock bolt design.

Key block theory was proposed by Goodman & Shi (1985). In the current version of GeoMAP, the functions of searching the key block and performing stability analysis of the key block are incorporated. The input data of the analysis is connected to the geological data pool mentioned above and quick data outputs can be obtained



(a) Non-transparent View (b) Transparent View

Fig.6 3-D Geological Block Diagram by GeoMAP



(a) Inside Tunnel (b) Outside Tunnel

Fig.7 Tunnel in a VR World by GeoMAP

such as those shown in Fig. 9. The output data contain the 3-D shapes and sliding vectors of the potential key blocks, and these are useful data in determining the required reinforcements to restrict the sliding of an unstable key block within an acceptable factor of safety.

APPLICATIONS

Pilot tunnel Data Input

In the western portal of the Hsuehshan Tunnel, the excavation of the pilot tunnel was carried out by the drilling and blasting method. Here, the geological data obtained from five consecutive excavation rounds located at station 27k+812.0, 27k+813.5, 27k+815.0, 27k+816.5 and 27k+818.0 respectively are quoted as example cases. The sketched geological data in the report sheets by the site geologist are shown in Fig. 10. Sometimes it was possible that in digitizing the geological data, bad data were noticed which would normally show inconsistent results between the input and the output trace line of rock discontinuities, as observed in sta. 27k+815 in Fig. 10(c). In such circumstances, calibration work must be done to ensure the data were input in correctly.

Prediction of Tunnel Conditions ahead of Main Tunnel

Some data attributes of the associated weak planes are shown in Table 1. Altogether there are 8 bedding planes picked out as input from the above five faces. Only the joints at station 27k+812.0 are outlined in the table. There are eight joints grouped into two sets.

The steps of reconstructing the geological model using GeoMAP are summarized as follows:

* Input the shape of tunnel : This can be done by importing and then digitizing a tunnel sectional

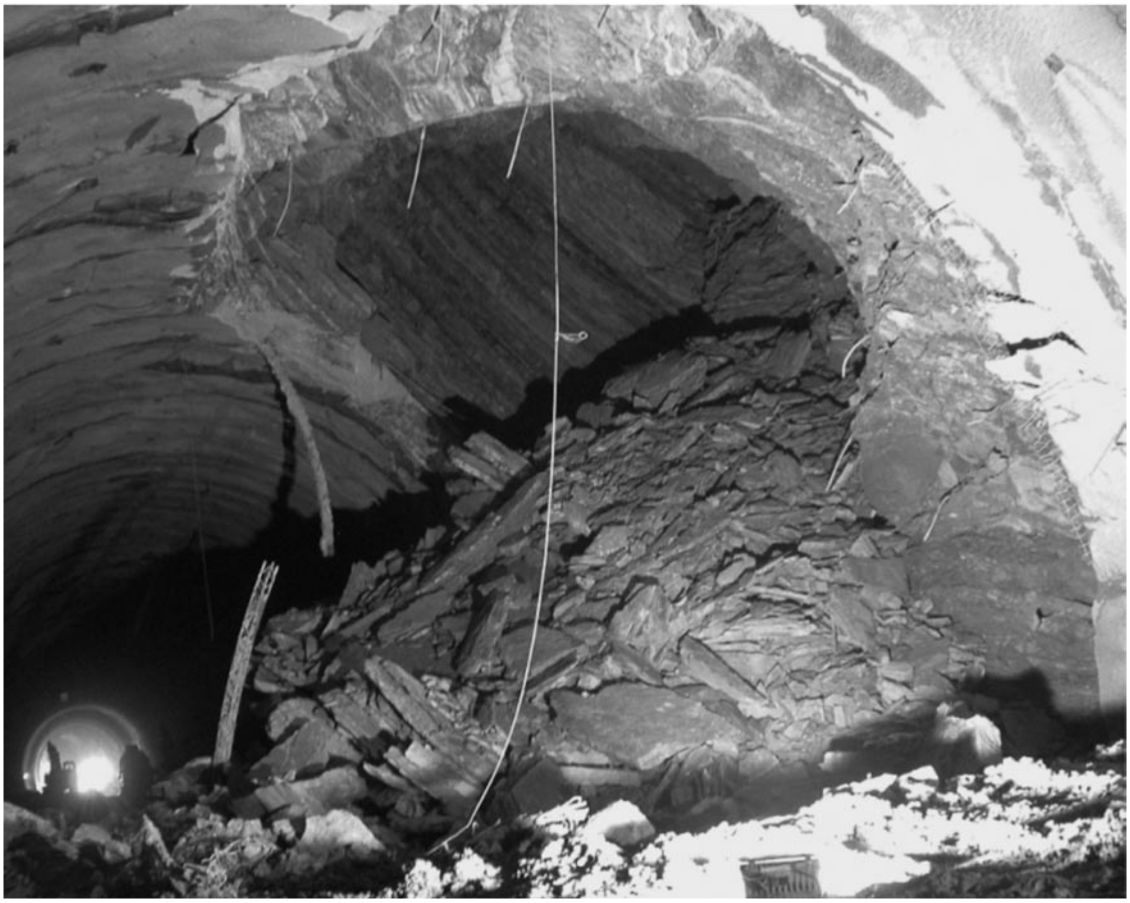


Fig. 8 Failure of Tunnel Section Induced by Unstable Key Block

image files (*.bmp), or opening a formatted data set. Multiple cross sections are allowed as those in the Hsuehshan Tunnel where there were 3 tunnels in parallel.

* Specify the tunnel bearing angle (0-360).
* Input weak plane locations (x1, y1)-(x2, y2) : this can be done by digitizing an image derived from sketch or photo at a given station (z).
* Input attitude and discontinuity type for each weak plane.
* Output the tunnel unrolled geological map.
* Display the tunnel in 3-D VR.
* Perform key block analysis if required.

The output of the tunnel unrolled geological map for the example case, which shows the bedding planes only, is shown in Fig.11. Intervals between each bedding plane are painted with preset colors to exhibit lithological change. Fig.12 shows the identical plot as Fig.11 when the joints are present. It can be noted that the joint traces are plotted with 100 % continuity here and grouped into three sets by different colors. In fact, the spatial distribution of joints is difficult to show in a 3-D world because of its finite dimensions in a plane and the real shape is irregular in nature. Fig.13 shows the statistical distribution of three sets of joints in a plane for the current case taking into account the scale effect using the technique proposed by Yu (1999). In GeoMAP, the plotting of each joint plane is simulated by a circular plane with a certain radius.

The ultimate application of GeoMAP in the Hsuehshan Tunnel project is to predict the geological condition ahead of the main tunnel using the data collected in the pilot tunnel. In Fig. 14 the 3-D tunnel view with geological data in a VR world is presented where the pilot tunnel is in the middle, and the Eastbound main tunnel is on the left hand side while the Westbound main tunnel is on the right

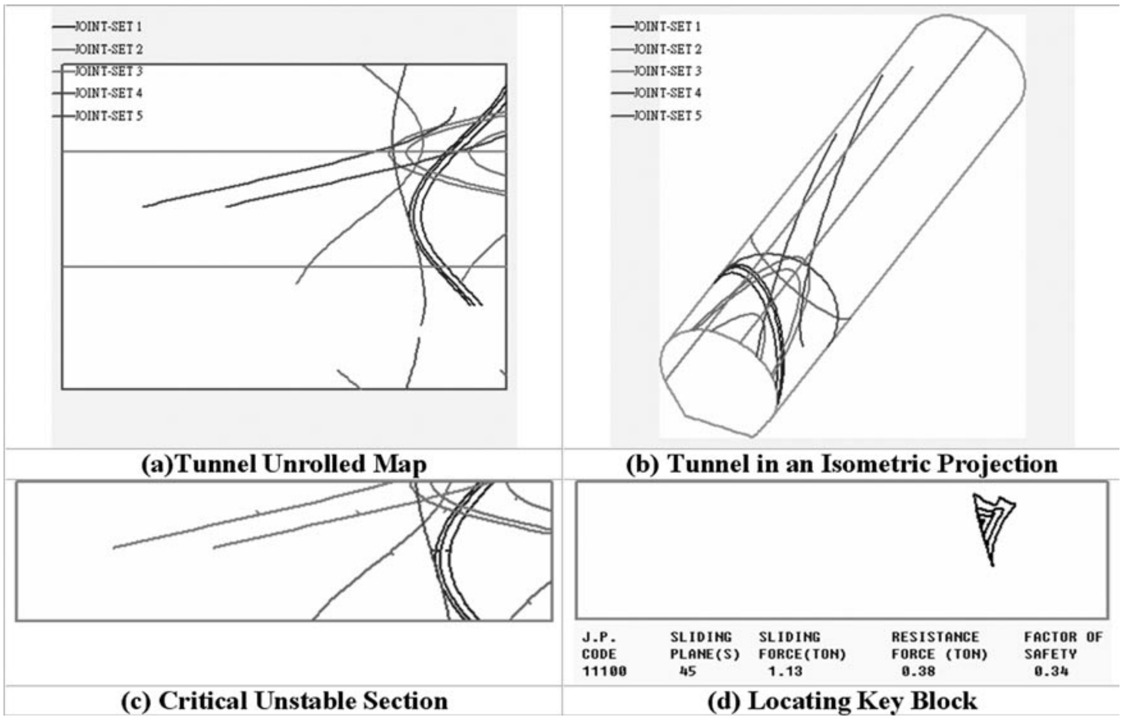


Fig. 9 Key Block Analysis in GeoMAP

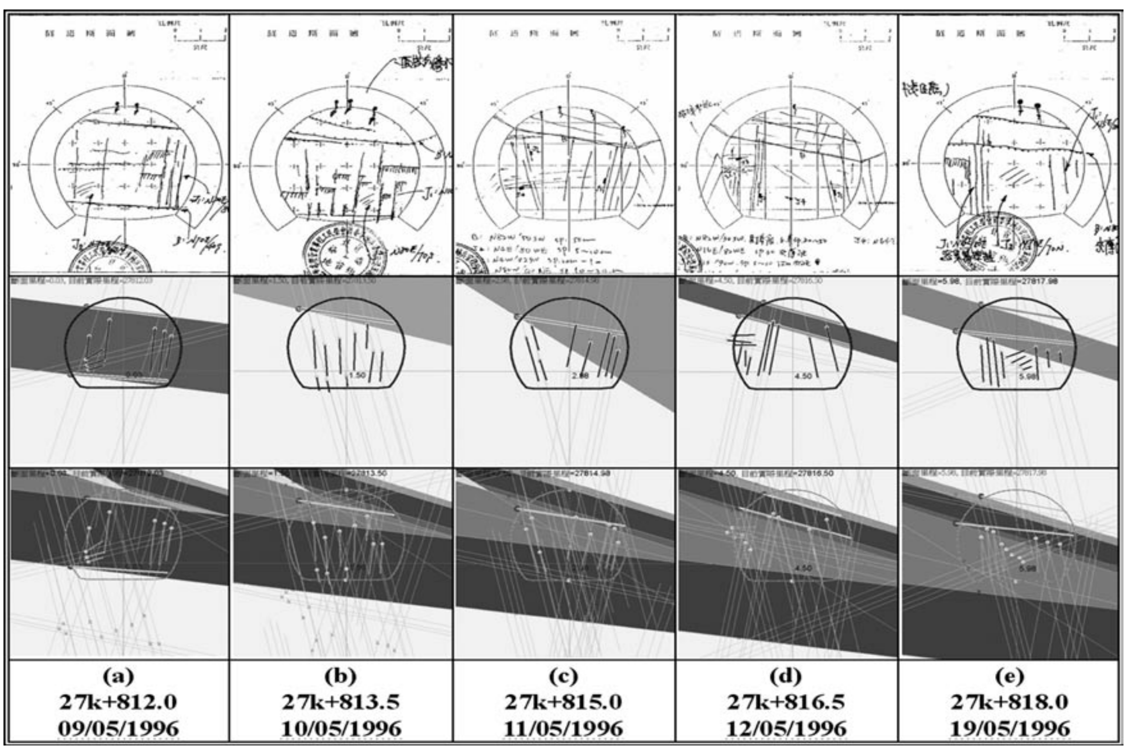
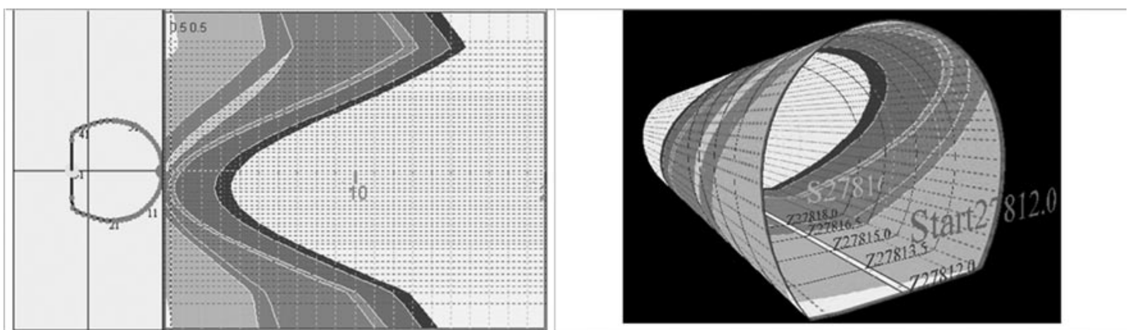


Fig. 10 Geological Data by Hand Sketch, Digitized Data from Photo image and the Combined Data for Five Faces

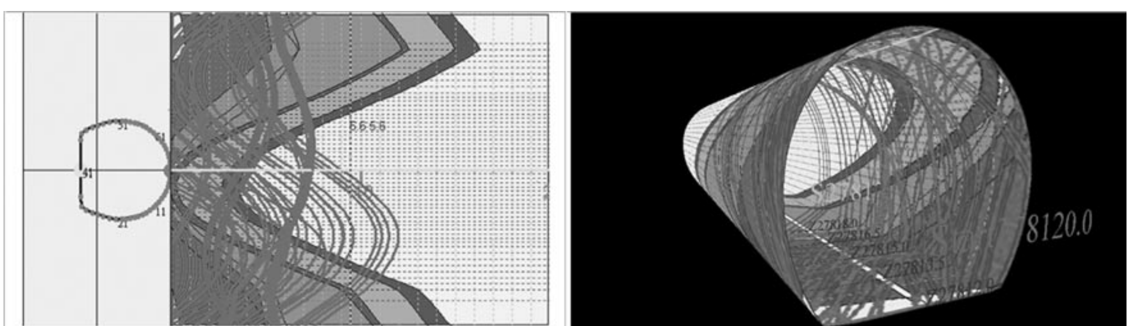
Table 1 Data Attributes of the Associated Weak Planes

ID NO.	X1	Y1	X2	Y2	STATION	DIP DIRECTION	DIP ANGLE	PLANE TYPE
1	-1.63	3.44	2.04	2.91	27812	160	40	0:bedding
2	-2.36	-.2	1.96	-.55	27812	160	40	0:bedding
3	-2.11	3.32	2.11	2.56	27813.5	170	40	0:bedding
4	-2.31	2.91	2.41	2.01	27815	188	50	0:bedding
5	-2.36	2.96	2.56	1.36	27816.5	188	30	0:bedding
6	-1.26	3.67	2.11	2.56	27816.5	188	30	0:bedding
7	-1.56	3.57	2.26	2.76	27818	190	30	0:bedding
8	-2.66	2.16	2.46	1.51	27818	190	30	0:bedding
J-1	-1.51	1.86	-1.71	.15	27812	110	80	1:joint
J-1	-.6	2.71	-.85	.5	27812	110	80	1:joint
J-1	1.41	2.26	1.21	-.1	27812	110	80	1:joint
J-1	1.86	2.11	1.61	-.1	27812	110	80	1:joint
J-1	2.16	1.86	1.91	.1	27812	110	80	1:joint
J-2	-1.66	.6	-.9	1.16	27812	340	60	1:joint
J-2	-1.61	.3	-.85	.55	27812	340	60	1:joint
J-2	-1.56	.05	-.9	.25	27812	340	60	1:joint



(a) 2-D (b) 3-D

Fig. 11 Tunnel Unrolled Geological Map for the Example Case Showing the Bedding Plane Only (Sta. 27k+812 to 27k+832, geological data from 27k+812 to 27k+818)



(a) 2-D (b) 3-D

Fig. 12 Tunnel Unrolled Geological Map Showing the Bedding Plane with Joints

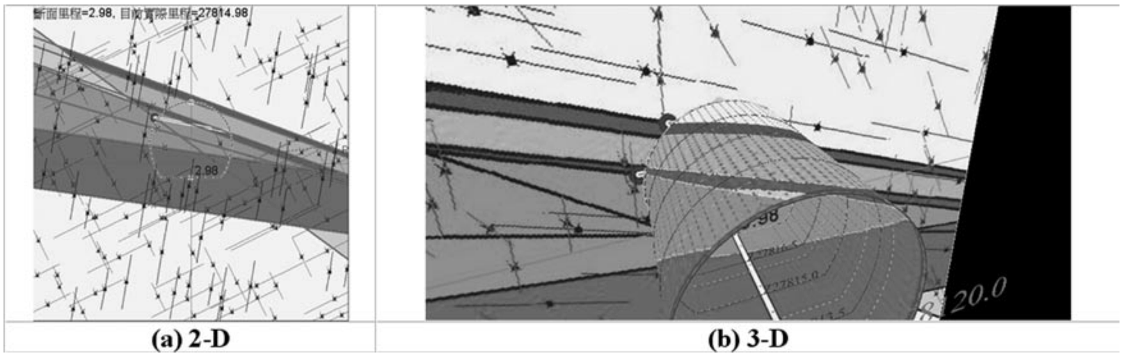


Fig. 13 Distribution of Joint Sets in a Plane with Scale Effects of Joint Traces (Sta.27k+815)

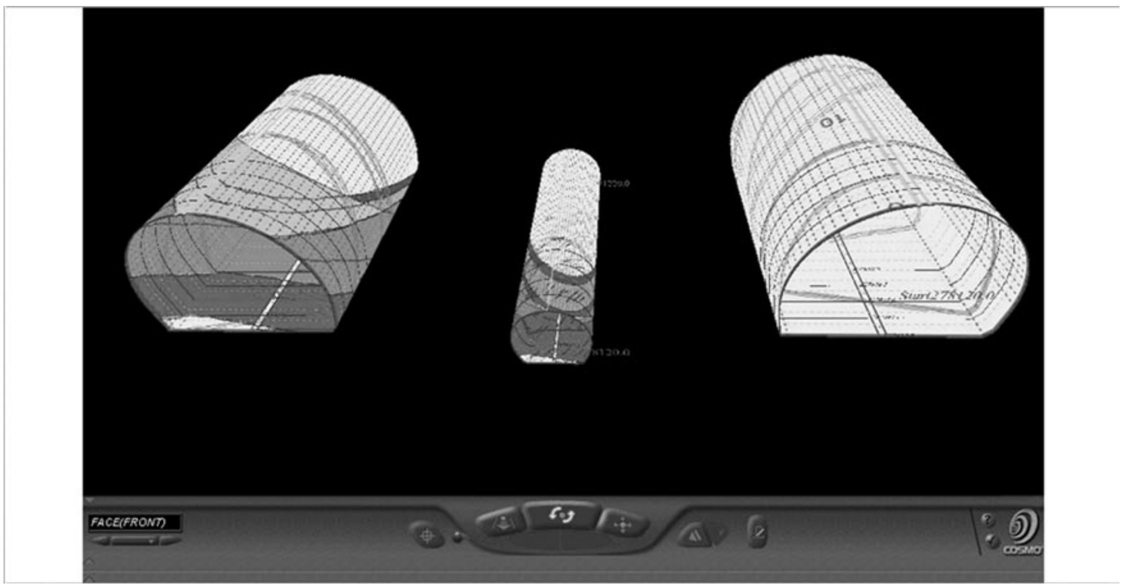


Fig. 14 3-D Tunnel Unrolled Geological Maps for Three Parallel Tunnels
(Sta. 27k+812 to 27k+832, geological data from 27k+812 to 27k+818)

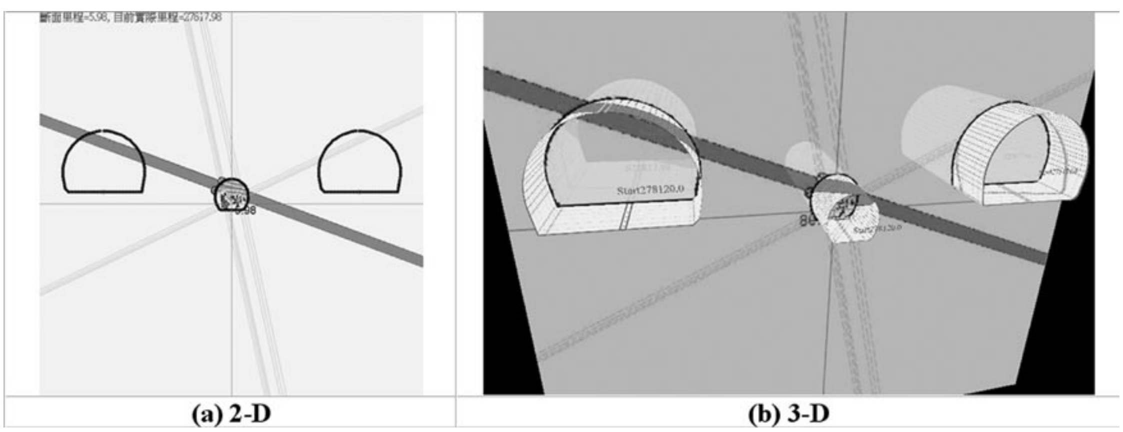


Fig. 15 Predicting the Geological Condition Ahead of the Main Tunnel
(Geological Data from 27k+818, Viewed at Station 27k+818)

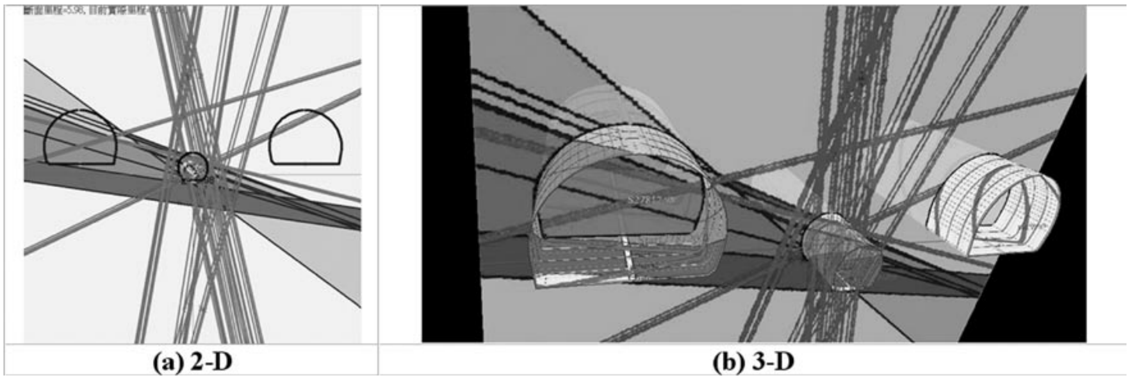


Fig. 16 Predicting the Geological Condition Ahead of the Main Tunnel
(Geological Data from 27k+812 to 27k+818, Viewed at Station 27k+818)

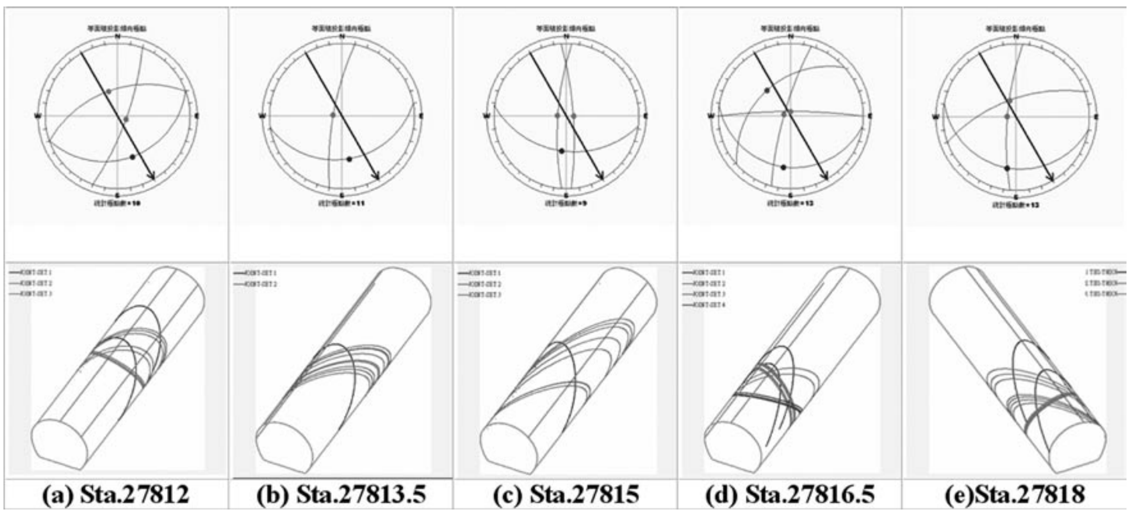


Fig. 17 Pole Densities and Tunnel Images of Major Weak Planes for Each Face

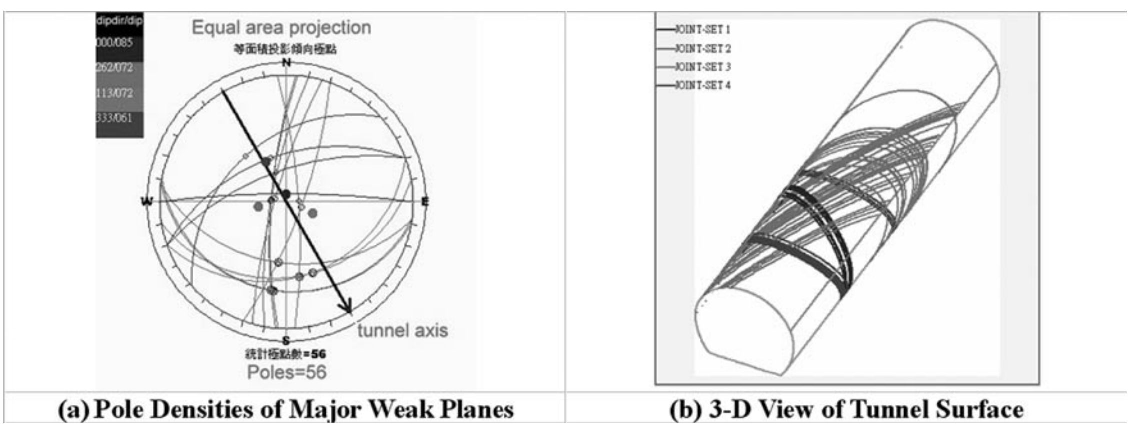


Fig. 18 Pole Densities and Tunnel Images of Major Weak Planes from Sta.27812 to 27818

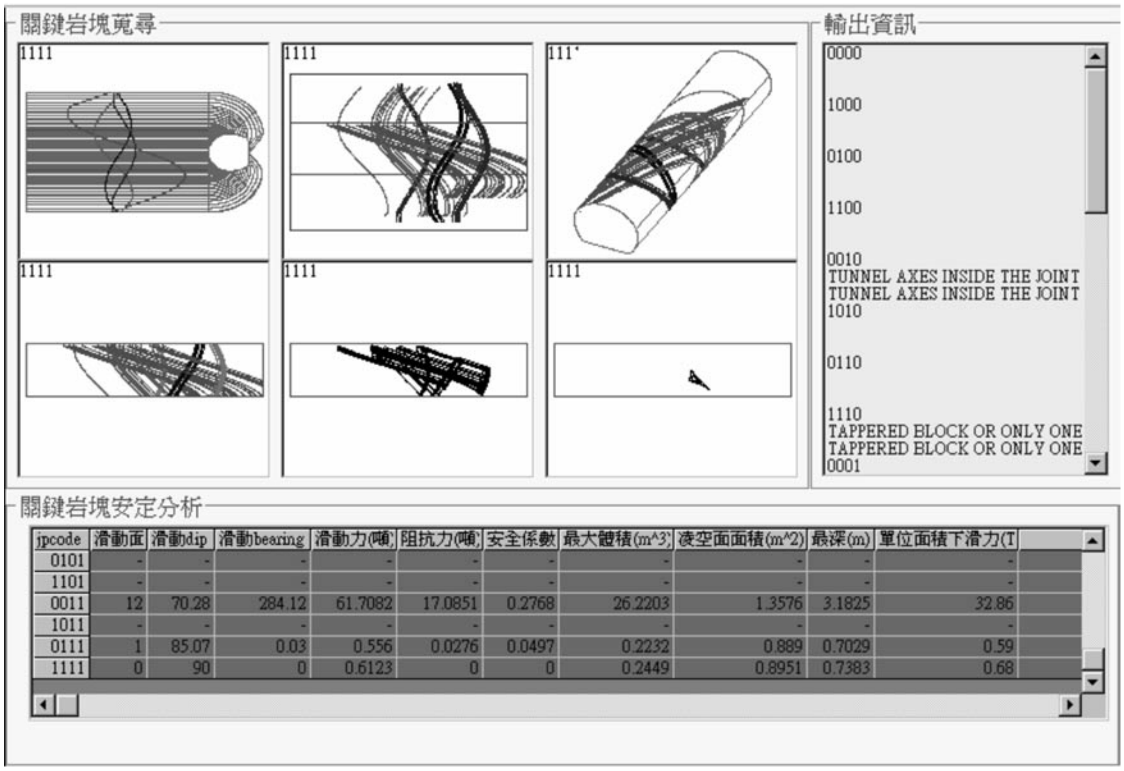


Fig. 19 Key Block Analysis for the Example Case (for Key Block no. 1111)

hand side. It is noted that there is no bedding plane that will be truncated by the Westbound main tunnel in the given domain by this example.

Key Block Aanalysis

Fig. 15 shows the output from GeoMAP where the input data adopted were retrieved from one excavation face at station 27k+816.5 only. In contrast, Fig. 16 shows the output from GeoMAP when the input data used all five excavation faces from 27k+812 to 27k+818.

The key blocks analysis of the example case has been carried out to examine the existence of unstable key block. Fig. 17 shows the pole densities and tunnel images of major weak planes found on each face, and Fig. 18 shows those from sta.27812 to 27818. For the data from each single face, no apparent key block was found since the major joints are so steep and the joint numbers limited. However, for the case of that in Fig. 18, the four pole densities of the weak plane orientations at 000/085 (J-1), 262/072 (J-2), 113/072 (J-3) and 333/061 (J-4) were identified and key blocks existed for joint pyramids numbered (0011), (0111), (1111) as shown in Fig. 19. The maximum dimensions of these key blocks were calculated to be in the order of 26.2 m3, and the associated factor of safety is extremely low with a value of 0.2768. It has to be noted here that the above calculation was done under the assumption that the joint trace length is 14 m which is considered very conservative. Nevertheless, use of GeoMAP to find potential key blocks and calculate the safety factor for identified key blocks of significant dimensions is recommended to the site geologist in tunnel projects.

CONCLUSIONS

One major purpose of the excavation of the pilot tunnel in the Hsuehshan Tunnel project was to investigate the geological conditions ahead of the main tunnel to ensure tunnel safety. A computer system (GeoMAP) aimed at utilizing the geological data collected in the excavation face during the construction of pilot tunnel and constructing of geological model for predicting the geological conditions ahead of main tunnel was developed.

The example case shows that the developed system can automatically produce the tunnel unrolled geological map and the 3D geological block diagram in a given tunnel domain. Multiple tunnels in parallel can also be simulated, and it is noted that geological conditions can be foreseen by reconstruction of collected data derived from pilot tunnel sections. The pole densities of major weak planes can be analyzed and used to survey the existence of potentially unstable key blocks, to perform stability analysis, and to plan the rock bolt design. All the results can be exported into a VRML97 format, and displayed in the computer as a virtual reality world.

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