Implement TST Geological Prediction Solution in TBM Environment

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Chapter 1. Introduction

TST Principle

TST (Tunnel Seismic Tomography) means tunnel seismic CT prediction. This technology was developed by Dr. Zhao, Chinese Academy of Sciences (CAS) from the beginning of the 1990s to 2003 , which represents latest achievements on tunnel prediction. The observation system is spatial arrangement: receivers and shot system can be set on two sides of the tunnel or on the tunnel face. Data process integrates seismic migration image, velocity scanning and structural grain analysis with travel time inversion image, which is especially for tunnel prediction in the area of complex geologic structure, such as successful applications in all kinds of tunnel construction projects national wide.

Seismic wave, meeting wave equation, is first shot in tunnel wall rock, spread widely and reflected and refracted while encountering the interfaces with different wave impedance. Reflection wave returned to receivers is recorded. This is like reflection on the surface. The complexity of reflection seismic wave inside the tunnel occur due to coming from different direction and being converted no the tunnel surface. Seismic sources and receivers are set around the surface of the tunnel in TST pattern. The strength of surface wave is very strong and spreads along both of axial and radial direction. As the affected depth inside wall rock is about one wavelength, geophone will record strong surface wave if buried in a shallow place. P and S wave spreading inside the wall rock will generate converting wave on the surface around the tunnel, that is P to S and surface and S wave to P and surface wave. These wave groups all are recorded at the same time. Figure 2 is the test record when there is a hole in the front of the tunnel. Seismic wave along the tunnel surface can also generate sound wave in the air inside the tunnel. Besides, explosive source can also generate strong sound wave inside the tunnel. Secondary field inside the wall rock generated by sound is very weak and can be ignored. Therefore, the disturbance of sound wave can be avoided if the geophone is buried inside the wall rock and well sealed with soil. Figure 1and 2 show wave front profiles of axial and radial sections, from which travel time characteristics of P wave, S wave and kinds of converted wave can be clearly seen. During seismic observation in tunnel geological prediction, the geophone is buried in depth of 1.5-2.0m in order to effectively reduce the surface wave while observing direct and reflected P waves. Inevitably, kinds of converted wave may be recorded around the surface of wall rock, which should be cleared out during the preprocess of seismic data.

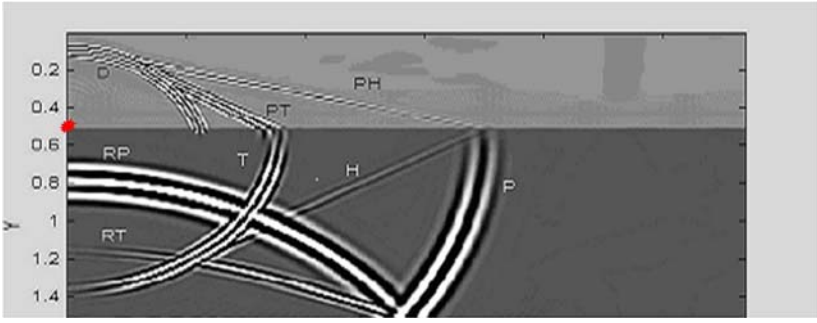


Figure 1. Wall rock

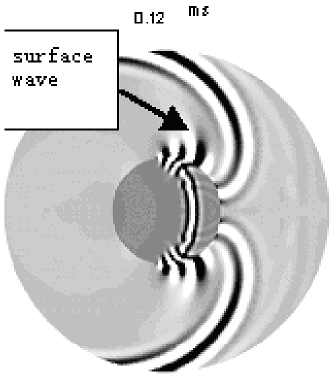


Figure 2. Surface wave inside wall rock

Advanced Unique Features

TST has three unique features that can lead to more accurate and reliable prediction results compared to other Geological prediction techniques. These are achieved as follows i.e.

(1) By using F-K filtering, TST filters out the tunnel surface wave and sidewise reflected wave to ensure only the wave from ahead of the tunnel face will be used in migrated image computations.

(2) By spatial observation and rock velocity scanning, TST provides the rock velocity distribution along the tunnel.

(3) By using scattering migration image theory TST achieves higher image resolution.

The processing steps in TST are described below.

- **3D seismic wave fields in Tunnels**

The tunnel seismic wave field from a source at the face extends in three-dimension. Analyze and differentiation of individual wave paths is critical to tunnel geological prediction techniques.
As shown in Figure 3, there are many reflection wave paths. Usually, the reflected waves from the ground surface (mountain top) are the strongest. What we need for tunnel geological prediction analyzing are only the waves from ahead of the tunnel face. All other waves need to be filtered out.

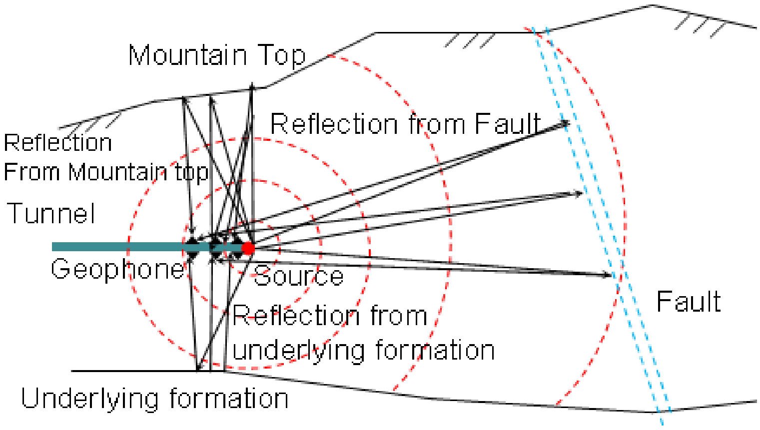


Figure 3. Complex path of 3D wave field

1) Within the tunnel there are different kinds of waves produced i.e., direct wave, reflected wave, P-wave, S-wave, PS-converted wave and airwave. Air and S waves cause strong tunnel surface wave (R) at the tunnel walls extending 1 or 2 wavelengths into the surrounding material. And are the major interference source. Figure 4 shows these waves at a three-component (3C) geophone coupled to tunnel wall.

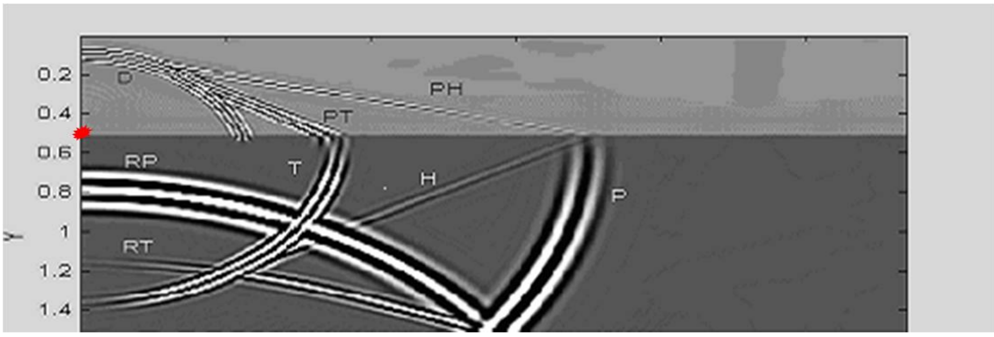


Figure 4. Different kinds of seismic waves in the tunnel

2) The magnitude of the signal received by each component will be the sum of the signals produced by each of the waves. This signal can be described by the following equation i.e.

$$Ux = Uxxp + Uxys + Uxzs$$
$$Uy = Uyyp + Uyxs + Uyzs$$
$$Uz = Uzzp + Uzxs + Uzys$$

In the equation, Ux,Uy,Uz represent the displacement of each component. Uijp,Uijs, i is the displacement direction, j is the path direction, P and S is the wave type.

From this equation, we can see that the signal from each component is the stacking of P and S waves at different paths but tunnel geological prediction only needs the waves reflected from the front.

- **Separation and F-K filtering of 3D wave field**

There are three steps to achieve separation and directional filtering of the 3D wave field in TST.

1) Utilize F-K transform to separate wave field.

According to F-K theory，waves reflected from different path appear with different apparent velocity, and occupy different area of F-K domain in Figure 5 . The direct waves with positive appear velocity, occupy the middle of 1, 3 quadrant. The waves reflected from the tunnel front with negative apparent velocity stand in the middle of 2, 4 quadrant. The waves coming from side wall with higher apparent velocity appear at top and bottom triangle area. The tunnel surface waves with lower velocity appear at left and right triangle area.

2) Select Filtering factor setting

Filtering factor is selected as 1 for front wave area in F-K domain, and as 0 for other areas.

3) Perform inverse F-K transformation.

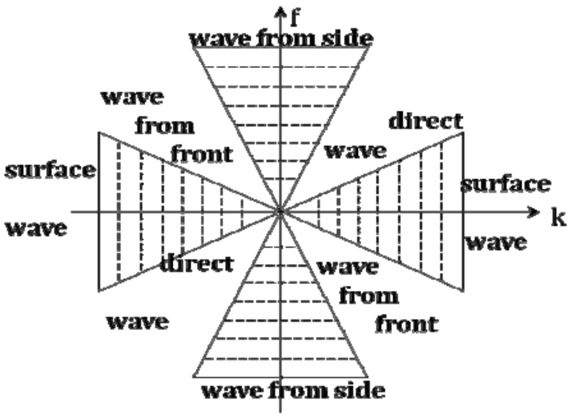


Figure 5. F-K domain of different path waves

Figure 6 shows a sample of tunnel seismic data before and after F-K filtering. The left side of Figure 6 show the data before F-K filtering where the direct wave stronger than the reflected wave from ahead of the face. After F-K filtering, the reflected wave from ahead of the face is clearly observed on the right side of Figure 6 clearly.

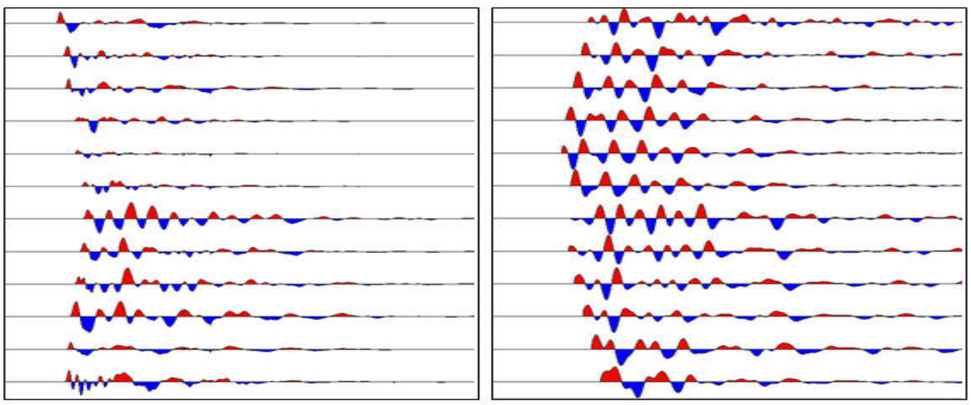


Figure 6. Before (left) and after (right) F-K filtering of tunnel seismic data

- **Rock velocity determination in front of tunnel face**

Rock velocity distribution in front of tunnel face is crucial for rock type determination and geological structure location and must be determined before imaging migration. Data obtained with different offsets and velocity analyze methodology are used together to ensure and accurate rock velocity scanning process. The information obtained by spatial observation of TST data at different transverse offsets, allow velocity scan analysis.

Reflected wave travel-time, rock velocity, offset and reflecting interface are connected by the following analytical relationship:

$$t^2 = (t_0 - \frac{Z_i + Z_j}{V_1})^2 + (\frac{X_i - X_j}{V_2})^2$$

$$t_0 = \frac{2Z_f}{V_2}$$

In the equation t is reflection travel time observed. t0 represent the minimum travel time to the reflector ahead of the face(an unknown value).

(Zi,Xi),(Zj,Xj) are known values, representing the coordinate of shot and receiver points respectively.（Zf,0）represent the coordinate of reflector ahead of the face. The origin of coordinate is at the centre of tunnel face, front direction as positive.

There is four unknown values in the equations. They are rock velocity V1 of tunnel excavated section, tunnel front face rock velocity V2, minimum travel time t0 and reflector distance Zf. Direct wave velocity V1 can obtain from the seismic data. There need at least three another three of travel time data with different offset of Xj and Xi to calculate V2 and t0 and Zf are needed.

If there are no different transversal offsets in the seismic data , the travel time equation will turn to be, Xi -Xj=0, the V2 and Zf can not be solved in the case.

$$t = t_0 - \frac{Z_i + Z_j}{V_1} \qquad t_0 = \frac{Z_f}{V_2}$$

In practice, the real rock velocity calculation is not via this equation, it is through velocity scanning. TST builds a common scattering point (CSP) velocity scanning technique. CSP is based on migration stack energy maximum principle. The first scan to calculate the average velocity, and then performs sub-area scans together with velocity optimization.

Figure 7 shows the process for a velocity scan.

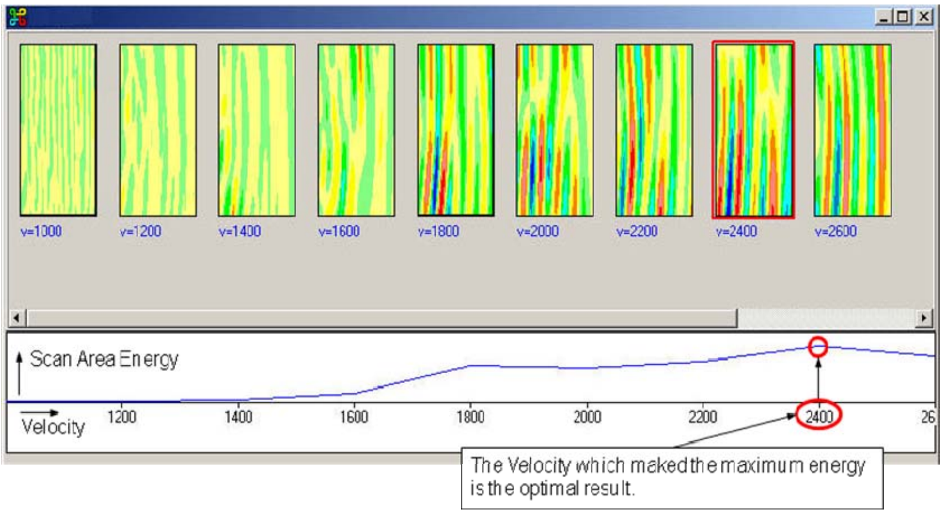


Figure 7. Velocity scan process

After velocity scan, TST gives the velocity distribution displaying as shown in the example in Figure 8. The abscissa represents tunnel mileage and ordinate represents velocity. The rock velocity shows the rock's engineering mechanics characteristics. High velocity indicates a dense and hard lithology while lower velocity indicates fragmented lithology.

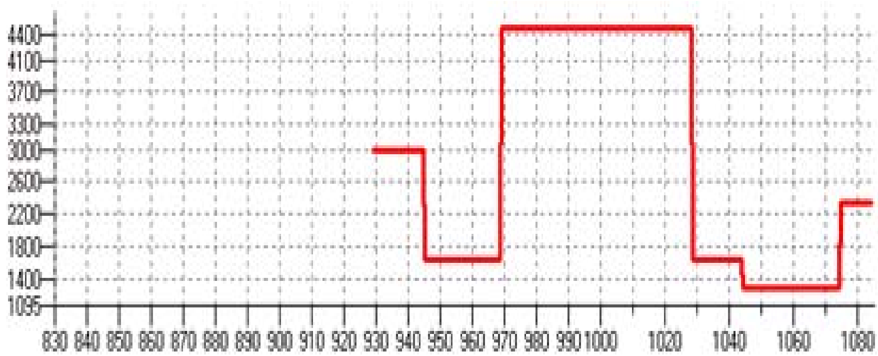


Figure 8. Velocity distribution

Scattering migration image with high resolution

Most of the current tunnel geological prediction techniques are base on reflection theory; however, TST is the only one which based on scattering theory. Scattering theory can give higher resolution in migration image than reflection theory. Reflection theory is suitable only for the larger size reflecting interface vs. wave length. But in tunnel geological prediction, the actual geological interface is smaller than or equal to the wave length. Reflection theory works on that reflection angle equal to incident angle. Reflection wave of skew-structured object/faults cannot be received and any small object or fault can not be found in the prediction.

After F-K filtering and velocity analysis, geological structure imaging is obtained by scattering migration image technique.

As shown in Figure 10, abscissa of imaging represents tunnel mileage and ordinate of imaging represents the horizontal distance to tunnel axes. Red color represents an interface of which the rock lithology turning from soft to hard. Blue color represents an interface of which the rock lithology turning from hard to soft. The combination of red after blue represents a fault zone.

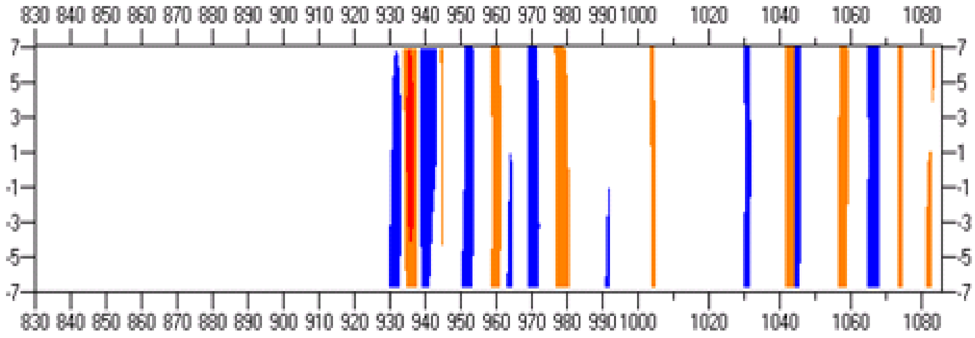


Figure 10. Geological structure imaging

Summary, TST is a new tunnel geological prediction technique that are three important technologies They are F-K filtering of the 3D wave field, velocity scanning, and scattering migration. This combination of provides more accurate and reliable predictions of geological conditions ahead of the tunnel face as has been shown in many tunnel prediction projects in China.

TST Equipment

TST system is composed of hardware and software. Hardware is related to obtain the single, software is the core for this technology, it is a post-process application to analyze the received signal and give the imaging of geological structures and rock velocity.

- **Hardware specification**

Including:

- Seismograph
- TBM tunnel Geophones
- Signal Separation Adapter
- Control Center
- Tunnel Cables
- Seismic source and accessory.

Seismograph –DMT Summit II Compact	
Sample Interval	1/48, 1/32, 1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8 ms
Record Length	0.5 K samples, …, 120 K samples
Preamp Gain	0 dB, 20 dB or 40 dB
A/D Converter	24 bit delta sigma technology
Maximum Input Signal	2.0 Volt RMS5.6 Volt peak to peak
Input Impedance	20 kOhm
Instantaneous Dynamic Range	⩾ 120 dB @ 2 ms sampling interval
Equivalent Input Noise	Less than 0.3 μV RMS @ 2 ms sampling interval and 40 dB preamp gain
Crosstalk	⩾ 112 dB (between channels)
Total Harmonic Distortion	⩽ 0.0008 %
Common Mode Rejection Ratio	⩾ 100 dB
Gain Accuracy	Typical 1 % (between all channels)
Time Accuracy	Typical 5 ppm (between all channels)
Power Supply	+ 9 -18 VDC @ 0.2 W / channel
Dimensions	20.0 x 15.0 x 29.0 cm
Weight	4.9 kg
Analogue Anti-Alias Filter	7.2 kHz 6 dB/octave
Analogue Low-Cut Filter	1 Hz 6 dB/octave
Digital Anti-Alias Filter	0.8 x Nyquist
Rejection at Nyquist Frequencies	-120 dB
Passband Ripple	+/-0.05 dB
Built-In Test Functions	-Sine wave -Pulse -Instrument noise -Geophone step -Sweep transfer -Auto correlation -Cross corelation
System Check	-Battery status -Equivalent input noise -Total harmonic distortion

	-Instantaneous dynamic range -Common mode rejection -Cross talk -Time accuracy
Geophone Check	-Impedance -Damping -Natural frequency -Noise -Leakage

Control Center -- Panasonic TOUGHBOOK CF-31	
CPU	Intel Core Duo 2.93GHz
Memory	2GB
HDD	80GB

- TBM tunnel Geophones: Integrited with IC amplifier, enable longer transmit distance to 250meters. Reusable, a 2.5m-long cable is used to pull out geophone from borehole.
- Signal Separation Adapter: to support the function of IC amplifier integrited with Geophones.
- Tunnel Cables: 200meters long, waterproof coated.
- Poles: for sending the coupling mud and geophones, 2meter in length.
- Device Case: two water-proof device cases.
- Sparker Seismic Source: energy source excitation, 220v AC power supply.

Software specification

TST Software is the spirit for this system. Its features are described in Chapter 1.

- TST software running in Windows environment, support window XP ,Windows 2003 and windows 7.
- TST software require an Intel based PC or labtop, the minimum configuration can be 1GHZ CPU and 2GBMemory. The recommendation configuration is Intel Core Duo P8700@2.53HZ, 4GB memory or above.

Chapter 2. Geological Prediction Solution

Task

Geological Description:

Nauseri ~ Thotha diversion tunnel sections, the surrounding rock lithology is hard, in hard sandstone and soft shale as the main feature, large differences in rock mechanics, especially the soft shale deformation, will be instable when meeting with water . Along the faults, geological structure is complicated. These geological disease will bring risk to TBM evacuation.

TST's task:

TST act as e a long-term or middle-term for-casting tool, to predict the geological disease 50-100m away ahead of the working surface. The disease include, fault structures, lithological types of interfaces and rock's engineering factors, TST will also alert the possible area which lead to rock bursting. The error percentage is within 10%, the resolution is 1 meter in scale.

TST Observation System in TBM

TST observation system can be implemented from the first TBM installed shield. The existing grounting hole can be used to install geophones.

Observation scheme is as follows:

1) 12 geophones installed on both sides of the wall, each side there are 6 geophones. Shown in Figure 11.

2) 6 source holes, arranged on both sides of the wall, each side 3. Shown in Figure 11.

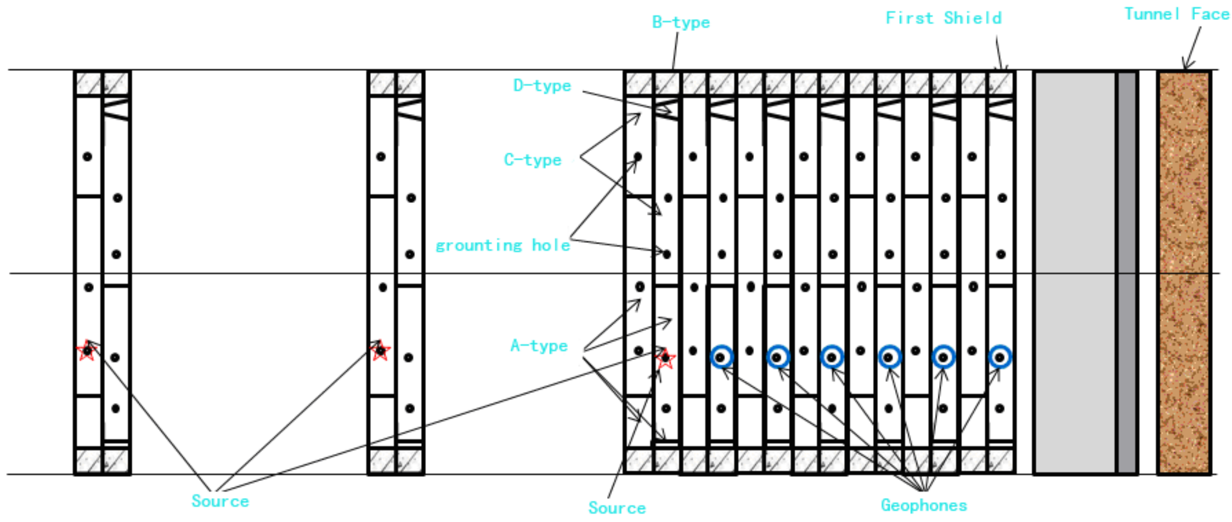


Figure 11. TST Observation Scheme for TBM

3) Deaper the existing holes with pea gravel φ45 pneumatic drilling tool, source hole depth> 1m. Shown in Figure12.

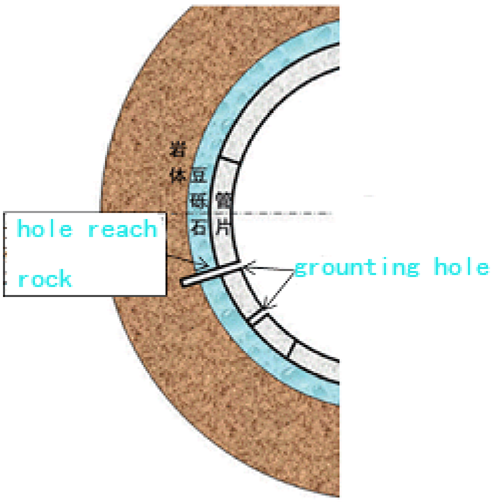
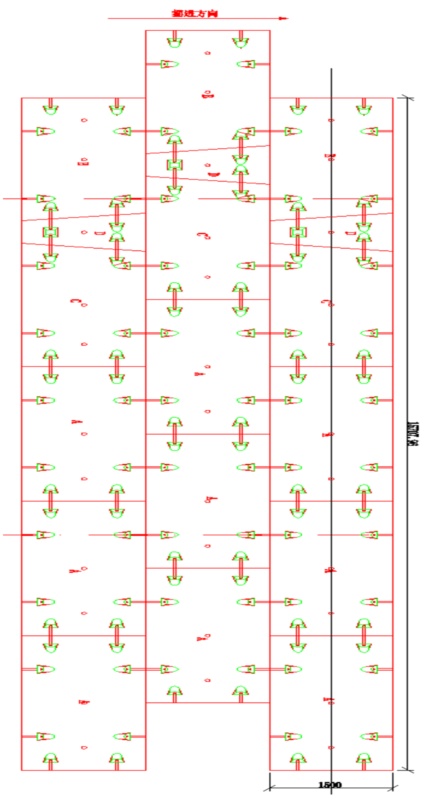


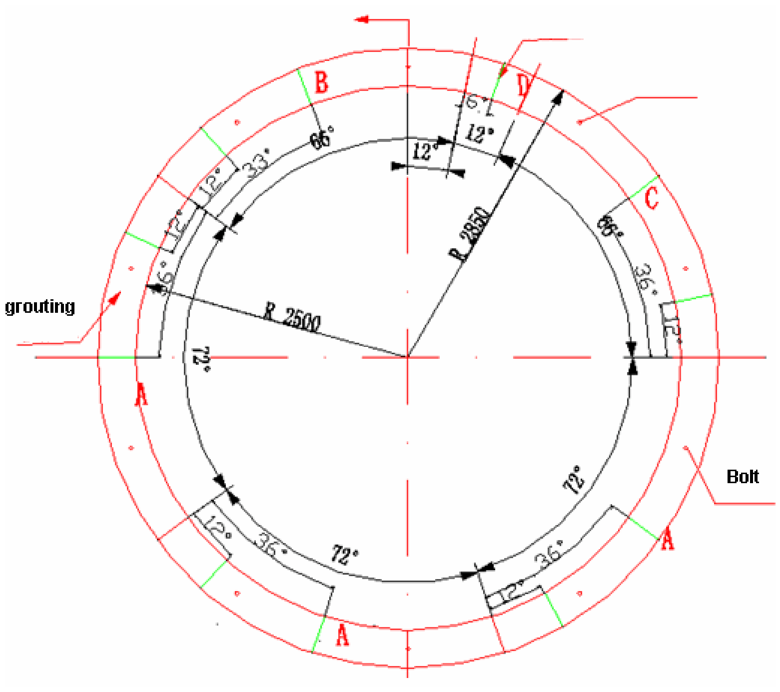
Figure 12. Source hole

Field Task

1. Install Geophones, into A-type Segment on TBM machine. The installation method is indicated in figure 13.
   - As shown in figure 13, install 40cm thick clay into the grounting hole, make sure it is solid.
   - Install Geophone into the Clay, make sure it is solid.
   - Use extra clay to seal the hole.



Segment connecting expansion plan



Cross section of segment

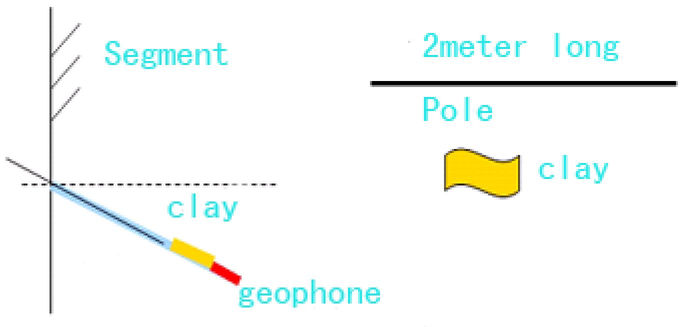


Figure 13. Geophone install

2. Install Sparker Seismic Source , shown in Figure 14. Plumbing water and wire into plastic bag, put it into the bottom of the hole.

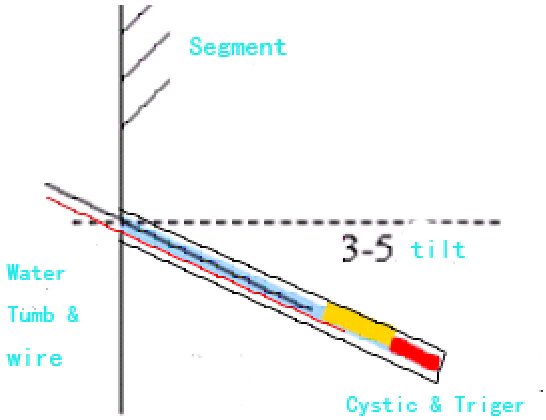


Figure 14 Install Sparker Seismic Source

3. Discharge electricity one by one. Seismograph begin to record the signals.
4. Save all records into 6 files. That is the end of data collecting step.

Data Interpreting

TST data interpreting process

There are five steps in data interpreting.

Step 1. Signal preprocessing

Purpose of seismic records from the original seismic record is extracted, filtered, removal of noise, such as removing dead channel preparation treatment. Figure 15 shows the original record and the record after preprocessing. It is very clear the meaningful signal turns to be more outstanding after signal preprocessing.

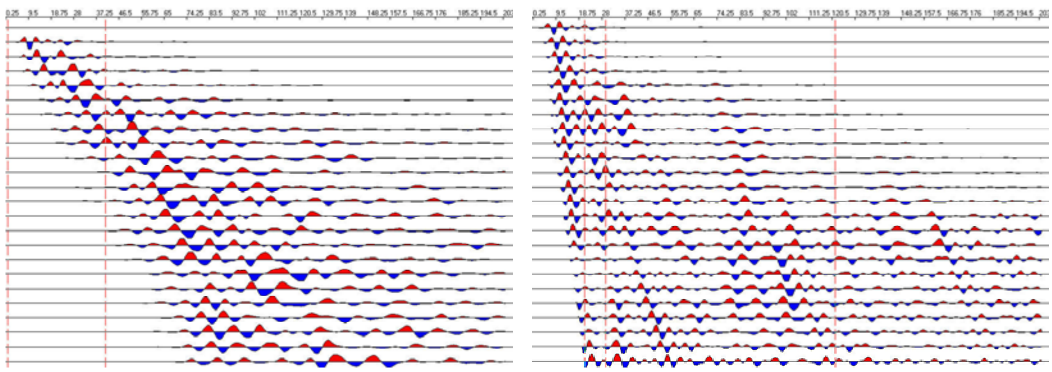
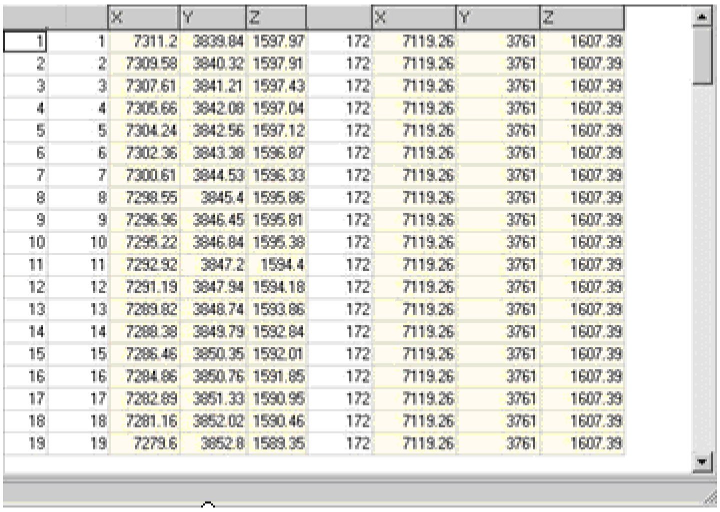


Figure 15. Comparison of original record and

Step 2. Observation Coordinate Geometry Editing

Observation geometry coordinate editing system is used to do the coordinate input, arranged in the shot Stake, Stake detectors and other data. It is a prepare step for next interpreting. Shown in Figure 16.



		X	Y	Z		X	Y	Z
1	1	7311.2	3839.84	1597.97	172	7119.26	3761	1607.39
2	2	7309.58	3840.32	1597.91	172	7119.26	3761	1607.39
3	3	7307.61	3841.21	1597.43	172	7119.26	3761	1607.39
4	4	7305.66	3842.08	1597.04	172	7119.26	3761	1607.39
5	5	7304.24	3842.56	1597.12	172	7119.26	3761	1607.39
6	6	7302.36	3843.38	1596.87	172	7119.26	3761	1607.39
7	7	7300.61	3844.53	1596.33	172	7119.26	3761	1607.39
8	8	7298.55	3845.4	1595.86	172	7119.26	3761	1607.39
9	9	7296.96	3846.45	1595.81	172	7119.26	3761	1607.39
10	10	7295.22	3846.84	1595.38	172	7119.26	3761	1607.39
11	11	7292.92	3847.2	1594.4	172	7119.26	3761	1607.39
12	12	7291.19	3847.94	1594.18	172	7119.26	3761	1607.39
13	13	7289.82	3848.74	1593.86	172	7119.26	3761	1607.39
14	14	7288.38	3849.79	1592.84	172	7119.26	3761	1607.39
15	15	7286.46	3850.35	1592.01	172	7119.26	3761	1607.39
16	16	7284.86	3850.76	1591.85	172	7119.26	3761	1607.39
17	17	7282.89	3851.33	1590.95	172	7119.26	3761	1607.39
18	18	7281.16	3852.02	1590.46	172	7119.26	3761	1607.39
19	19	7279.6	3852.8	1589.35	172	7119.26	3761	1607.39

Figure 16. Observation Coordinate Geometry Editing

Step 3. 3-D spatial wave field separation

This is a key step for TST data interpreting. Select Filtering factor setting to separate wave from font tunnel interface. Figure 17 shows the data before F-K filtering where the direct wave stronger than the reflected wave from ahead of the face. After F-K filtering, the reflected wave from ahead of the face is clearly observed on the right side of Figure 17 clearly.

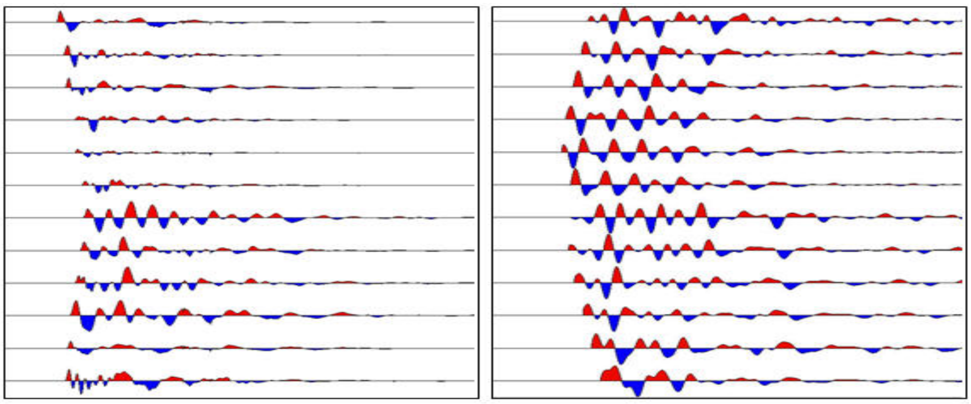


Figure 17. Before (left) and after (right) F-K filtering of tunnel seismic data

Step 4. Velocity Scan

Velocity scan is to determine the velocity distribution of geological body. Choose the area to scan and velocity incremental value, computer will automatically calculate and match rock velocity distribution.

Perform a background velocity scan , to get the average velocity and the basis of sub. Scan each section after that. Figure 18 is an example for section scan.

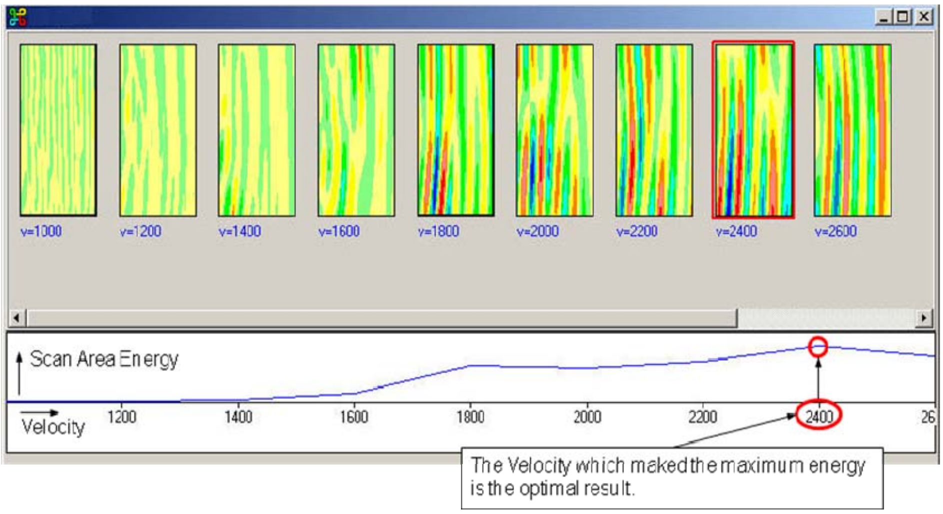


Figure 18. velocity scan

Step 5. Imaging migration

Use of echo data and the velocity structure in front of data migration to obtain migration image which reflected the real geological structure. Figure 19 is an example of imaging migration.

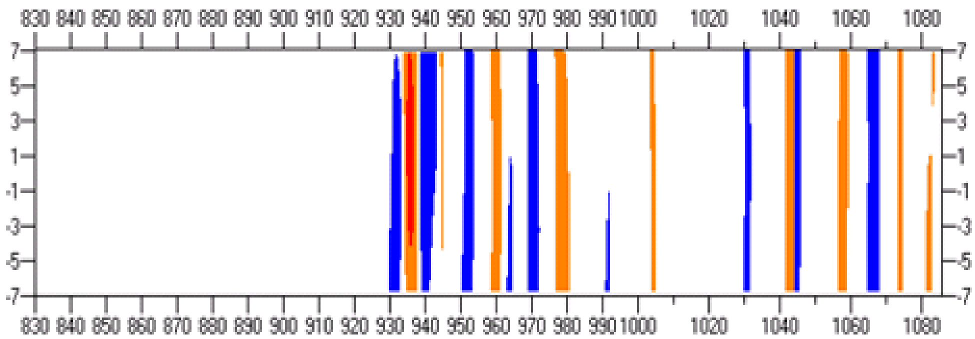


Figure 19. Geological structure imaging

Step 6. Combine geological information to give final report

Combined with above imaging migration result, velocity scan result and a comprehensive analysis of geological data, geological prediction can be preformed. Report including,

- T he exact location of lithological boundaries
- Both sides of the change in rock engineering analogy
- The location of fault

Chapter 3. Diversion Tunnel Reference Case

TST is participate in Knowledge Innovation Project of Chinese Academy of commitment. The project named ***key geological problems research of the safety of long deep tunnel.*** Below is the translation form for one of the report for ‘Qinghai YinDa JiHuang Diversion Tunnel geological prediction’. YinDa is the short term.

YinDa Project Background

TBM

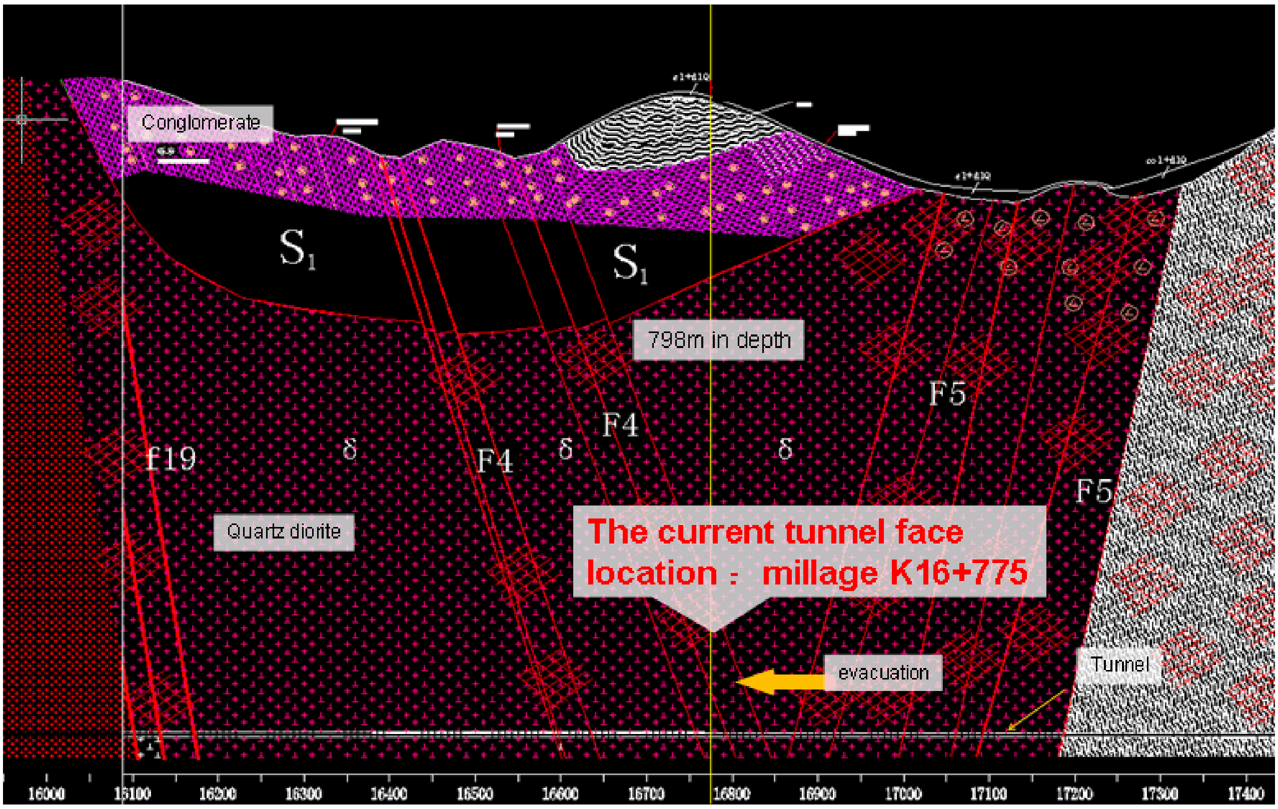
The tunnel is a diversion tunnel located in QingHai province, China north west. The investment for YinDa is 1.3 billion RMB. YinDa tunnel cross Daban mountain, the maximum depth below the mountain is 1100m, tunnel length is 24.165km, mainly TBM construction, tunnel diameter of 5m.
Precast reinforced concrete lining in TBM construction section. Segment diameter 5700mm, diameter 5000mm, width of the segment ring 1.5m, 0.35 m thick lining in every loop 6 segment, single maximum weight of about 4.5t, Block D-cap segment for the wedge. The segment assembly methods using the joint assembling method of TBM machine. The gap of segment and the rock is filled with pea gravel. The pea gravel is backfilled and grouted.

Geological Information

YinDa Tunnel is located in the regional northern margin of the Tibetan Plateau, in the Qilian geosyncline fold system. Tectonic movement in the region dominated by vertical movement, accompanied by folds, faults and other tectonic activity. Seismic activity is very active.

Complete formation and development project area, along the diversion tunnel axis of the exposed strata from new to old are: R,J, T_3^2,T_3^1,P,S_1,Q_3 and P_{t1}. Quaternary thickness is less than 30m, located in the surface. Between the strata of different ages are exposed fault or unconformity.

Daban Mountain is the watershed. Inlet section of the lowest erosion surface of Datong, river export zone to treasure the lowest erosion surface.



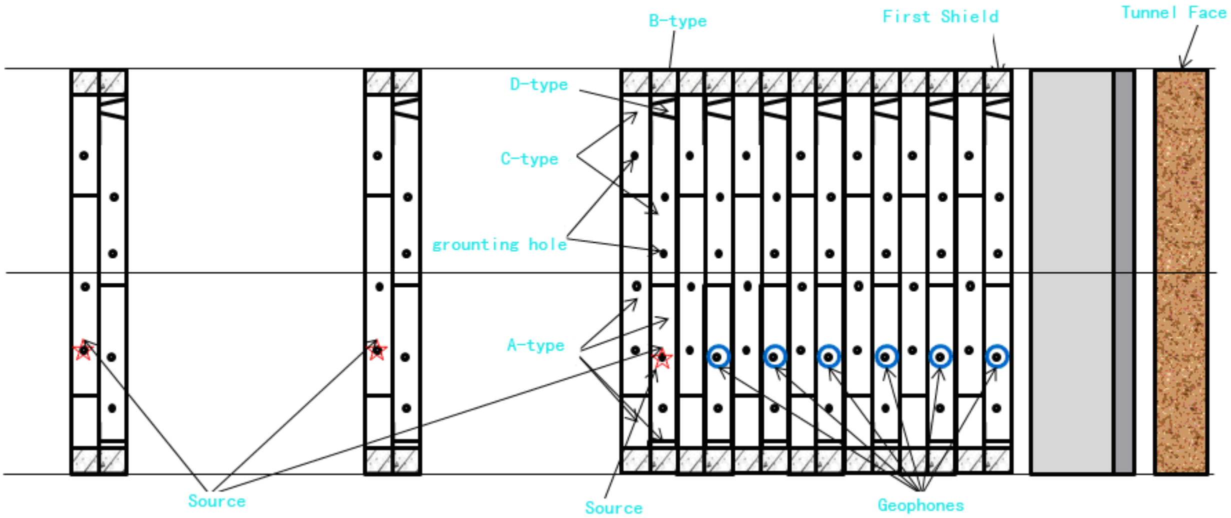
Tunnel evacuation progress

1. From 2006.10.4 to 2008.4.3 running normal, totally 5.825KM.
2. From 2008.4.3 to 2010.10.4 met 9 times TBM sticking, evacuate only 365meter. The key problem is entering DaBan Mountain South edge, high stress causes soft rock deformation too fast. After TBM cutting, before supporting action is utilized, the cutter already stuck.
3. Currently, the upper half part excavation is performed by human. The lower half part excavation is performed by TBM. The progress is very slow.

TST Geological Prediction

Observation System tailored for TBM environment

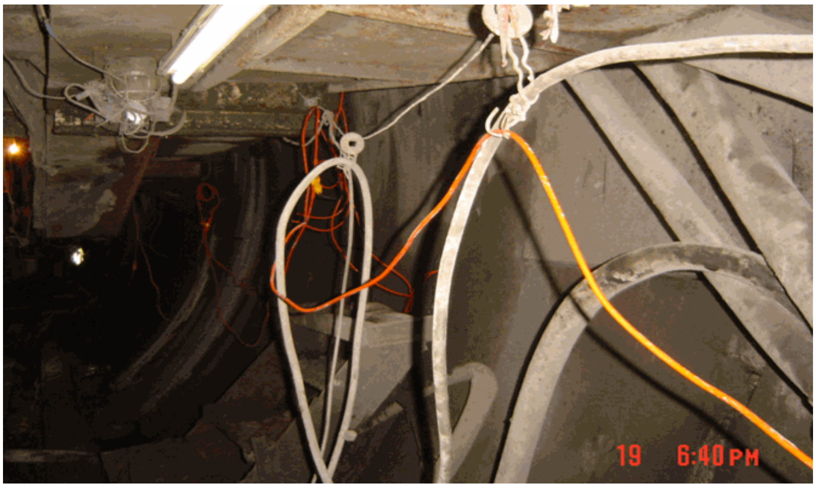
Similar with none-TBM tunnels, geophone pitch is 3m, source pitch is 18m, they all use the existing grount hole on TBM segment. The depth of the geophone hole is about 0.5m. The depth of source hole is 1m. Use explosion source. The amount of emulsion explosive is <50g. Clay can mixed with glue.



1. Install Geophone

2. Seal the hole with clay.

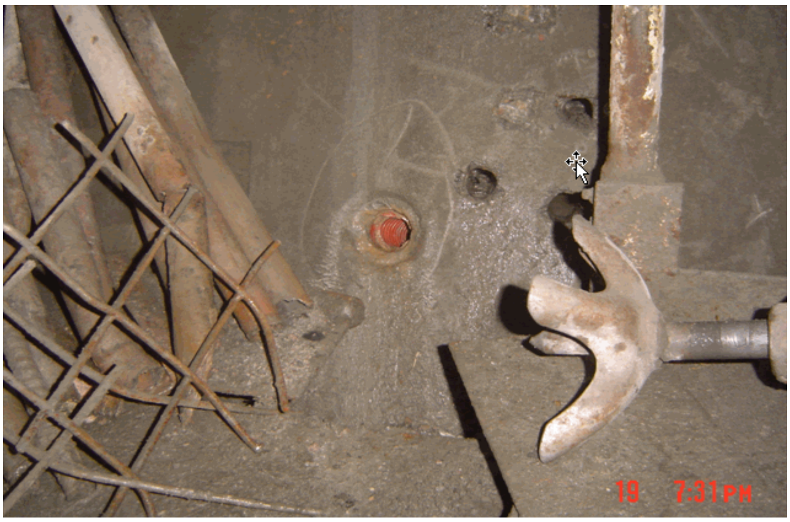
3. Cable the seismograph.



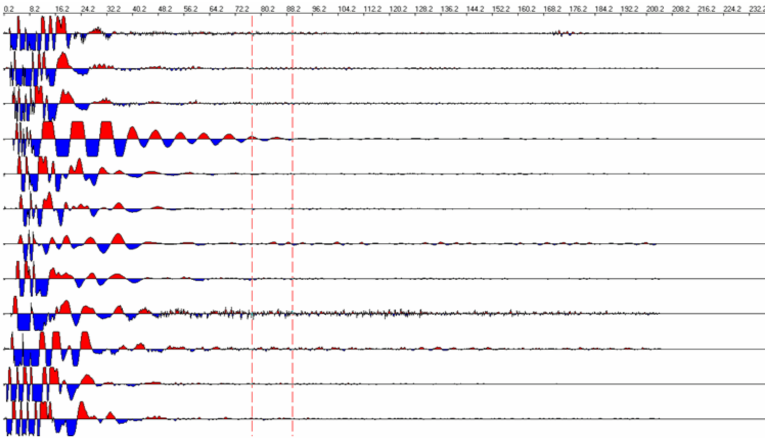
4. Fill explosive source powder.

5. Before exposive.

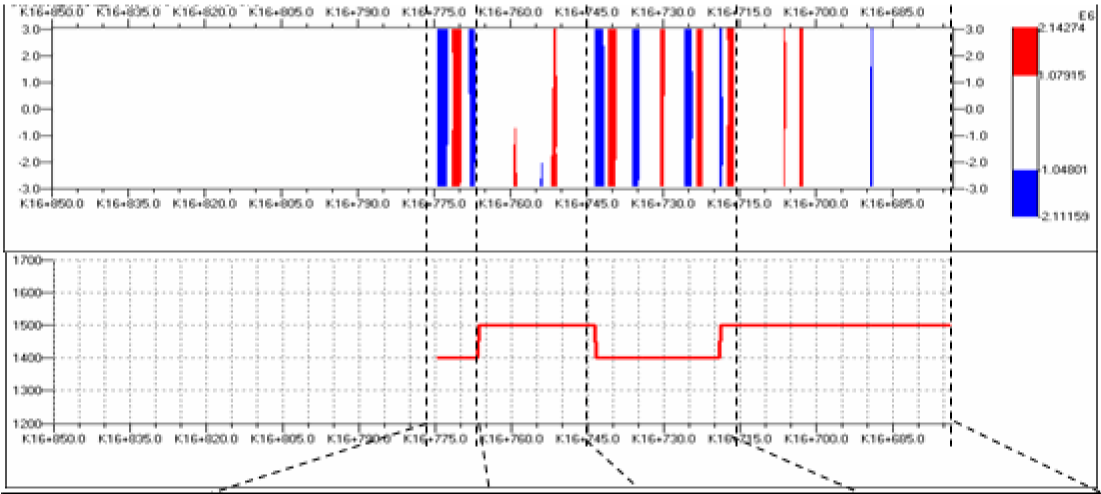
6. After exposive.



7. Save the record.



8. Post interpreting with TST.



Millage	K16+775 ~ K16+765	K16+765 ~ K16+745	K16+745 ~ K16+715	K16+715 ~ K16+675
Distance（m）	10	20	30	40
Velocity（V_p）km/s	1.4	1.5	1.4	1.5
Rock type	V	V	V	V
Geological Prediction with TST	Fault and fraction zone, the rock stability is extremely bad. plenty of underground water, water is visible to be dripping or linear. Possibly lead to collapse and TBM stuck.	The rock stability is a little bit better, underground water is seepag or dripping.	Fault zone, the rock stability is extremely bad. plenty of underground water, water is dripping or linear. Possibly lead to collapse and TBM stuck.	The rock stability is a little bit better, underground water is seepag or dripping.