**PROCEEDINGS PIT HAGI 2012**
37th HAGI Annual Convention & Exhibition
Palembang, 10-13 September 2012

# Implementation of Crosshole Seismic Travel Time Tomography for Predicting Near-surface Geological Structure During the Develoment of SMART Tunnel in Kuala Lumpur – Malaysia

*Adree Octova (1) & Rachmat Sule (1)*
*(1) Geophysical Engineering Department, Institut Teknologi Bandung, Indonesia*

**Abstract**

A tunnel with a dual function was built in Kuala Lumpur - Malaysia during 2003 - 2008 in order to solve flood and traffic congestion problems. During the development of this tunnel, crosshole seismic travel time tomography method was implemented in order to give approximation of subsurface image beneath obstacle surface and in order to detect cavities in the front of tunnel path. This could be realized by placing sources and receivers inside 5 boreholes in the area close to Istana Island, Kuala Lumpur. First arrival travel times are used as main input data, besides the exact information of sources and receivers coordinates. This study is devided into three steps. The first step is construction of synthetic model, in which the model a 4 x 4 $m^2$ positive and negative anomalies are positioned in the center of model, and the same aquisition configuration as used in the field is implemented in this step. This process is done in order to test the software and to know whether acqusition configuration could still recognize the anomalies. The second step is applying inversion process for the real data in Malaysia. The last step is testing the resolution of tomogram by using the checker-board resolution test in order to localize the area that could be nterpreted inside the tomograms. The tomographic seismic data processing is conducted by using FAST software. The tomograms indicates cavities in several places between the boreholes. Based on the results of checker-board resolution tests, anomalies can still be identified if their sizes are at least 2 x 2 $m^2$. As conclusion, cross-hole seismic travel time tomography proves as a very good method in describing subsurface structure and boundary layers.

Key words: Crosshole seismic tomography, first arrival travel time, SMART tunnel.

**Introduction**

The Stormwater Management and Road Tunneling Project (or Smart Project) was begun at the end of 2003 and has been completed at the end of 2008. A 9.8 km huge storm water tunnel development (outer diameter of 13.2 m), including a 3 km double-decker motor highway inside the tunnel is a strategic project in Malaysia with the total cost of about € 450 million. The goal of the project is to prevent Kuala Lumpur (KL) from flood hazards, if heavy rains occur. Statistical studies show that the number of floods in the city has increased significantly (Abdullah, 2004). The main cause of the flooding is due to the increase of run-off surface water from the surrounding area of Kuala Lumpur into the Klang River, which traverses through the heart of the Malaysian capital city. Based on several studies, the increase of run-off water into the Klang River is mainly due to the rapid development of public housing and industries in the surrounding area near Kuala Lumpur. Three river confluences into Sungai Klang, i.e. Sungai Ampang, Sungai Bunus, and Sungai Gombak make the maximum water flow into the Klang River to be around 798 $m^3/s$ (Abdullah, 2004). By opening the bypass discharge of the Smart tunnel, the water flow through KL will decrease to around 598 $m^3/s$ in which the 30 m depth of Sungai Klang at the Tun Perak Bridge can still retain the total water volume, and therefore, the possibility of flood occurrences can be reduced.

This paper explains the importance of cross-hole seismic tomography investigation in a tunnel construction. As TBM works traditionally "blind", i.e. variations in rock or underground properties are not recognized well before they are drilled, the knowledge of subsurface condition is very needed, in order to prevent dangerous accidents and expensive delays (Kneib, 2000). Several two-dimensional cross-hole tomographic surveys were carried out in the area of Istana Island – Kuala Lumpur during 2005, before the TBMs passed through the planned alignment. The previous results of tomographic imaging have been reported to Gamuda-MMC JV, the main contractor of SMART tunnel development, and have been used only for in-house purposes. Here, we reprocessed the tomographic data by using more sophisticated software, namely First Arrival Travel Time Seismic Tomography (FAST), which is written by Zelt (1998). The aim of reprocessed tomographic data is to obtain better image, so that we hope that this method could be accepted in the tunnel business if the TBM path must excavate though complicated surface situation.

**Geological Setting beneath Kuala Lumpur City and the chosen TBM type**

The geological map around tunnel alignment can be seen in Fig. 1. Obviously, the tunnel alignment is almost 100% inside the formation of Kuala Lumpur Limestone. This formation consists majority of marble, which consists predominantly of fine to coarse-grained recrystallised calcite and dolomite. The Kuala Lumpur limestone formation is often intruded by the igneous rock and quartz veins, in which the mineralization of tin mineral often occurs. The shaded area on Fig. 1 shows the ex tin mining area around Kuala Lumpur, which is situated mostly inside the placer alluvium.

Based on preliminary geological study (especially from boreholes and available geological map), the TBM should excavate about 35% softground and mixed phase (loose soil on top and marble/limestone on bottom), and 65% of hard rock (limestone/marble). The ground water surface is very shallow, with an average depth of about 3 m. The UCS tests show that the rock strength for limestone varies from 25 MPa to 105 MPa. At the location of the TBM assembly, the water pressure is about 1.5 bar at the tunnel crown and about 2.8 bar at the tunnel bottom. Based on the complex geological setting along the tunnel alignment, a slurry mixshield TBM is chosen.

Since the tunnel alignment is mostly inside the Kuala Lumpur Limestone formation, sinkholes and bentonite leaks, which occurred on the surface, have been observed several times along the south alignment. The occurrences of sinkholes and bentonite leaks along Jalan Chan Sow Lin (see Fig. 1) have been documented by the MMC-Gamuda JV. The presence of sinkholes on the surface and large cavities inside the formation make worry the peoples involved in the tunnel construction, especially if they occur during and after excavation. Intensive investigations were made in order to prevent the worst cases that could be taken place if sinkholes occurred or the TBM excavates through big cavities.

**Tomographic Method**

The tomographic software FAST (Zelt, 1998) has been used in this work. The travel time calculation and ray paths determinations are based on finite difference methods (Vidale, 1990; Hole and Zelt, 1995). The inversion procedure is the regularisation scheme from Zelt (1998), which minimizes an objective function that includes norms that measure model roughness and data misfit. The objective function Φ minimized at each iteration is

$$\Phi(\mathbf{m}) = \delta\mathbf{t}^T \underline{\mathbf{C}}_d^{-1} \delta\mathbf{t} + \lambda[\mathbf{m}^T \underline{\mathbf{C}}_h^{-1} \mathbf{m} + \omega \mathbf{m}^T \underline{\mathbf{C}}_v^{-1} \mathbf{m}] \qquad (1)$$

where $\delta\mathbf{t} = \mathbf{t} - \underline{\mathbf{G}}(\mathbf{m})$ is data residual vector; $\mathbf{m}$ is the model vector; $\underline{\mathbf{C}}d$ is the data covariance matrix; $\underline{\mathbf{C}}h$ and $\underline{\mathbf{C}}v$ are the roughness matrices in horizontal and vertical direction, respectively; λ is the trade-off parameter; and sz is the vertical versus horizontal model smoothness. After minimization of the objective function Φ with respect to the model vector $\mathbf{m}$, it yields the system of equations

$$\begin{bmatrix} \underline{C}_d^{-\frac{1}{2}} \boldsymbol{L} \\ \lambda \underline{C}_h \\ s_z \lambda \underline{C}_v \end{bmatrix} \delta \boldsymbol{m} = \begin{bmatrix} \underline{C}_d^{-\frac{1}{2}} \delta \boldsymbol{t} \\ -\lambda \underline{C}_h \boldsymbol{m}_0 \\ -s_z \lambda \underline{C}_v \boldsymbol{m}_0 \end{bmatrix} \qquad (2)$$

where $\mathbf{L}$ is the kernel data matrix containing the ray segment in each pixel; $\mathbf{m_0}$ is the current model; $\delta\mathbf{m}$ is the model perturbation using which the update model is given by $\mathbf{m} = \mathbf{m}_0 + \delta\mathbf{m}$. The system equation 2 is solved with the iterative LSQR algorithm of Paige and Saunders (1982).

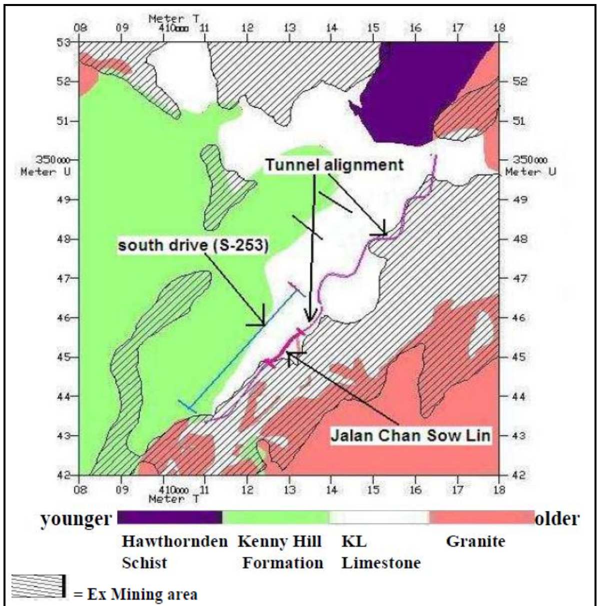


Figure 1. The geological map around the tunnel alignment (left) and a cross section through this area (right). The alignment traverses through almost 100% the Kuala Lumpur Limestone formation.

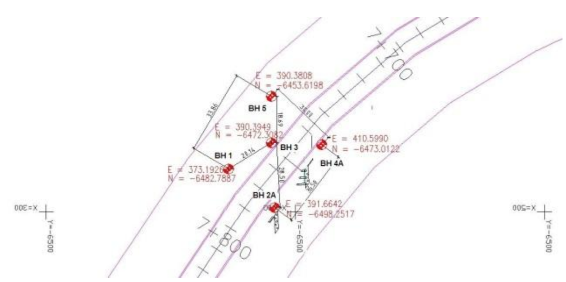


Figure 2. Boreholes position around Istana Island area

**Results of tomographic imaging method**

The 2D crosshole seismic tomography was carried out mostly on the areas where the resistivity method cannot be applied (or it is known as a very difficult area), and knowing the subsurface information is crucially important. The results of this method will show the distribution of P-wave velocities, which is dependent on the elasticity properties of the subsurface materials. A massive limestone or marble materials have P-wave velocity values between 3,500 m/s and 7,000 m/s. Fractured limestone and water-filled cavities should have smaller values than the massive limestone, perhaps below 3,500 m/s. This is the reason why this method could be used to localize the suspected weak zone or water-filled cavities if low velocity zones are found in the sections.

Five two-dimensional tomographic surveys were conducted at the ‘‘Istana Island’’ area, which is located below the beginning point of KL-Seremban Highway and just after SJB (around CH = 7740 and CH = 7775), as can be seen in Fig. 2. Here, five boreholes with depths between 30 and 40 m are situated, which enables investigations by using the crosshole seismic tomography.

Since the equipment (seismic source and hydrophone chain) is located inside the boreholes, the noise level inside the data is minimum. The first arrival travel times can be picked easily only from the raw data. The seismic source is an OWS, i.e. a kind of sparker source that is manufactured by OYO Corporation. In the application to this site, this kind of source can produce a high frequency signal with a dominant frequency of about 250 Hz.

For a starting model, a homogeneous P-wave velocity of 4521 m/s is used for all cells inside the model. The model is divided into cells, with a cell size of 0.1 x 0.1 $m^2$. One of tomographic inversion results is shown in Fig. 3 (section of BH2A-BH1). These are the inversion results after the $8^{th}$ iteration. The tomograms are already stable in which there are no significant changes in the results after that iteration. The ray paths through final model can be seen in Fig. 3 (left). It can be seen from ray paths image that almost all cells in the center of the model have been traversed by many rays, which make the resolution of the center part of tomogram is high and enable us to make meaningful interpretations. Figure 3 (bottom) shows the residual travel times between the observed data and the travel times calculated through the final model and using the same source-receiver pairs as have been used in the field. A conspicuous improvement of the results (after tomographic inversion) can be seen here in which the residual travel times are concentrated at about ± 0.1 ms and symmetrically about 0. These indicate that the final models are not biased.

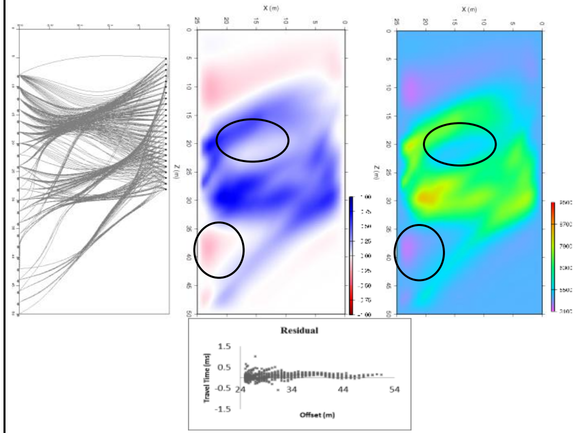


Figure 3. Inversion results of BH2A-BH1. Top Left to right: ray paths from sources to receivers through final model, perturbed final velocity model, and absolute final velocity model. Bottom: residual travel times between observed travel times and calculated travel times.

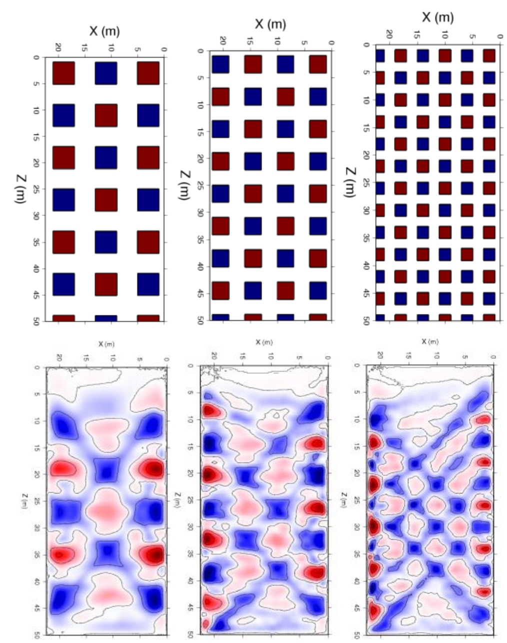


Figure 4. Checker-board resolution tests by using block size of 4 x 4 $m^2$ (left), 3 x 3 $m^2$ (middle), and 2 x 2 $m^2$ (right). Although smearing effect can be seen here, but the boards can still be identified.

Generally, the results of tomographic inversion show P-wave velocity of soft upper part earth material (below 3,500 m/s) and rocks (more than 3,500 m/s). The upper part earth material is also confirmed from the borehole data. More compacted rocks result in a higher value of velocity. Solid limestone and marble could have a velocity range of more than 5,500 m/s. The boundary between upper part earth material and rock is quite clear, which could be correlated with boundary of intensive weathering there. Some other important interpretations can be made as follow: Fig. 3 shows 2 zones that could correspond to weaker (fractured and more porous) limestone or perhaps related to waterfilled cavities that are marked as the area inside the ellipse. Both areas could be related with fractured limestone because higher water saturation could be situated there. Theoretically, a porous rock can be characterized by lower values of P-wave velocities. Because the tunnel will excavate through this area at that time, the engineers and the TBM drivers should take into account the worst case scenario which has been indicated in this image.

### Checker-board resolution tests and construction of cavities model

The checker-board resolution test is a way which allows to check the reliability of the obtained images and to know how close the images to the actual structure are. Three schemes of checker board resolution tests are presented here, i.e. by using block size of 4 x 4 $m^2$ (left), 3 x 3 $m^2$ (middle), and 2 x 2 $m^2$ (right). It could be interpreted that the block size of 2 x 2 $m^2$ could still be resolved, thus the anomaly that has a size of 2 x 2 $m^2$ could still be identified in the tomograms.

### Conclusions

The use of 2D tomographic imaging method has succeeded in determining the velocity structure, especially related to the occurrence of suspected cavities inside subsurface. This method has a capability in answering the possibility of cavities or rock boulders occurrences inside subsurface. It is hope that this method could be implemented during tunnel excavation by using TBM.

### References

Abdullah, K., 2004, Stormwater management and road tunnel (Smart) a lateral approach to flood mitigation works, Proceeding of International conference on bridge engineering and hydraulic structures, Selangor-Malaysia.

Hole, J. A., and Zelt, B. C., 1995, Three-dimensional finite-difference reflection traveltimes, Geophys. J. Int., 121, 427-434.

Kneib, G., Kassel, A., and Lorenz, K., 2000, Automatic seismic prediction ahead of the tunnel boring machine, First Break, Vol. 18.7.

Paige, C. C., and Saunders, M. A., 1982, LSQR: An algorithm for sparse linear equations and sparse least squares, Assoc. Comput. Mach. Trans. Math. Software, 8, 43-71.

Vidale, J. E., 1990, Finite-difference calculation of travel times in three dimensional, Geophysics, 55, 521-526.

Zelt, C. A., 1998, Three-dimensional seismic refraction tomography: A comparison of two methods applied to data from the Faeroe Basin, J. Geophys. Res., 103, 7187-7210.

### Acknowledgements

We thank the Department of Irrigation and Drainage - Malaysia for the permission in using the data.