Applications of engineering geophysics to underground space development

ROBERT J WHITELEY[1]

[1] *Coffey Geosciences Pty. Ltd. (e-mail: bob_whiteley@coffey.com.au)*

Abstract: Population pressures, environmental and heritage issues are increasing underground space use for infrastructure development within tomorrow's cities. This has led to technological innovation, with large diameter tunneling and directional boring machines that can handle a wide variety of geological conditions. However, there are still major geotechnical risks associated with these machines when unexpected geological or hydrogeological hazards or rapidly changing ground, are encountered. Conventional engineering geological investigation frequently fails to identify these hazards as drilling sites are restricted in urban environments. Engineering geophysics is being called upon to locate these features, to target boreholes and extend their radius of investigation and for evaluation of ground improvement works prior to tunneling and following incidents.

Detailed gravity was applied to route selection for the Burnley Street road tunnel in Melbourne, Australia, defining a major palaeochannel beneath basalts and alluvials and allowing targeted drilling at key locations along the final route. In Hong Kong, directional bore installation of a cable tunnel below a water crossing in weathered granite was required. Underwater seismic refraction imaging mapped subsurface conditions along the alignment and defined likely weathering grades. Also in Melbourne, during the construction of the North Western Sewer in alluvials using an EPB tunnel boring machine, voids were created at some locations. These were mapped using SEWREEL seismic imaging between the tunnel and the ground surface. At one location, the tunnelling induced road settlement and SUBS seismic imaging from boreholes defined the extent of the voided region and tested the effectiveness of remediation grouting. SUBS seismic imaging was used assessment of ground improvement works above the soft ground section of the Richmond Transport Tunnel in San Francisco, identifying areas that could require additional grouting.

Conventional engineering geological methodologies combined with appropriate geophysical technologies are a powerful tool for reducing geotechnical risks associated with underground space development.

Résumé: Les issues de pressions de population, environnementales et d'héritage augmentent l'utilisation souterraine de l'espace pour le développement d'infrastructure dans les villes de demain. Ceci a mené à l'innovation technologique, avec le grand perçage d'un tunnel de diamètre et les aléseuses directionnelles qui peuvent manipuler une grande variété de conditions géologiques. Cependant, il restent des risques géotechniques principaux liés à ces machines quand des risques géologiques ou hydrogéologiques inattendus ou la terre changeante rapidement, sont produits. La recherche géologique de technologie conventionnelle fréquemment n'identifie pas ces risques pendant que des emplacements de forage sont limités dans les environnements urbains. La géophysique de technologie est invitée pour localiser ces dispositifs, pour viser des forages et pour prolonger leur rayon de recherche et pour l'évaluation des travaux au sol d'amélioration avant de percer un tunnel et après des incidents.

La pesanteur détaillée a été appliquée au choix d'itinéraire pour le tunnel de route de rue de Burnley à Melbourne, Australie, définissant un palaeochannel important sous des basaltes et des alluvials et permettant le forage visé aux endroits principaux le long de l'itinéraire final. Dans Hong Kong, l'installation directionnelle d'alésage d'un tunnel de câble au-dessous d'un croisement de l'eau en granit survécu à a été exigée. Conditions à fleur de terre tracées par formation image séismique sous-marine de réfraction le long de l'alignement et des catégories survivant àes probables définies. En outre à Melbourne, pendant la construction de l'égout occidental du nord dans les alluvials à l'aide d'une aléseuse de tunnel d'EPB, des vides ont été créés à quelques endroits. Ceux-ci ont été tracés en utilisant la formation image séismique de SEWREEL entre le tunnel et la surface au sol. À un endroit, le perçage d'un tunnel induit le règlement de route et la formation image séismique SUBS des forages a défini l'ampleur de la région vidée et a examiné l'efficacité du jointoiement de remédiation. La formation image séismique SUBS était évaluation utilisée des travaux au sol d'amélioration au-dessus de la section au sol molle du Tunnel de Transport de Richmond dans San Francisco, identifiant les secteurs qui pourraient exiger le jointoiement additionnel.

Les méthodologies géologiques de technologie conventionnelle ont combiné avec des technologies géophysiques appropriées sont un outil puissant pour réduire des risques géotechniques liés au développement souterrain de l'espace.

Keywords: geophysics, gravity, hazards, risk, seismic, tunnels

INTRODUCTION

Increased geotechnical risks to underground space developments by tunnelling and directional boring occur when unexpected geological, hydrogeological or manmade hazards are encountered. These events dramatically impact safety and construction budgets. Unfortunately, many potential hazards are missed or poorly defined with widely spaced boreholes, usually employed when geotechnical risks are assessed during feasibility and design stages of such developments. While this limitation of conventional geotechnical investigations is well known it invariably increases expectations that subsurface hazards could be present. This, in turn, adds to the cost of underground space developments as greater risk is embedded in, and can become a significant component of the construction contract price.

Application of appropriate geophysical technologies integrated with conventional geotechnical investigations can greatly reduce these risks and costs and can assist ground condition assessments following incidents arising during underground construction. Detailed gravity and seismic imaging methods are appropriate geophysical methods for application to tunnelling projects in city and urban environments. The conventional gravity method (Reynolds, 1997) responds to density variations in earth materials and is principally for bedrock mapping along tunnel routes when less dense sediments overly bedrock (Whiteley & Parker, 2001) and for locating large voids, old mine workings and major geological structures such as faults. This method is relatively easy to apply but requires considerable effort in data correction to remove the effects of surrounding buildings and additional data must be acquired outside of the area of direct interest to ensure that three-dimensional subsurface effects are fully accounted in the interpretation otherwise significant depth errors can result (Whiteley & Parker, ibid.) Typical gravity station spacings for underground space developments range from 1 to 20 m.

Seismic refraction methods have also been extensively employed to map rockhead levels and are enjoying a re-vitalisation with improved field and interpretation approaches (Whiteley, 1994) using interactive ray-tracing (Whiteley, 2004) and inversion with Wavefront Eikonal Tomography (Schuster & Quintius-Bosz, 1993) that to some extent overcome the severe limitations of the Reciprocal interpretation methods that have been widely used to date (Leung, 2003). Seismic imaging methods can also be used to extend the radius of investigation of boreholes that are drilled along the alignment for geotechnical purposes but specially drilled holes can be employed at specific sites where hazards are expected or for difficult areas such as water crossings or steep slopes. Seismic imaging is achieved from individual boreholes (surface-to-borehole methods) or between pairs of boreholes (crosshole methods) or a combination.

The surface-to-borehole seismic technique is sometime called walk-away vertical seismic profiling or site uniformity borehole seismic testing (SUBS, Whiteley, 2000). Typically, the most cost-effective way of obtaining borehole seismic imaging data in the field is to use a downhole hydrophone detector array and sources ranging from sledgehammers to small explosive charges depending on the depth and spacing of the boreholes. If two boreholes are appropriately spaced (less than 2 to 3 times their depth) along the alignment then most information is obtained if SUBS and crosshole methods are combined. As the investigation radius decreases with depth it is preferable to deepen holes to as far as possible below the proposed tunnel level. SUBS testing from fewer, deeper boreholes is often a more cost-effective option than more shallow geotechnical holes, particularly if the tunnel is in a city or town. If the area has a significant thickness of low velocity materials e.g. soils and weathered rocks, the radius of investigation is considerably increased due to refraction effects at the strong rock interface.

For SUBS, an array of closely spaced hydrophone detectors encased in an oil-filled tube or eel, is lowered into a water tight, PVC-cased and filled borehole with an internal diameter exceeding 50 mm. Seismic coupling of this array to the earth is achieved by filling the hole with water or drilling fluid. The in-hole detector array typically has a length from 22 to 46 m, and the borehole may be tested by multiple sensor placements, to depths in excess of 100 m. A maximum horizontal investigation radius to two or three times the depth of the deepest hydrophone is possible, depending on local conditions. The horizontal range extends the effective radius of investigation of the borehole considerably and allows detailed calibration with geotechnical and geological information at the borehole. Seismic waves that travel from each surface-impact point to the detector array are modified by the ground conditions around the borehole within an effective volume of investigation. Should the subsurface conditions or elastic properties of these materials vary laterally around the borehole, the travel times to each subsurface detector will be different for identical source offsets around the borehole. Any significant condition that weakens the material will scatter the seismic energy and delay its travel time.

Typically, resolution of SUBS is plus or minus 2 m vertically and varies from plus or minus 2 m horizontally near the hole to plus or minus 5 m at the greatest distance from the hole. This resolution can be improved with closer source and detector spacings, but is ultimately limited by the seismic signal bandwidth. Up to 4 SUBS holes to depth of about 90 m can be completed in one day with multiple seismic scans in different directions from each hole. For some underground space development projects detailed gravity and borehole seismic imaging can be usefully applied at different stages to target boreholes and to test conditions between boreholes (Whiteley, in press).

If the conduit or underground opening can be accessed during construction than another seismic imaging technology called SEWREEL is available. This method was developed as an adaption of crosshole seismic to provide detailed information on the materials between the opening and the ground surface. SEWREEL has been extensively used in conjunction with CCTV inspection to provide comprehensive information on the internal and external sewer conditions (Whiteley, 2001). In this test, an array of closely-spaced hydrophones, encased in an oil-filled tube, called an ‘eel,’ is placed along the invert of the conduit or accelerometers are grouted at discrete intervals to the tunnel wall. The detector array remains stationary while the impact seismic energy source is deployed on the surface above the tunnel at close spacing along the alignment. SEWREEL imaging can be performed to a depth of about 50 m at a rate up to 300 m per day and the seismic images allow high-resolution definition of subsurface features along the sewer alignment. Typical resolution is plus or minus 1 m horizontally and plus or minus five percent of depth to the base of the opening vertically. Voids as small a 0.6 m high and 3 m long have been identified and confirmed over shallow conduits. Application of these geophysical these geophysical methods to underground space developments using tunnelling and directional boring is illustrated with the following short case studies.

CASE STUDIES

Burnley Road Tunnel, Melbourne, Australia

The Burnley tunnel is part of the Melbourne City Link Project (Short et al. 1999). This is a 3.4 km long driven road tunnel from 9 to 12 m high and 16m wide that was constructed by road header from 1996-98 in high strength variable Silurian Mudstone to a maximum depth of about 65 m (Lamb et al. 1998). This tunnel follows the course of a large paleochannel (the Jolimont Valley) that incises this mudstone and is infilled with basalts and Tertiary and Quaternary alluvial materials. This feature represented a major construction risk to the Project due to the uncertainty of ground conditions (Rozek, et al. 2001). Even through extensive geotechnical investigations were completed these were constrained by the city environment. A detailed gravity survey along the tunnel route was completed through the Melbourne streets as a cost-effective option to better define the limits and axis of this palaeochannel. This method had been previously successfully applied to other tunnelling projects in Australia (Whiteley, 2005).

Figure1 shows the Bouguer gravity map and with the approximate limits of the paleochannel marked. The tunnel route is also shown together with the channel axis from the gravity interpretation compared with that from the gravity interpretation. These are considerably different on the western side of the alignment.

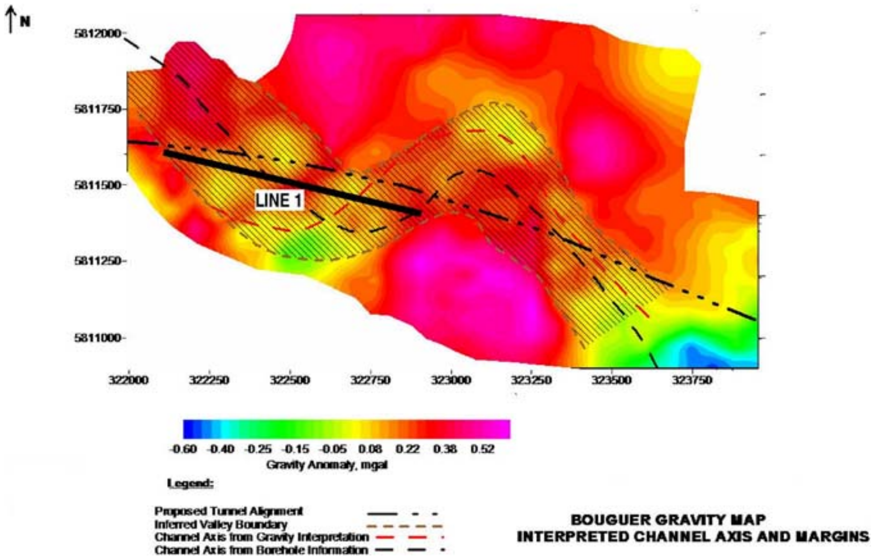

Figure 1. Bouguer Gravity Map of the Burnley Tunnel alignment.

Figure 2 is an interpreted gravity profile (Line 1) along the paleochannel in this region together with the available drilling information. This shows the complexity of the channel floor and the final gravity model with six irregular layers of differing density. The gravity results were used to assist in refining the geotechnical model for final tunnel design.

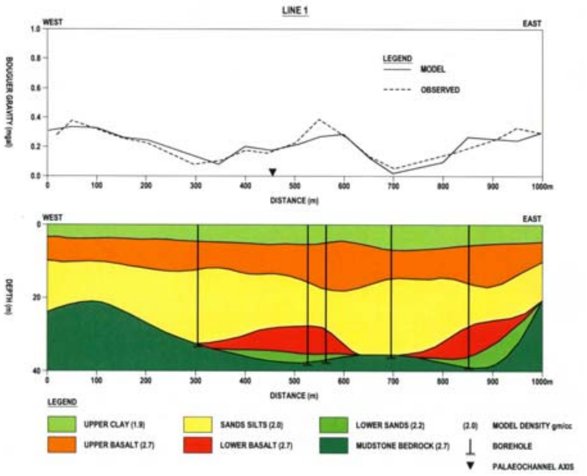

Figure 2. Interpreted Gravity profile along the palaeochannel

Power Cable Directional Bore, Lantau Island Hong Kong

Electrical power upgrades for the environmentally sensitive Lantau Island, Hong Kong required the installation of 132kV power mains by directional boring a 300 m water crossing at Pui O beach that also traversed the Tolo Channel Fault, Hong Kong's largest fault structure that is observed as a feldspar porphyry dyke swarm within granites. As overwater geotechnical boring was not permitted for environmental reasons, an underwater seismic refraction imaging was completed along the proposed cable tunnel alignment. The interpretation of the seismic refraction data was achieved by interactive ray tracing (Whiteley, 2004) and the final subsurface seismic model with the field and synthetic travel-time data set for a 200 m length of the alignment is shown in Figure 3. Three irregular layers of differing seismic velocity, that were correlated with a nearby land borehole, were identified in this interpretation. The seismic velocities in these layers were also correlated with the likely weathering grade for Hong Kong granites (Fletcher, 2004). The upper layer has a uniform seismic velocity of 1600 m/s represents saturated sandy sediments and Grade V to IV granite. The intermediate layer with velocities ranging from 2900 to 3200 m/s represents Grade III to Grade II granite with possible corestones. The upper surface of this layer corresponds to rockhead. The lower layer has velocities in the range 3850 to 5850 m/s this corresponds to Grade II to Grade I granite and is the preferred medium for the directional bores. Sjogren et al. (1979) showed that seismic velocities for fresh, Scandanavian igneous rock including granites (Grade I) depends on the depth and degree of fracturing or jointing. In these materials, seismic velocities greater than 5500 m/s correspond to fresh granites with less than 3.5 cracks per m, increasing by about 3 to 4 cracks per meter for every 1000 m/s velocity decrease to 3500 m/s. Crack density within the lower velocity sections of the preferred boring medium estimated from the seismic interpretation and hatched on Figure 3 can be expected to exceed 6-7 cracks/m and generally about half of this elsewhere.

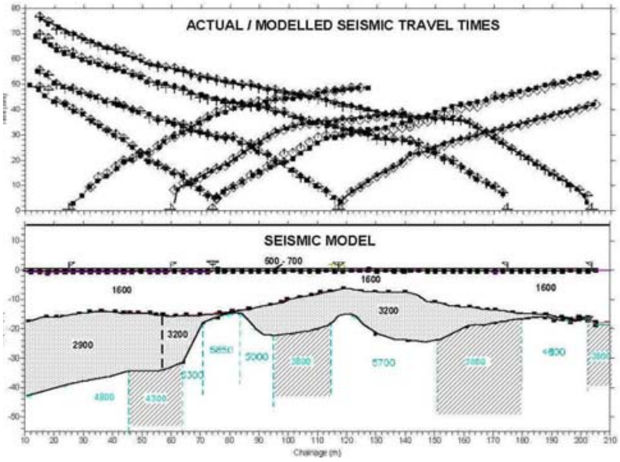

Figure 3. Interpreted seismic refraction section, Pui O beach.

North Western Sewer, Melbourne, Australia

The North Western Sewer is an 11 km tunnel with 9 shafts up to 35 m deep and was a major upgrade of the sewerage system through the Melbourne's western suburbs that was constructed between 1992 and 1997 (Stevenson & A'Vard, 1997). The first 3 km was driven in basalt by a 5.5 m diameter Robins tunnel boring machine with the remainder constructed using a 4 m diameter Lovat EPB machine mainly in Tertiary, fine to coarse sands and silty to sandy clays, sometimes beneath basalts and Quaternary soils.

Significant geophysical investigations using seismic imaging were undertaken at two locations along the mixed ground section of this tunnel where problem were experienced during tunnelling. Beneath basalt layers, along one 150 m section of the tunnel, increased waste volumes were experienced and there were concerns that water charged, free-flowing sands above the crown of the tunnel might cause voids to form that could destabilise the overlying fractured basalt possibly causing large block to impact the crown of the tunnel. SEWREEL was used to image the subsurface between the tunnel crown and the road surface. This involved bolting geophones to the liner along tunnel crown at 2 m intervals and impacting the road surface along this section at 5 m intervals. The resulting seismic image, with the generalised geological section is shown on Figure 4. There were some constraints in the limits of the higher velocity fractured basalt section used to construct this image that was produced with curved ray tomographic algorithms. In the sands/silts materials above the tunnel near Ch. 3900 and from Ch. 3940 to Ch. 4000 low velocity regions indicative of voids were identified, these were confirmed by drilling and direct observation. The higher velocity zones within the latter section were found to be basalt rocks resting on the tunnel.

A more serious situation occurred during construction of Section 3 of this tunnel (Stevenson et al. 1999) when a 4 m by 4 m section asphalt pavement within the roadway collapsed above the tunnel axis. This incident and the subsequent remedial works are more fully described by Pedler & Whiteley (2000). At the time of the collapse the tunnel was at 18m depth within Tertiary alluvial material and beneath Quaternary alluvials. There were no basalts in this area. Surface-to-borehole, SUBS seismic imaging between a pair of cased boreholes (BH 365 and 366) either side of the collapse area was used to assess its extent in the subsurface and to evaluate the effectiveness of the remedial grouting works.

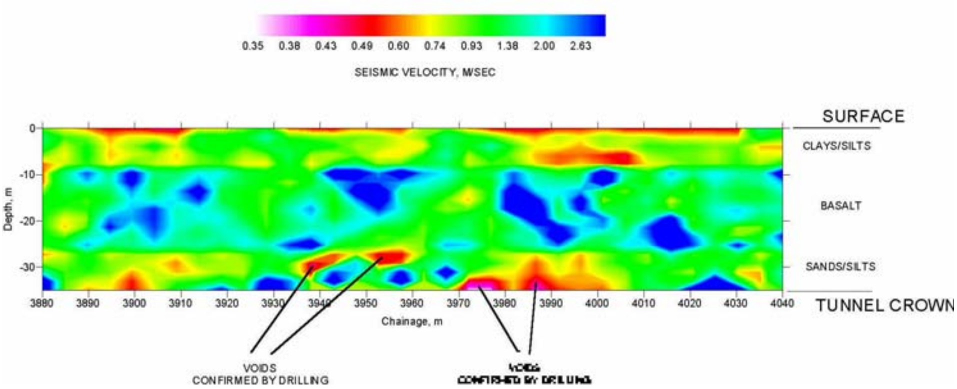

Figure 4. SEWREEL seismic image, North Western Sewer

The SUBS method involved placing a hydrophone array with detector at 1m intervals in a water-filled borehole and impacting the ground surface at 2 m intervals along scan lines radiating from each borehole. Figure 5 shows seismic images that were taken through the centre of the collapse area at various stages during the remediation works that were used to stabilise the near surface materials. The deeper materials were stabilised by grouting from the tunnel. An initial image, obtained prior to grouting but after placement of stablised fill, defined the approximate limits of loose and very loose soils as low and very velocity zones (< 0.8 km/s) extending to a depth of about 12 m. Figure 5a is the seismic image obtained after the first phase of bentonite cement grouting from other boreholes on the surface. Unfortunately this grouting accelerated surface movement and subsidence area was re-excavated from the surface and filled with stabilised sand. Second phase grouting was then completed. Figure 5b is the seismic image obtained after this phase. The extent of the seismic low velocity zone and the inferred loose soil zones have been greatly reduced and the area has remained stable since the tunnel was completed.

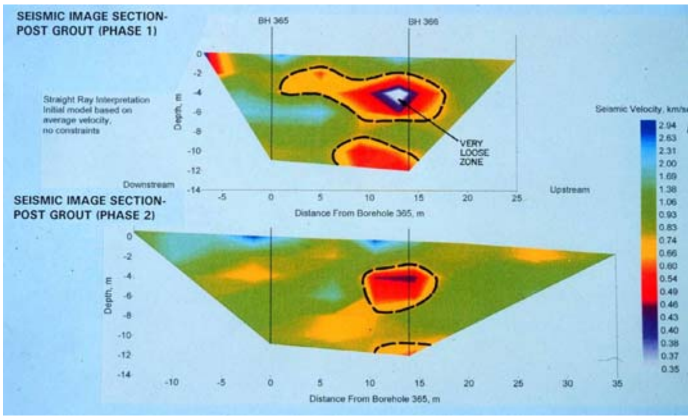

Figure 5. SUBS seismic images of collapse area at various stages of remediation.

Richmond Transport Tunnel, San Francisco, USA

The Richmond Transport Tunnel was constructed in 1996 to alleviate stormwater and sewage pollution of Baker and China Beaches and San Francisco Bay that frequently followed significant rainfall events. This 4.3 m diameter tunnel is about 3.1 km in length and has both hard and soft rock sections. The soft rock section is located beneath a roadway and is about 365 m long, varying in depth from about 6 to 30 m. The geological conditions in this area are saturated, cohesionless dune sand and weakly cemented sands of the Colma Formation that are described more fully by Klein et al. (2001). Groundwater levels varied from about 1.5 to 15 m below ground surface. The main concern for tunnelling the soft ground section was the potential for the sands to exhibit unstable behaviour and cause surface settlement that could damage to shallow services, pavements and the expensive residences on either side of the alignment. The approach adopted for tunnelling this section was to dewater from 12 pumping wells about 37 m deep and to use an open face tunnelling machine.

In order to stabilise the soils at the tunnel level and to minimise the risks of catastrophic face loss and uncontrollable surface settlements, chemical grouting was carried out from the shield in advance of tunnelling by drilling grout holes from the tunnel to about 18 m ahead of the face. This provided an approximately 2m thick zone of stabilised soils around the tunnel margin. The potential for surface settlement during tunnelling was further reduced by compaction grouting from vertical holes drilled from the surface at 1.5 m intervals along the tunnel centreline. The compaction grouting involved injecting a bulb of thick low slump grout above the tunnel crown and the average volume required was about 3.5% of the volume of the tunnel excavation (Klein et al. 2001).

Following construction, SEWREEL seismic testing was carried along the soft ground section of the tunnel to check for any remaining voids or loose sands above the tunnel invert. This was followed by targeted drilling and SPT testing. Figure 6 shows a SEWREEL seismic image of a section above the soft ground section tunnel over an interval of about 60m (9560 to 9740) where generally lower seismic velocities were measured. The blocky nature of these images is due to the grouting operations. This image also shows some very low velocity regions indicative of voiding near the tunnel at Ch. 9620 and some lower velocity regions above the tunnel crown. BH 4 and 5 were targeted to directly calibrate these velocities. BH4 was in a lower velocity region and showed generally lower SPT values with some very low velocities well above the crown. These conditions were not considered to indicate that further grouting was required but did show that lateral variations in soils density with some possible local voiding were present. Surface settlement during tunnelling was limited to less than 13 mm with no damage to residences and the ground surface has remained stable since construction.

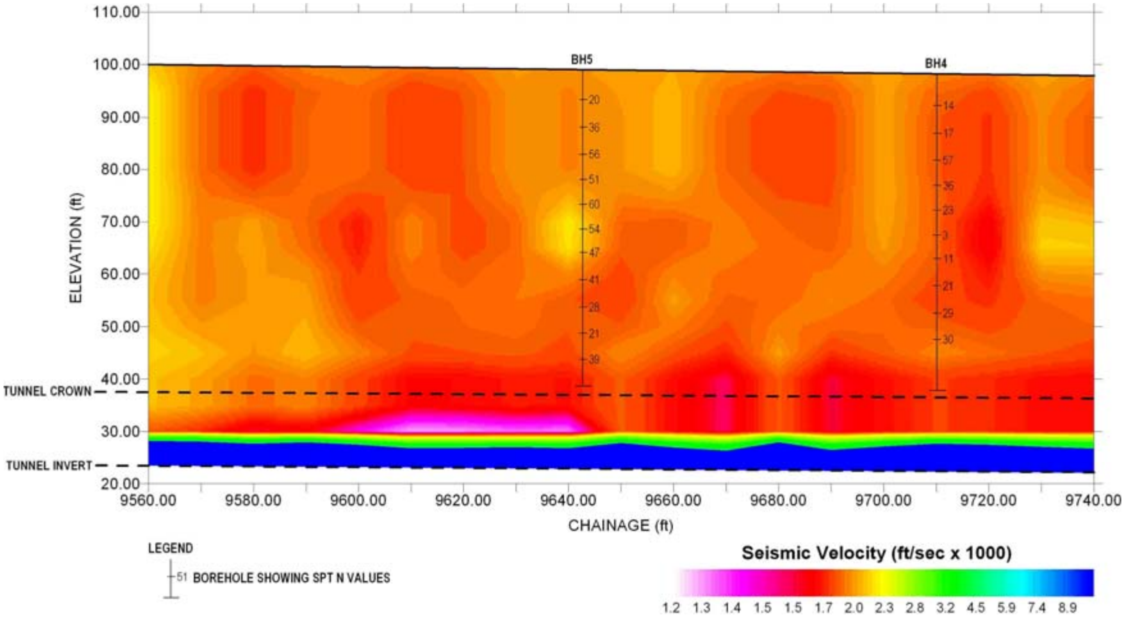

Figure 6. SEWREEL seismic images above the Richmond Transport Tunnel.

CONCLUSIONS

Detailed gravity surveying is a useful technology for bedrock mapping and identification of major geological hazards at the feasibility and design stages of underground space developments. Seismic refraction and imaging technologies implemented from geotechnical boreholes or underground openings allow a more comprehensive of ground conditions than provided by drilling alone. These methods are also useful to assess changed ground conditions following construction incidents and remediation works. When these geophysical technologies are fully integrated with conventional geotechnical assessments the risks to underground construction from unexpected geological hazards can be greatly reduced with positive benefits to planned or actual underground construction costs.

Corresponding author: Dr Robert J. Whiteley, Coffey Geosciences, 8/12 Mars Road Lane Cove West, Sydney, New South Wales, 2066, Australia. Tel: +61 2 9911 1000. Email: bob_whiteley@coffey.com.au.

REFERENCES

FLETCHER, C.N.J. 2004. Geology of Site Investigation Boreholes from Hong Kong. AGS (HK), 132p.

KLEIN, S., KOBLER, M. & STRID, J. 2001. Overcoming difficult ground conditions in San Francisco- the Richmond Transport Tunnel, San Francisco County, California, *Engineering Geology Practice in Northern California, Bull.* **210**, *Div. of Mines and Energy*, 13-22.

LAMB, I.A., COULSELL, J.B. & HUTCHISON, B.J. 1998. Melbourne City Link Tunnels – Part 1: Engineering geology in an urban environment. *Proceedings of the 8th Congress of the International Association for Engineering Geology and the Environment, Vancouver, Canada.* Balkema, Rotterdam, 5, 3723–3730.

LEUNG, T.M. 2003. Controls of traveltime data and problems of the generalized reciprocal method. *Geophysics*, **68**, 1626-1632.

PEDLER, I.V. & WHITELEY, R.J. 2001. Applying innovative geophysical methods to assist identification of road collapses. *Aust. Geomechanics*, **36**(2), June 2001, 57-63.

REYNOLDS, J.M. 1997. *An Introduction to Applied and Environmental Geophysics*, John Wiley & Sons, 806p.

ROZEK, J., MATHERS, K. & CONLEY, T. 2001. Melbourne City Link Tunnels: End Play. *2001 RETC Proceedings*, **Ch. 45**, 553 – 563.

SCHUSTER, G.T. & QUINTUS-BOSZ, A. 1993. Wavepath eikonal traveltime inversion: Theory. *Geophysics*, **58**, 1314 – 1323.

SHORT, M., WEEKS, N., WOODALL, R. & PORTER S. 1999. Design of the Melbourne City Link Tunnels, *Proceedings of the 10th Australian Tunnelling Conference Melbourne, 21-24 March 1999*, 2-12.

SJOGREN, B. OFSTHUS, A. & SANDBERG, J. 1979. Seismic classification of rock masses qualities. *Geophysical Prospecting*, **27**, 409-422.

STEVENSON, A. & A'VARD, R. 1997. North Western Trunk Sewer. *World Tunnelling*, June 1997, 197-200.

STEVENSON, A., HAKE, D., MILTON, R. & SPRAGUE, H. 1999. The North Western Sewer Tunnel Project – Section 3. *Proceedings of the 10th Australian Tunnelling Conference, Melbourne, 21-24 March 1999*, 335 -342.

WHITELEY, R.J. 1994. Seismic Refraction Testing – a tutorial. In: *Geophysical Characterisation of Sites*. ed. R.C.Woods, A.A. Balkema, Rotterdam.

WHITELEY, R.J. 2000. Seismic imaging of ground conditions from buried conduits and boreholes. *Proceedings of Paris 2000, "Petrophysics meets Geophysics," Paris, 6-8 Nov. 2000*, **paper B-15**.

WHITELEY, R.J. 2001. Condition risk assessment of underground utilities with SEWREEL seismic imaging. *Proceedings of SAGEEP 2001, Denver, 4-7 March 2001*, 1-7.

WHITELEY, R.J. & PARKER, C. 2001. Application of geophysical and geotechnical technologies to major tunnels in Sydney, Australia. *2001 Proceedings of the Rapid Excavation and Tunnelling Conference, SMME, San Diego*, Ch. 24, 285-298.

WHITELEY R.J. 2004, Shallow seismic refraction interpretation with visual interactive ray tracing (VIRT) Modelling, *Exploration Geophysics*, **35**(2), 116-123.

WHITELEY R.J. 2005. Gravity mapping and seismic imaging of paleochannels on large tunnel routes in Sydney Australia. *Geotechnical and Engineering Geophysics, Vol. 2 Case Studies*, ed D. W. Butler, Society of Exploration Geophysics, Tulsa, Ch. 15, 549-558.