Role of Engineering Geology in Design and Construction of a Large Road Cut, Ballina NSW

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ABSTRACT

The development of a reliable geological model for a proposed 20m high cut located within the northern section of the Ballina Bypass project presented particular challenges with respect to design and construction. The cut geology comprised variably weathered Tertiary basalt underlain by an approximately 1.5m thick, sub-horizontal unconsolidated 'tuff' layer and a highly irregular bedrock surface. Concept Designs for the cut based on assumed geological models proposed the use of extensive rock anchors to support the cut.

As part of Detailed Design studies, engineering geological skills were found to be invaluable in the development of the geological model, in particular the observation of rock exposed along the coast and in nearby quarries, and the re-inspection of available rock cores.

Following refinement of the geological and hydrogeological models of the cut, and analysis of critical geological sections as part of the design studies, it was concluded that there was no need for slope support measures to be installed. The project demonstrates the importance of developing reliable geological models based on sound engineering geological observations and interpretation early in the design process, with consequent substantial savings both in time and money.

Keywords: engineering geology, road cut, design

1 INTRODUCTION

The northern section of the Ballina Bypass project in north-eastern New South Wales involves the upgrade of approximately 5.3km of the Pacific Highway to a two lane dual carriageway extending from Cumbalum in the south to Tintenbar in the north. Within the northern hillside section of the Bypass, Cut 4, an approximately 300m long by 20m deep side-cut in variably weathered basalt, presented particular design challenges with regard to the extent of possible slope support and slope drainage measures.

Geotechnical investigations for the Bypass commenced in 1995 and continued in a number of stages through to completion of final design in 2008, with opening of the northern hillside section to traffic in 2011. Preliminary interpretation of the geology at the cut identified the presence of a 1.5m thick, sub-horizontal unconsolidated 'tuff' layer near the proposed floor level of the cut. Consequently, Concept Designs for the cut based on assumed geological models, proposed the use of extensive rock anchors to support the cut.

The cut was designed and constructed with 2H:1V batter slopes; with a maximum vertical spacing of 10m between benches; and with 4.5m wide bench widths. The cut comprises four batters and three benches, with the crest of the cut near RL.55m and the toe at approximately RL.20m AHD.

This paper describes the process by which the engineering geological model of the cut was developed through the various design stages and the implications this had on design and construction.

2 GEOLOGICAL SETTING

The site is located in the New England Fold Belt and is underlain by the Neranleigh-Fernvale Beds (referred to hereafter as 'argillite') which are of Devonian to Carboniferous age. These beds comprise a thick turbidite sequence of weakly metamorphosed argillite (claystone, siltstone and shale) with minor lithic sandstone and quartzite. Subsequent to deposition, the argillite rocks were subject to several periods of deformation during the New England Orogen, resulting in small to large scale folding, foliation and shear zones. Such deformation has resulted in a general north-south foliation strike and both east and west steeply dipping bedding planes. Uplift of the area is thought to have occurred in the late Cretaceous, and subsequently the land surface was subject to weathering and erosion over a period of tens of millions of years.

During the Tertiary Period, extensive basaltic volcanism associated with the Lamington Volcanics (centred on the Mount Warning shield volcano to the north) occurred across the region (Smith 2002), with basaltic lavas extruded onto a highly irregular landform. The basalt comprises layered deposits of massive lava flows forming laterally extensive sheets, palaeosol soil horizons representing weathering episodes between successive flows, isolated tuff layers (consolidated rhyolitic volcanic fragments) representing ash fall deposits associated with distant volcanism, and volcaniclastic breccias (agglomerates) originating from volcanic vents.

At the time of extrusion of the basalt lavas, the Tertiary land surface was highly irregular with variable slope angles and a complex drainage pattern (relict land surfaces of up to 55° were mapped during site investigations). In addition, colluvial deposits (talus or breccia) were locally present on the Tertiary surface, further confirming the variability of the often extensively weathered Tertiary land surface. Given the highly variable Tertiary land surface, the basalt flows and volcanic ejecta (volcaniclastic breccia and tuff) are known to have followed localised features such as valleys and channels; some of which may have been active streams with associated alluvium. Due in part to the sub-tropical climate and the inherent susceptibility of basalt to weathering, the hillside terrain is deeply weathered with very few outcrops.

3 DEVELOPMENT OF GEOLOGICAL MODEL

3.1 Concept Design Geological Model

Concept Design phase geotechnical investigations at the site involved the drilling of approximately 20 cored boreholes and the excavation of a number of test pits between 2002 and 2007. Based on these investigations, the geology of the site was interpreted to comprise variably weathered volcanics overlying argillite. The variably weathered volcanics include basalt derived clay, basalt derived clay matrix with basalt corestones and variably weathered basalt rock. In the southern part of the cut, an apparently continuous sheared tuff derived clay layer was inferred to be present. Beneath the basalt there was inferred to be a sheared clay contact with the argillite, argillite derived clay and highly weathered argillite

The initial interpretive work identified some key geological features within the site. The first was a basalt/argillite interface interpreted as dipping at around 20°-25° to the west in the southern part o f the cut and at around 25° to the south in the northern part of the cut. A number of cored borehole logs indicated the presence of polished and slickensided surfaces at the boundary between the two lithologies, inferring the presence of a sheared contact between the basalt and the argillite.

The second key feature was the presence of a sub-horizontal poorly consolidated sediment layer within the basalt succession, located immediately below the toe of the cutting within the central and southern portion of the cut. This layer was interpreted as a ‘tuff’ horizon. Shearing was also inferred within this layer due to the presence of slickensided surfaces and polished fissures.

3.2 Detailed Design Geological Model

The Detailed Design Model was developed by the Ballina Bypass Alliance from 2007 onwards. During the detailed design stage investigations, engineering geological studies included a review of all available site investigation data, a re-inspection of available rock cores and inspection of basalt/argillite contacts exposed in nearby quarries and in coastal cliffs. An example of one of the key cross sections developed for the cut by the Ballina Bypass Alliance is presented in Figure 1.

The coastal outcrops expose basalt flows (comprised of a number of separate flow events) overlying sedimentary strata. The overlying basalt was observed to have deformed the underlying strata during deposition, resulting in buckling and rafting of the underlying sediments producing a highly irregular contact (Figure 2).

The relationships exposed within these coastal outcrops provide an analogy for the processes that may have occurred during basalt deposition at the cut. It is inferred that the slickensided and polished fissures observed within the ‘tuff’ layer within the cut basalt succession are actually the result of syn-depositional shearing. Irregularities in the thickness of the ‘tuff’ layer and angled bedding/laminae within the layer may be attributed to deformation shortly after basalt deposition. Similarly, polished surfaces noted at or adjacent to the interface between the basalt and underlying argillite may also be the result of syn-depositional movement.

In addition to observation of rock outcrops in nearby quarries and along the coast, a re-inspection was made of available rock cores. Specific boreholes were scrutinised, particularly those reported to contain sheared contacts, both at the basalt/argillite contact and also within the sub-horizontal layer inferred to be ‘tuff’. This detailed re-inspection of rock cores did not corroborate the presence of a sheared contact between the argillite and overlying basalt. Although some polished planes were evident within residual argillite close to the contact, these were inferred to be polished fissures developed with the argillite prior to basalt deposition. Secondly, with regard to the sub-horizontal ‘tuff’ layer within the basalt succession, the presence of some polished/slickensided surfaces within this material was confirmed in several boreholes.

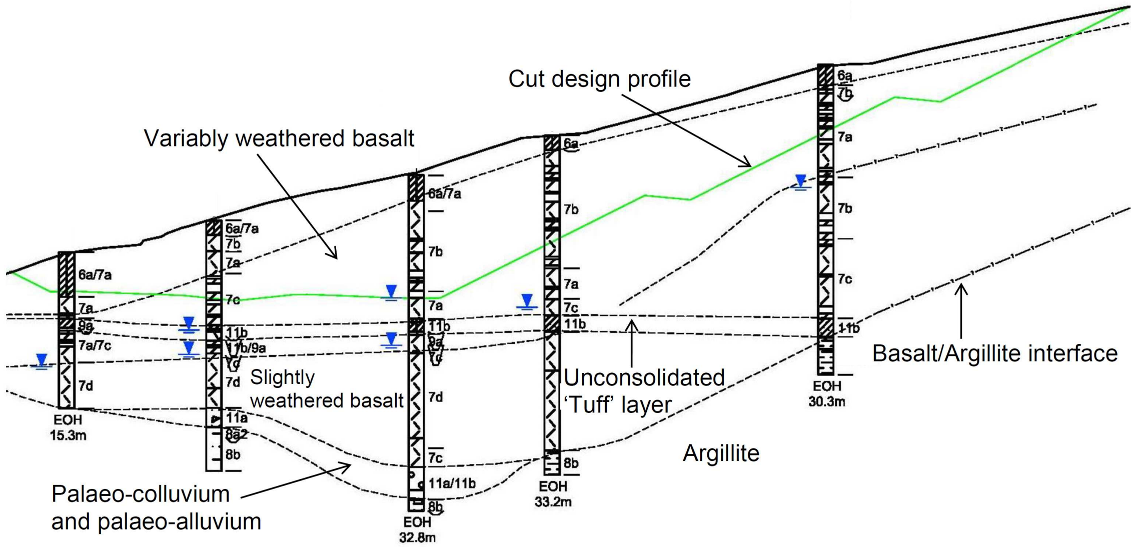

Figure 1. Detailed Design Model and Final Cut Design

Careful inspection of the rock core during the review revealed that in some instances the identification and interpretation of tuff was incorrect. Although the presence of 'tuff' within this sub-horizontal layer was assessed to be correct in some boreholes, it would appear that the extent of the tuffaceous material was far more restricted than previous work would suggest. It was assessed that much of the material that had previously been identified as 'tuff' would actually appear to be of colluvial and fluvial origin. The material often had no apparent structure, with a seemingly high proportion of kaolinite and was observed to contain fine quartz and lithic gravel. The proposed mechanism for the formation of this material was the erosion and reworking of adjacent 'highland' material (composed primarily of argillite) with subsequent deposition in depressions and channels over basalt flows. Carbonaceous material, including petrified wood, was commonly identified near the top of the 'tuff' layer indicating vegetation had once been established. This material may then have been reworked further by fluvial processes before eventually becoming covered by subsequent basalt lava flows.

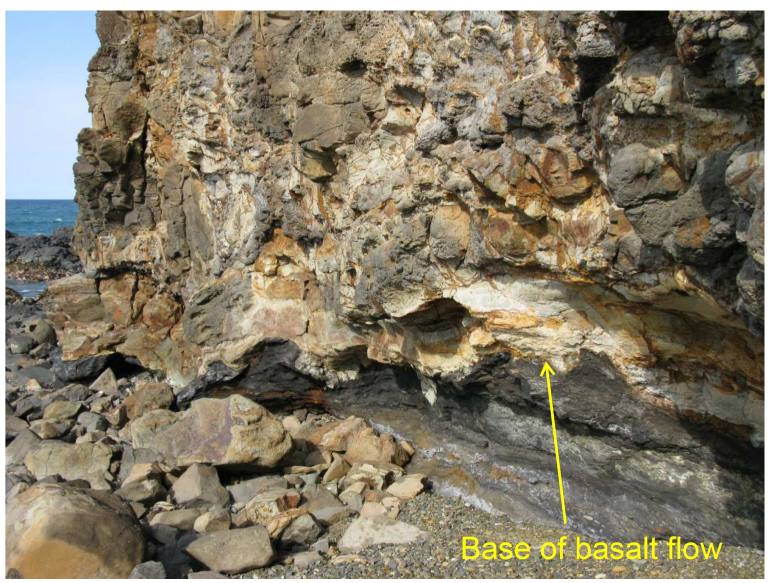

Figure 2. Coastal basalt exposure showing highly irregular contact with underlying sedimentary strata

Palaeosol horizons, characterised by layers of reddish brown clay/extremely weathered rock within the basalt succession were also indentified during the review of rock core which are interpreted to represent periods of weathering between separate basalt flow events.

As part of the Detailed Design Studies, a final phase of site investigation was carried out. This comprised the drilling of an additional 9 boreholes targeted to intercept specific geological features. The primary focus of this investigation was the sub-horizontal 'tuff' layer within the basalt succession. Greater insight into the nature of this material and a better understanding of its extent and variability at the site was needed. The additional boreholes also enabled further sample recovery and subsequent strength, petrographic and XRD analyses. A series of standpipe piezometers and data loggers to assist in the development of a more refined hydrogeological model were also installed at this time.

The additional boreholes allowed the basalt/argillite interface to be mapped with relative confidence, enabling the palaeotopography to be modelled.

Where encountered, the sub-horizontal ‘tuff’ layer within the basalt succession was found at a relatively consistent level, although its thickness was inferred to vary from approximately 1m to 2m. The sub-horizontal ‘tuff’ layer was noted to be variable in composition over short distances (<20 m) with tuffaceous material, reworked argillite and other detrital sediment present in varying proportions. The presence of tuffaceous materials interbedded with the sedimentary units indicates that these deposits are all intimately associated and contemporaneous with one another, all co-existing within the same palaeoenvironment. The palaeoenvironment at the time of deposition of these sediments was likely a highly dynamic one, with a complex interplay of erosion, deposition and reworking of the various sediment types. A schematic block model of the likely palaeoenvironment at the time of deposition of these sediments is presented in Figure 3 below.

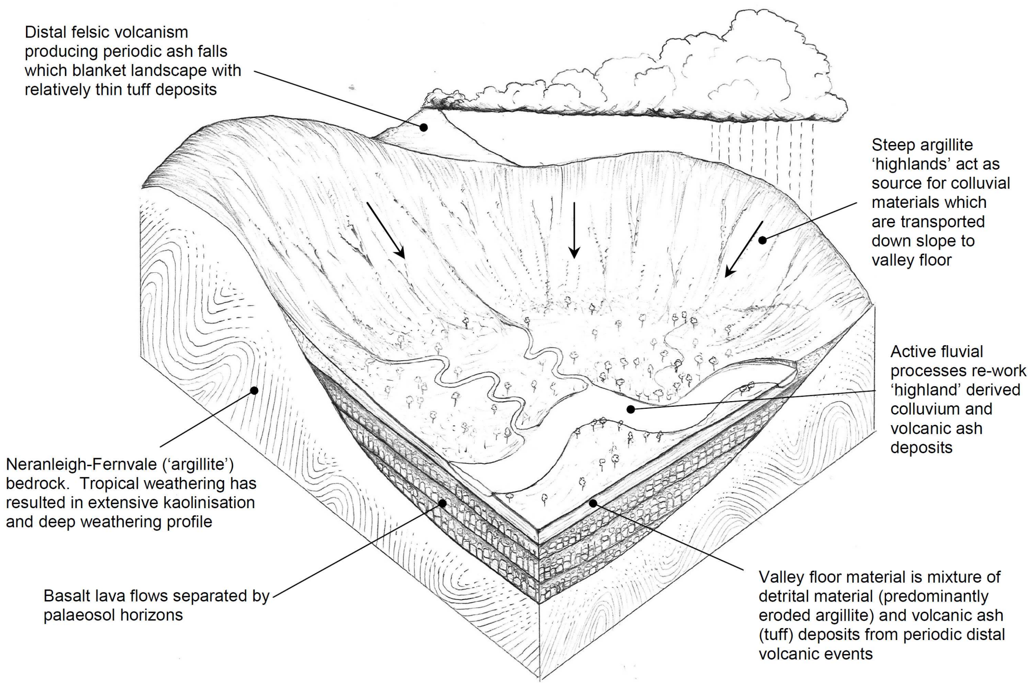

Figure 3. Schematic block model showing inferred palaeoenvironment at the time of deposition of the ‘tuff’ layer.

Petrographic and XRD analyses on samples taken from the ‘tuff’ layer confirmed the highly variable origin of this material, with some XRD samples indicating smectite contents up to approximately 50% and crystal shapes characteristic of derivation from a felsic volcanic source. Other analyses indicated dominant kaolinite/illite and strained quartz grains more characteristic of a weathered metamorphic terrain source. The results of the petrographic and XRD analyses strongly supported the geological model of erosion and deposition of proximal deeply weathered low grade metamorphic terrain, contemporaneous volcanism, and the final reworking of these materials by sedimentary processes.

4 GEOTECHNICAL DESIGN

The geotechnical model of the cut developed for the Concept Design Phase assumed a sheared basalt/argillite contact with strength parameters of c’=0kPa and $\phi'=10^0$, and a ‘tuff’ layer with strength parameters of c’=2kPa and $\phi'=12^0$. Based on these critical strength parameters and assuming a piezometric surface was maintained (by effective sub-horizontal drainage) 3m above the basalt/argillite contact, a Factor of Safety (FOS) of less than one was obtained. To achieve a FOS of at least 1.5, slope support was required over a length of approximately 280m and comprised up to 4 rows of 900kN anchors at 1m centres, or alternatively, 1.8m diameter bored piles with 1300kN to 2600kN tie back anchors at 3.6m centres longitudinally.

Following formation of the Ballina Bypass Alliance, as more geological, hydrogeological and laboratory test data became available, refinement of the geotechnical model enabled subsequent reductions in slope support measures. Early in the design process it was shown that the Concept Design stabilisation options were able to be reduced in the Preliminary Design to a length of 50m where two rows of approximately 30m long, 700kN anchors at 1m centres were needed. This was due primarily to the adoption of less conservative design parameters following reassessment of the material types and the fact that the shearing observed within the 'tuff' horizon was assessed as localised and syn-depositional and not indicative of more recent slope movement.

Further site investigation drilling, laboratory testing, and monitoring of groundwater levels was carried out during Detailed Design to refine both the geological and hydrogeological models. This work allowed the sheared basalt/argillite contact to be eliminated from the design model, together with revision of the design parameters for the now localised 'tuff' layer (c'=0kPa, ϕ'=20^0), and replacement by unconsolidated Tertiary sediments (c'=10kPa, ϕ'=26^0). Design phase analyses indicated that with the adopted geotechnical unit strength parameters and assumed groundwater levels, FOS in excess of 1.5 were achieved for the three most critical geological cross-sections analysed. Parametric studies of the impact of variations in groundwater levels and material parameters in the geotechnical units critical to slope stability also indicated FOS in excess of 1.5 (for all but the most pessimistic of material parameters). Given the above, it was concluded that apart from the possible need to install sub-horizontal drainage holes to control local slope instability, there was no need for major slope support measures (such as rock anchors or bored piles) in the Final Design for the cut.

5 CONSTRUCTION STAGE GEOLOGICAL MAPPING

Regular inspection and geological mapping of the exposed batter faces by an engineering geologist was performed throughout construction. The observed geology and groundwater conditions were generally as inferred from the site investigation data, with the following variations to the assumed geological model of the cut:

- The contact between the basalt and the underlying argillite at the northern end of the cut, although with an average dip of 20° (to the south) was more variable than predicted with dip angles as steep as 60° to 75°, and as low as 10° at other locations, together with variable dip directions. This highly irregular contact confirms the predicted irregular surface topography prior to deposition of the basalt.
- Within the northern half of the cut (and exposed across both carriageways) an approximately 3m to 5m thick layer of poorly consolidated sediments was more variable than envisaged during design. In the vicinity of Stn.132,280, a relatively shallow depression estimated to be approximately 2m deep, 15m wide and 30m long and oriented approximately parallel to the centreline, had been eroded into the underlying argillite. This depression had been infilled with horizontally bedded, mostly sandy clay sediments, including several 30-50mm thick carbonaceous siltstone layers, together with wood fragments and coalified organics.
- On the lowermost cut batter within the poorly consolidated sediment layer an irregular lense (some 3m long by 1m high) of carbonaceous siltstone was exposed, containing sub-rounded, essentially fresh, vesicular basalt cobbles. This rock mass, of uncertain geological origin, further highlights the complexity of the geological conditions surrounding the deposition of the Tertiary volcanics and sediments.

The geological mapping undertaken during construction confirmed that the palaeoenvironment at the time of deposition of the Tertiary volcanics and sediments comprised a dynamic and complex interplay of deposition, erosion and reworking of the various sediment types, onto either a highly irregular argillite surface or as interbeds between basalt flows.

As a result of the geological conditions mapped during construction, a number of slope and pavement drainage measures anticipated during Detailed Design of the cut were able to be more accurately delineated. In particular, the thickness of the drainage blanket was increased to 600mm (from the designed 300mm) to provide a competent subgrade over an area of wet, weaker foundations, and twelve 30m long sub-horizontal drainage holes were installed near the centre of the cut to help control groundwater levels.

6 POST CONSTRUCTION MONITORING

During construction three inclinometers and three piezometers, located at toe and on the first and second benches, were installed to monitor slope movements and groundwater levels at a critical section of the cut centred on approximately Stn. 132,200.

Since construction, lateral movements have been recorded in each of the three inclinometers. The largest movement (approximately 37mm) was recorded at a depth of about 2m below the toe of the cut. This corresponded to a contact between an approximately 1.5m thick poorly consolidated sediment layer and underlying competent, essentially fresh basalt. Following construction of a longitudinal drain at the toe of the slope; installation of a deepened drainage blanket; and completion of the concrete pavement adjacent to this inclinometer, no further movements have been recorded at the toe of the cut.

Monitoring of the inclinometers located on the first and second benches, indicated total movements of approximately 21mm and 17mm respectively, at a level corresponding to the contact between the base of the unconsolidated sediment layer and the top of the underlying competent bedrock (Figure 4). These movements are considered to be a result of stress relief following the removal of the overlying basalt and not due to overall slope instability.

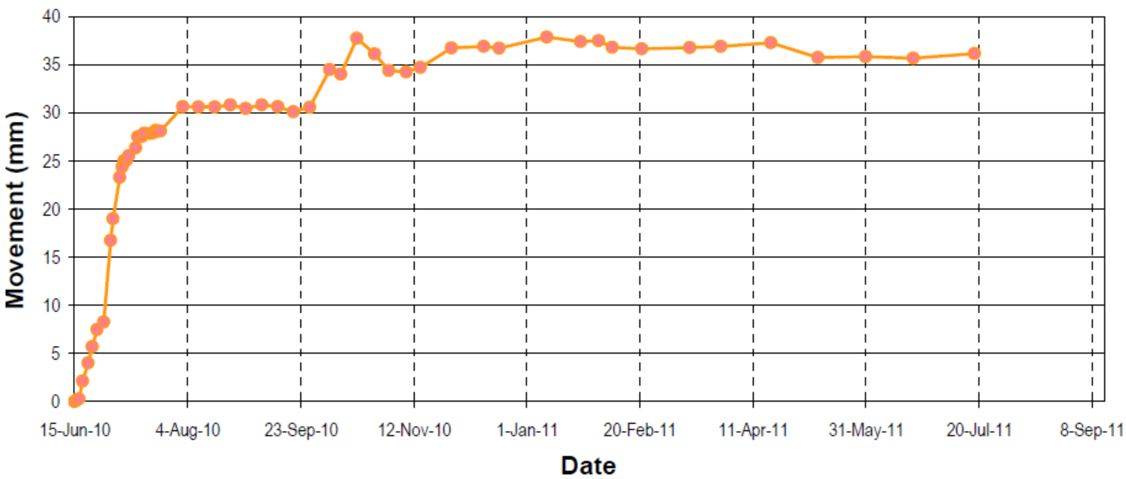

Figure 4 - Lateral Movements at Inclinometer located at toe of cut.

Down-hole data loggers were also installed in three piezometers located at the cut to monitor variations in groundwater levels. Since installation of the longitudinal drains, a deepened drainage blanket, and the sub-horizontal drains in December 2010, groundwater levels at the cut have fluctuated in a narrow range in response to rainfall events, within the 1.5m unconsolidated 'tuff' layer. This is significant, as groundwater monitoring before the installation of the drainage measures indicated groundwater fluctuations of up to 3m to 4m in response to significant rainfall events.

7 CONCLUSION

The staged development of the geotechnical model of Cut 4 on the Ballina Bypass has demonstrated the important role that engineering geology plays in the engineering design process, and of substantial savings both in terms of cost and time that can accrue as a result of this specialist work.

Initial Concept Design geotechnical models assumed the presence of an apparently continuous sheared tuff layer and sheared contacts between basalt and the underlying argillite. By the Final Design stage it was demonstrated that such features were either not present or of very limited extent and hence it was possible to eliminate all slope support measures from the design.

During the design process as more and more geological and hydrogeological data became available, refinement of the geotechnical model enabled subsequent reductions in slope support measures to be made. Early in the design process it was able to be shown that the Concept Design stabilisation option of support of a 280m cut section by 2 to 4 rows of 900kN anchors at 1m centres, was able to be reduced in the Preliminary Design to a length of 50m with two rows of approximately 30m long, 700kN anchors at 1m centres. These support measures were able to be further reduced during the design process, such that in the Final Design, apart from the possibility of installing sub-horizontal drainage holes to control groundwater levels, it was able to be demonstrated that no slope support measures were required.

The engineering geological skills of particular significance to this study were the observations made of the basalt/argillite contacts remote to the cut, at nearby quarries, coastal exposures and in deep test pits. Also of significance was recognition of the importance of re-inspection and re-evaluation of existing rock core samples as new geological information and interpretation was made.

The project demonstrates that the development of reliable geological and hydrogeological models based on sound engineering geological observations and interpretation is essential early in the design process, with the potential for substantial savings both in time and money.

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