GEO-LOGIC and the Art of Geotechnical Practice

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ABSTRACT

This paper critically reviews the concept of "Art and Science in Subsurface Engineering" that was first enunciated by Ralph B. Peck in 1962, concluding that his comments are as relevant to geotechnical practice today as they were 50 years ago. Examples presented from more than 35 years of practice in engineering geology, from shallow erosion problems in dispersive soils through large-scale slope instability to tunnelling projects, demonstrate that unless we "read the ground" successfully we are at a distinct disadvantage. The "geological site model" is fundamental to successful construction, despite the considerable advantages now available from improved testing methods and computer analysis. Failure to adequately consider the landscape into which we are placing civil or mining structures, and implications this has for geotechnical hazards and environmental management, risks higher project costs, significant delays to satisfactory completion, or even on occasions "overt failure". There is an abundant literature available on geological and geotechnical precedent, which provides much better guidance than any computer programme, and complements quantitative data analysis techniques.

Keywords: subsurface engineering, geotechnical practice, engineering geology, loess erosion, lime stabilisation, construction on dormant landslides, tunnelling practices, construction documentation

1 INTRODUCTION

We live in a fast-developing technological age, in which powerful computer storage and processing of data is commonplace, and manipulation and presentation into standard formats can be expedited. The ground into which we place civil structures, and for that matter mining developments, is however a complex mix of rock, soil and/or water. No amount of testing by drilling, trenching or instrumentation can replace the information that is only evident when we fully excavate the site, and truly appreciate the geotechnical significance of features that may only have been partly disclosed. The site model evolves through iterative practices, including where appropriate underground exploration by adits or shafts, and the development of a three-dimensional (3D) site model is a clear aim of site investigation. To this should be added the fourth dimension of time-evolution of the landscape, as the 4D-model provides us with an ability to understand process and the complementary prediction of future hazard.

There is an abundance of literature available on past failures of structures, and the lessons that have been learnt. The St Francis Dam in Southern California, a 60m high concrete gravity structure, failed on 13 March 1928 when the storage was within 0.3m of full supply level (FSL). The loss of life and the financial costs resulted in fundamental changes to the investigation and design of gravity dams, and six different Committees of Inquiry comprising engineers and geologists reported to various bodies within six weeks of the event. Nowadays libraries consider anything older than the last decade is only fit for storage in the basement, or for disposal, yet the history of civil engineering practice is littered with examples of failure to "read the ground". This paper addresses what is, in this author's opinion, a fundamental matter for geotechnical practitioners: how do we "read the ground" successfully?

2 ART AND SCIENCE IN SUBSURFACE ENGINEERING

In 1962 Ralph B. Peck began his paper on "Art and Science in Surface Engineering" (Peck, 1962) with the statement "Subsurface engineering is an art; soil mechanics is an engineering science". He went on to enunciate three attributes necessary in the successful practice of "subsurface engineering" as "knowledge of precedents, familiarity with soil mechanics, and a working knowledge of geology". Of course Peck's expertise was in the field of soil mechanics, and in 1962 the science of rock mechanics had barely been conceived. However, these three attributes remain the cornerstones of successful geotechnical practice, and the only suggested change is "familiarity with geomechanics".

Knowledge of precedent is fundamental to successful geotechnical practice, and in my view remains as pertinent now as it did when Peck made those remarks. He commented (Peck, 1962, p61) that "…soil mechanics has made it practicable to utilize the vast amount of precedent and experience already accumulated…" He was referring to things like the effective stress concept, and the effects of soil variability (ie heterogeneity) on slope stability. Today we know considerably more about behaviour of both rock and soil masses, and appreciate more critically the role of water in material response, but when we move to a "new" type of ground "geological surprises" must still be anticipated.

Peck commented that "Geology…is as basic to subsurface engineering as is soil mechanics" (Peck, 1962, p62), and he went on to observe "Possibly its most significant role is to make us aware of the departures from reality inherent in our simplifying assumptions". He then made the extremely valid point that "…every interpretation of the results of a test boring and every interpolation between two borings is an exercise in geology" (Peck, 1962, p62). Nothing in the last 50 years has changed this situation, and no amount of computer-aided drafting can disguise the realities of the ground itself. It matters not whether it is a hand-drawn sketch of the exposed ground conditions, or a programme-generated drawing: we have either observed and recorded accurately what is there, or we haven't.

3 CONTRIBUTIONS OF STAPLEDON AND HUTCHINSON

Prof David Stapledon has been a firm advocate of understanding the geological realities of a site, and of clarifying the project requirements in soil or rock mechanics terms. In an unpublished 1977 paper entitled "Subsurface Engineering: in search of a rational approach" Stapledon talked of the need to develop a 3-D site model, and of using "geo-logic" or "earth-logic" as the means of establishing a realistic "geotechnical model". He has long been an advocate of the iterative approach for identifying and resolving geotechnical issues, and he expanded Peck's three attributes to six, these being a knowledge of precedents, geology, soil and rock mechanics, civil engineering design, civil engineering construction, and above average application (Stapledon, 1977, p13).

In his Fourth Glossop Lecture the late Prof John Hutchinson provided a thorough documentation and review of a fundamentally similar subject in his paper entitled "Reading the Ground: Morphology and Geology in Site Appraisal" (Hutchinson, 2001). Whilst acknowledging the importance of quantitative determination of soil properties, especially in relation to landsliding, Hutchinson commented that we have to avoid "…the mistaken and all too common belief that qualitative knowledge is inferior to quantitative and of little worth" (Hutchinson, 2001, p38). He provided a table summarising a number of earthworks failures in the United Kingdom, and attributed the causes to a lack of initial site appraisal by means of desk study, geomorhological mapping and/or trial trenches.

Quantification of material and mass characteristics, whether in soil or rock, is an essential component of site investigation practice and geotechnical design. Equally, identification of the geological and geomorphological characteristics of the site or slope, and recognition of the geotechnical implications, should precede implementation of the site investigation programme and final design. Development of a rational "4-D Model" for the site or area provides the framework for investigations, and neglecting the time factor in landscape evolution diminishes our understanding. If the quantitative analyses do not match with our intuitive or "back-of-the-envelope" calculations, then we have probably failed to identify a key aspect: geology and geomorphology is the framework within which we must engineer.

4 EROSION AND INSTABILITY ON THE PORT HILLS – CHRISTCHURCH

Loess is windblown silt, with variable clay and fine sand, and is extensively developed in the South Island of New Zealand because of the Late Quaternary geological evolution of the landscape. Rapid urban growth onto the lower loess-covered slopes of the Port Hills, Christchurch, in the early 1970s resulted in rainstorm-triggered shallow landsliding, and accelerated development of rill- and tunnel-gully erosion (Bell and Trangmar, 1987). Research into soil dispersion and chemical stabilisation led to the systematic implementation of measures to remediate the problems, with lime-stabilisation using either quicklime (CaO) or hydrated lime ($Ca(OH)_2$) being preferred. Shallow translational landsliding, which is controlled by pedological layering within the soil profile, requires stormwater control as the primary mechanism (Bell et al, 1990: Bell, 1994). Erosion and instability controls became well understood by geotechnical practitioners, and Councils insisted on such measures from the 1990s.

Rockfall has been an issue in residential development on the Port Hills since the 1970s, and there are records of localised rockfall events more than 100 years ago. Depending on the slope angle, either free-fall events with near-vertical trajectories occurred, or boulder bounce-and-roll took place on more moderate (25-45°) slopes. Because rockfall events were sporadic, and runout was usually confined to the talus apron, remediation consisted of scaling, buttressing or anchoring at source; catch fence construction, with ditch or bund protection in many cases; or avoidance of high risk areas. Volumes of basaltic rocks released tended to be small, with a $50m^3$ event being considered large before February 2011. The M_w = 6.3 earthquake on 22 February 2011, however, caused large-scale cliff collapse, including several deaths: thousands of boulders were released, properties had to be evacuated, and the final solution involving retreat and protection is still under investigation. Interestingly, widespread fissuring in thick (>20m) footslope loess profiles was also recognised, and is still being investigated: in the interim fissure filling with bentonite and sandy fine gravel has been implemented.

5 LARGE LANDSLIDES IN SCHIST TERRAIN – CENTRAL OTAGO

Landslides with volumes in the range 10^6 to 10^9m^3 have long been recognised in Central Otago (Bell, 1994), and were a major stabilisation concern with the Clyde Power Project which necessitated buttressing and drainage measures costing in excess of NZ$400M (Macfarlane, 2009). Development of an asymmetric valley profile is characteristic of these large creeping landslide features, with movement rates typically in the range 5-50mm/year and the formation of a distinctive hummocky landscape (Bell, 1994). Construction of the Paerau Diversion Scheme in the Maniototo Basin resulted in widespread foliation-controlled landsliding in schist dipping at 15-30° (Bell, 1994), and led to a 50% increase in project costs accompanying remediation: the classic asymmetric profile developed as a consequence, and studies of foliation shear zone materials that control instability have revealed φ_R values of ~10°. There is a clear relationship between geology, landscape evolution, and geotechnics.

Landslides are also regarded with suspicion by many geotechnical practitioners, and despite success of schemes such as the Clyde Power Project, building on these features in Central Otago is often deemed unacceptable. The Coronet Peak Landslide has a volume of $\sim10^9m^3$, and is located to the immediate north of Queenstown, with a major skifield and associated facilities on its upper slopes: in addition, several residential homes have been successfully constructed on the landslide, and there is no evidence for long-term structural damage. To improve the snowmaking capabilities at the Coronet Peak Skifield, an additional $165,000m^3$ of water is now stored in three separate ponds constructed in depressions in the landslide surface by means of a 3mm thick HDPE liner system and associated under-drainage measures. The ponds have performed successfully over three winter seasons, and are routinely monitored and maintained: facilities, including buildings, are performing satisfactorily.

By successfully “reading the ground”, and understanding landscape evolution, it is feasible to build safely on these effectively dormant features. The age of many of these large landslides is well in excess of 100,000 years (>100ka), and they are artefacts of tectonic uplift, valley incision and cold-climate modification. Clearly toe inundation, as at Clyde, creates its own set of geotechnical issues that must be remediated on a site-specific basis, but provided the quasi-stable state of the land is not disturbed then geological precedent can be invoked to justify developments such as at Coronet Peak. That is clearly not the case in the Young River to the north of Wanaka, however, where a landslide dam formed in August 2007 and the 11 Mm^3 feature remains in a state of only marginal stability.

6 TUNNELLING IN SCHIST BESIDE THE ALPINE FAULT – BIG WAINIHINIHI RIVER

The Big Wainihnihi Tunnel was constructed in the 1880s through schist immediately adjacent to (ie east of) the Alpine Fault, inland from Hokitika, for the purpose of gold-sluicing in bouldery gravels. It was closed as a result of landslide movements accompanying the 1929 Arthurs Pass Earthquake, in which the invert dropped more than 2m over a short section as part of a 65m long wedge block failure (Appendix; Figure 2). In the mid-1970s a decision was made to reinstate the tunnel on its existing alignment as part of the 10MW Dillmans Hydro-Electric Scheme, and because of stability concerns the tunnel was lined with doubly reinforced concrete. Detailed (1:50) engineering geological logging of the tunnel, and related mapping, was undertaken by the author at that time, and a full completion report was subsequently issued (Bell, 1986). The principal conclusion was that monitoring and regular inspection of the tunnel must be undertaken, with the expectation of short-term (<20-year) stability.

Regular tunnel surveys were carried out by the owners, and movement rates increased from 2000 to 2008 such that closure took place in the winter of 2009, by which time movement rates had reached 30mm/week. In the original completion report (Bell, 1986) it had been recommended that in the event of continuing movements forcing closure, further investigations should be undertaken with a view to realigning around the failing wedge. With the information available from that report, re-design was undertaken and construction proceeded in early 2010 along a partly deviated alignment of ~180m at a cost of NZ$2.8M. The contractor developed modular 100mm x 100mm steel sets at 1.2m centres for support, with the channel constructed inside by concrete pours: the design-build contract was completed on time and at the nominated cost. Construction details are given in Shelton et al (2011).

The original tunnel logging was carried out during construction of the reopened tunnel by operating a night shift, and the methods followed standard practice at the time. Plans were drafted onto A0 sheets and a total of 10 joint sets were recognised, together with two faults and two sets of schistosity readings (in situ and displaced). Tunnel cross-profiles were compiled every 10-15m through the failed area, as well as waist-height recording of principal rock defects at a nominal 1.0m above invert. The availability of the as-built records has facilitated the second reconstruction, and the Big Wainihinihi Tunnel has been contributing water to the hydro-electric scheme for almost two years. The risk of closure from earthquake-generating movements on the Alpine Fault, which is the plate boundary fault with an expected Mw ≥8.0, remains an issue for the Dillmans Hydro Scheme (and the adjacent parts of the West Coast). A recurrence interval of 300-350 years is now suggested for this segment, with the last rupture event identified in about 1717AD.

7 CONCLUSIONS

"Geo-Logic" is the ability to identify geological constraints potentially affecting a project from the outset, and to understand the landscape evolution of the site such that hazards, material properties and expected foundations can be anticipated. The need to "read the ground" correctly has been set out clearly by a number of authorities over the past 50 years, including Peck (1962), Stapledon (1977) and Hutchinson (2001). It is considered to remain a fundamental part of geotechnical practice.

Examples have been included from the South Island of New Zealand, where the author has practiced for more than 35 years. Originally presented as the 14th New Zealand Geomechanics Lecture, this paper develops key aspects of the material given in relation to loess soils and their stabilisation; the earthquake-initiated bedrock instability on the Port Hills in 2011; construction on the large (>$10^6 m^3$) schist landslides of Central Otago; and the Big Wainihinihi Tunnel reconstruction on the Alpine Fault.

The importance of site evaluation using a rational geological and geomorphological approach is emphasised in the context of site investigations, and as a guide to any quantitative assessment that might be deemed necessary for the specific project. Geological precedent in the context of 4D site analysis identifies the areal distribution of materials and property differences, depth variability, and importantly the chronology of site evolution insofar as this influences geotechnical hazards.

Finally, the importance of careful project documentation is identified for long-term management of a site, and of the changes that may have been made as part of the construction process. The idea that sites and foundations do not require long-term maintenance, in contrast to the structure itself, is rejected. The need to thoroughly document the site, and to instrument where necessary (eg for piezometric information) is considered essential, having a small incremental cost for high benefit.

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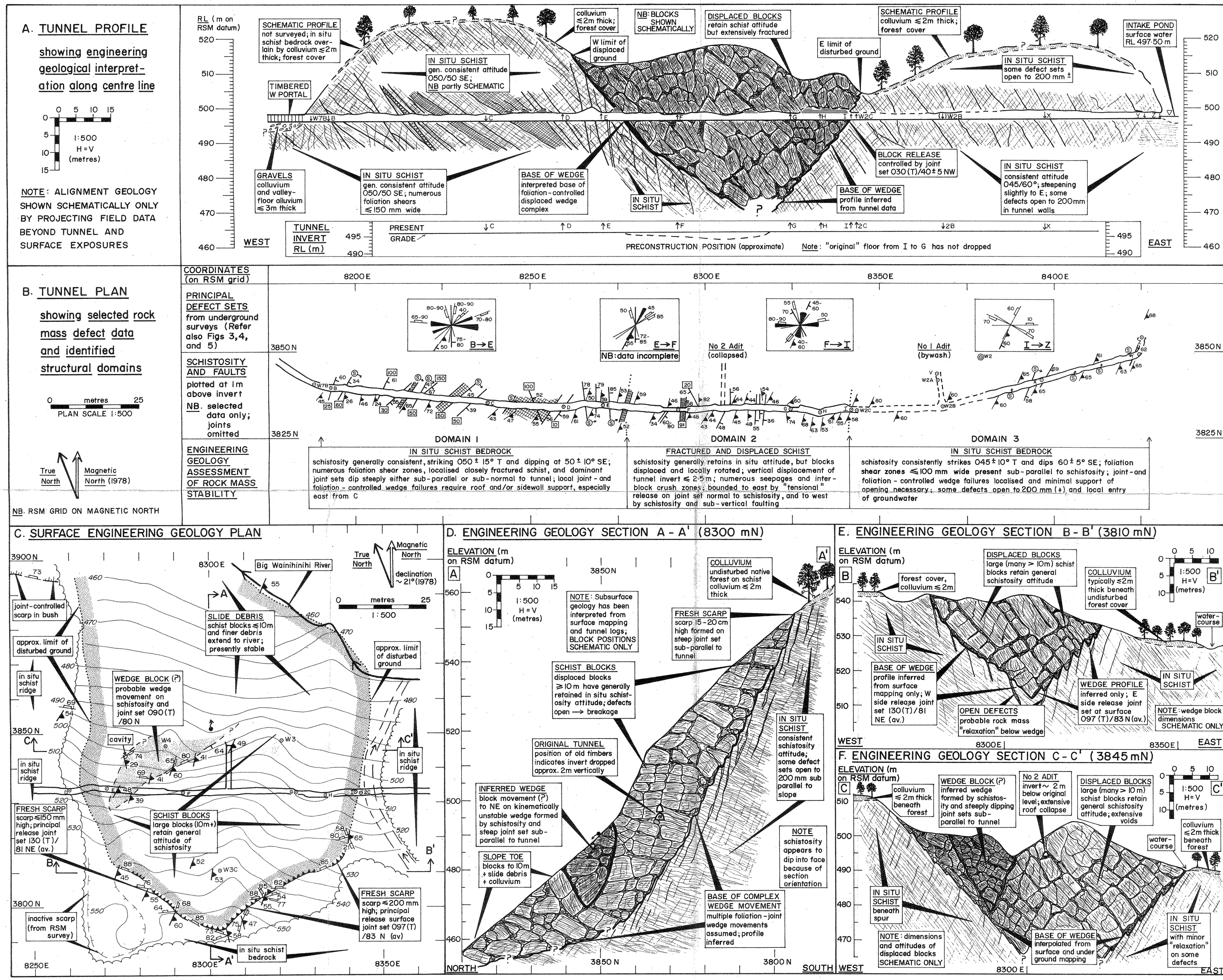
Appendix: Figure 2 from Bell (1986) – originally drafted at A1 size



G. LEGEND

Rock Mass Data

- schistosity (foliation)
- fault (including foliation shears) width(mm)
- open / closed joints
- crushed or sheared zones
- closely fractured zone
- greenschist
- underground / surface groundwater seepage
- fresh scarp
- inactive scarp
- approximate limit of disturbed ground (no obvious scarp)

Other Details

- G (section) / B (plan) survey control marks (RSM)
- contours (m on RSM datum)
- watercourses
- bush line
- timber / concrete supported ground in profile (schematic)

H. TUNNEL SURVEY DATA

Station	Coordinates North (m)	Coordinates East (m)	Invert RL (m)
B	3839·8	8192·6	496·26
C	3835·4	8237·5	496·32
D	3834·2	8259·4	496·40
E	3834·5	8270·5	496·40
F	3833·0	8292·2	496·53
G	3833·1	8324·7	496·60
H	3832·2	8333·2	496·61
I	3833·0	8342·0	496·62
W2C	3832·7	8343·3	497·08

Control Surveys by Royds Sutherland McLeay Ltd, Consulting Civil Engineers CHRISTCHURCH and GREYMOUTH

DILLMANS HYDRO SCHEME

Big Wainihinihi Race No 1 Tunnel

ENGINEERING GEOLOGY DATA SUMMARY

GEOLOGY: D H Bell, A Ormiston, G Smith
PLOTTING: D H Bell, Senior Lecturer, University of Canterbury
DATE: April-May 1986
DRAWN: L V Leonard, May 1986
SCALE: 1:500

FIG. 2