LIMITATIONS OF ROCK MASS CLASSIFICATION SYSTEMS FOR TUNNEL SUPPORT DESIGNS

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1. THE STATE OF PLAY

The publications of the RMR classification system by Bieniawski in 1973 [1] and the Q-system by Barton, Lien and Lunde in 1974 [2] were greeted with great enthusiasm by a large portion of the international rock mechanics fraternity, particularly those involved in support design for rock tunnels. Here appeared to be systematic, if not truly scientific, procedures for designing primary support.

Over the past 30 years the two classification systems have been proposed as being design tools for a wide range of structures. The RMR was modified to the MRMR, Laubscher [3], for underground mining. Hoek, Kaiser and Bawden [5] present a 'trimmed' version of the RMR system, called GSI (Geological Strength Index), to be used for calculating rock mass strength via the Hoek-Brown failure criteria. Q has been proposed as a means for estimating a whole suite of rock mass characteristics, including TBM productivity [6].

Like a good Jamie Oliver recipe, these classification systems are easy to apply, and they have now become so widely used that sight has been lost by some of their limitations, and, more importantly, of the principals of applied mechanics and structural engineering that should be the basis of tunnel support design.

Fortunately, a few papers are now appearing that question the validity of designing using classification systems. A recent paper by Palmstron and Broch (Ref 8) provides an excellent critique of many of the parameters used in determining Q values. They point out that, notwithstand claims by Barton to the contrary;

- the ratio RQD/J_n does not provide a meaningful measure of relative block size;
- the ratio JW/SRF is not a meaningful measure of the stresses acting on the rock mass to be supported.

They also point out that the Q-system fails to properly consider joint orientations, joint continuity, joint aperture and rock strength.

In essence Palmstron and Broch consider that the classification systems (Q and RMR) provide good checklists for collecting rock mass data, and may be of use in planning stage studies “for tunnels in hard and jointed rock masses without overstressing”. They do not support the use of these systems for final designs.

The writers have reached the same point of concern from experience with major tunnels and cavern projects in the Sydney region.

2. THE TUNNELS AND THEIR ENVIRONMENT

The Sydney area is underlain by a sequence of near horizontally bedded Triassic-aged sandstones and shales, with the near surface dominated by the Hawkesbury Sandstone Formation.

The geotechnical properties of the Hawkesbury sandstone are summarised by Pells [12] and Bertuzzi and Pells [13] and need not be repeated here. It is worth noting here that in many ways the properties are similar to the Bunter Sandstone of the UK and the Cave Sandstone of South Africa.

Over the past 25 years there have been many major tunnels and caverns excavated in these Triassic rocks, and the projects presented herein are:

(1)&(2) Ocean Outfall tunnels; 3.5 km by 4m diameter at North Head and 4 km by 4m diameter at Malabar [9],

(3) the Sydney Opera House underground parking station, doughnut shaped in plan with span of 18m [10],

(4) the M2 tollway tunnel, 450m of twin two lane tunnel.

(5) the Eastern Distributor, a tollway which includes 2.4 km of 3 lane double decker tunnel,

(6) the 4 km long M5 motorway, twin, two lane tunnel [16],

(7) the 19.5km long, Northside Storage Tunnel, comprising 3.8m to 6.3m diameter TBM drives [17],

(8) 3 parallel, 14m wide, 11m high and 120m long, gas storage caverns beneath Botany Bay [11],

(9) the Epping-Chatswood Rail Link, twin 14km long 7m diameter rail tunnels.

3. PROJECT DESCRIPTIONS

Space limitations dictate that only brief details can be given of the nine projects listed above. We have chosen to be more expansive on the projects where failure of the support occurred.

3.1 North Head and Malabar Ocean Outfall Tunnels

Design work for this project was completed in 1983 and tunnelling was finished in 1987. Designs for the sections of tunnel in the Hawkesbury Sandstone were prepared for what were termed Typical Conditions and Adverse Conditions [14].

The actual support installed depended very much on the method of excavation. It was concluded that the RMR system was conservative in terms of support requirements, particularly for machine bored tunnels. The Q-system provided a reasonable prediction where machine excavation was used, but was non-conservative where drill and blast was adopted.

3.2 Sydney Opera House Parking Cavern

The design and construction of this doughnut shaped cavern is described in detail in Pells, Best and Poulos [10]. The crown of the cavern comprised 6m to 8m of sandstone classified as:

Q	20 to 60;	design value = 50	(ESR = 0.8)
RMR	60 to 55;	design value = 65	

The support recommendations from the respective systems are as given in Table 2.

TABLE 2
CLASSIFICATION BASED SUPPORT DESIGN
FOR THE 18m SPAN OPERA HOUSE CAVERN

SYSTEM	RATING	PREDICTED PRIMARY SUPPORT
RMR*	65	3m bolts at 2.5m centres with occasional mesh and 50mm shotcrete where required.
Q	50	6m bolts at about 3m centres, no shotcrete.
*Recommendations only really apply for 10m span		

The actual support installed is shown in Figure 1 and comprised 3.6m (230 kN) dowels and 7.5m (450 kN) stressed anchors at an average spacing of 1.3m, plus weldmesh and 150mm shotcrete. The design was based on explicit structural analysis. Comparing this support with the predictions in Table 2 suggests that either the designers of the cavern were very conservative (which was not the view of the external reviewers), or predictions based only on the classification systems were dangerous.

Monitoring data was consistent with design expectations, indicating that the design support was either correct or on the slightly conservative side.

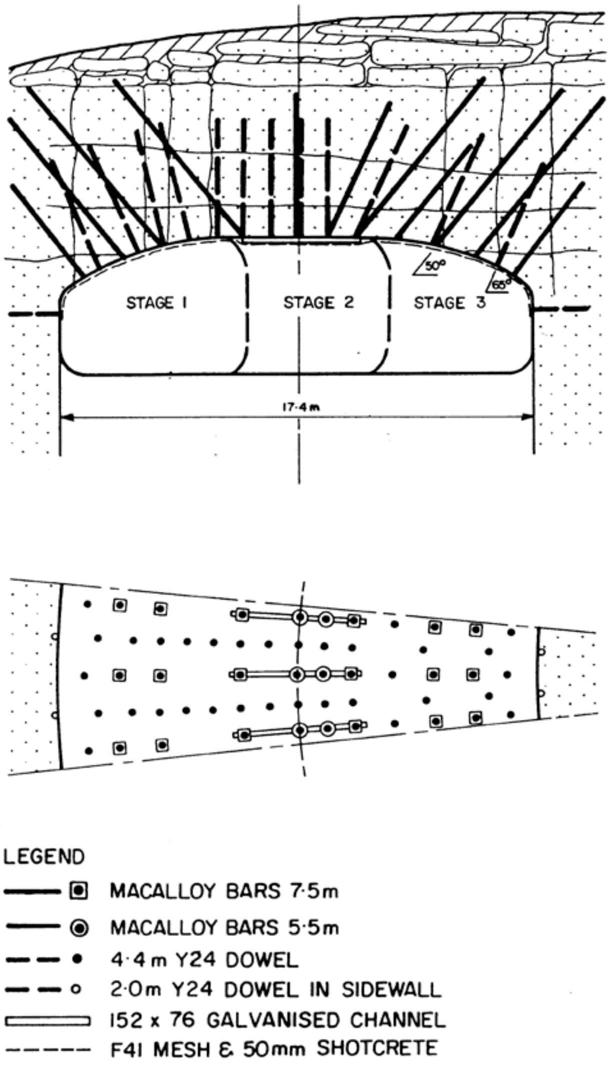

Figure 1: Roof support for the Opera House Car Park cavern

3.3 The M2 Tollway Tunnel (Norfolk Tunnel)

This project comprises two 11.9m wide, two-lane, tunnels separated by a 5.5m pillar. Cover is typically between 16m and 22m and comprises predominantly very good quality sandstone with some 1m to 1.5m horizons of poorer quality sandstone.

Q values in the crown ranged from 20 to 45 and RMR values from 55 to 75. Using these values the classification systems give the following designs.

RMR: 3m to 4m bolts at 1.5m to 2m centres with 50mm to 100mm shotcrete.

Q: 4m bolts at 2.5m centres and, in places, only 4m spot bolting (no shotcrete).

Actual support ranged from 4m bolts at 1.7m centres plus 110mm fibrecrete, to 2.4m centres plus 50mm fibrecrete. This is substantially more than indicated by the Q-system.

3.4 Eastern Distributor, 15m to 24m Span Section

The Eastern Distributor tunnels include a 550m length of double decker tunnel with crown span ranging from 15m to 24m. This discussion relates to the approximately 50m length where the span is greater than 20m.

Most of the tunnel is in sandstone with a Q value of about 40. Adopting an ESR value of 0.8, the Q-system [15] indicates support should comprise 6.5m bolts at about 2.6m centres with 40mm reinforced shotcrete.

The actual design support was prepared using the same methodology as for the Opera House cavern [10] but with the addition of detailed analyses using the program UDEC. The design and installed support is comprised 9m long, 450 kN ultimate capacity tensioned rockbolts at 1.75m centres, plus 135mm of steel fibre reinforced shotcrete (SRFS) and 40mm of unreinforced shotcrete used as corrosion protection for the bolt heads.

It is quite obvious that the adopted design is substantially greater than deduced from the Q-system. It should be noted that one of the international project reviewers recommended substantially greater support than actually adopted.

3.5 Gas Storage Cavern

Figure 2 shows the layout of the caverns that are at a depth of about 125m beneath Botany Bay. The cavern spans are about 14m.

The Q-value designated from the site investigation boreholes was 24. For ESR = 0.8, this would place this structure in Support Category 14 in the original Q-system [2] and would require tensioned bolts at 1.5m to 2.0m spacings at lengths of 3m, 5m and 7m plus chain link mesh. The updated recommendations [7 and 15] would require systematic bolting at 2.6m spacing with bolt lengths of 4.5m (no mesh, no shotcrete). The actual support prior to a series of collapses was similar to the updated guidelines.

The first collapse occurred in gallery A, near the centre of the top heading (see Figure 3). It was slab-like measuring some 9m wide, 10m to 16m long and 1m to 1.8m thick. At the time of the fall, the top heading was driven using an 8m wide central pilot heading, advanced about 8m ahead of the full span. The collapse occurred between the full section and the entrance to the pilot heading, shortly after the left-hand slash was fired. This slash had previously misfired when the two sides and pilot heading face had been fired about 5 hours earlier [11]. Support in the fall area and comprised 4m long Hollow Groutable Bolts (HGB) at 2m spacing. The bolts were end anchored but had been not grouted at the time of the collapse. Seventeen bolts pulled from their anchors and came down with the fall, 8 others were hanging in the roof, their plates and nuts sheared off.

The second fall occurred in Gallery C about 2 weeks later. This was also being driven with a pilot heading. The fall comprised about 50 cubic metres, in a few large blocks, from the right hand crown/shoulder region between the full span and the 8m wide pilot. The support was as at the first fall except the HGB's had been grouted. Several broken bolts were found in the muck pile.

After the collapses the project was put on hold. When it recommenced some 2 months later the support capacity had been substantially increased.

It may be argued that the Q value adopted from the site investigation boreholes was wrong. The writers have reviewed this matter using logging of the actual excavation. This suggests a Q value of about 13 (ie half the original value). However, the support recommendations would be the same. It may also be argued that the Q-system does not ‘propose’ ungrouted rockbolts and therefore the first collapse was an unfair test. However, in the second failure area all bolts were grouted.

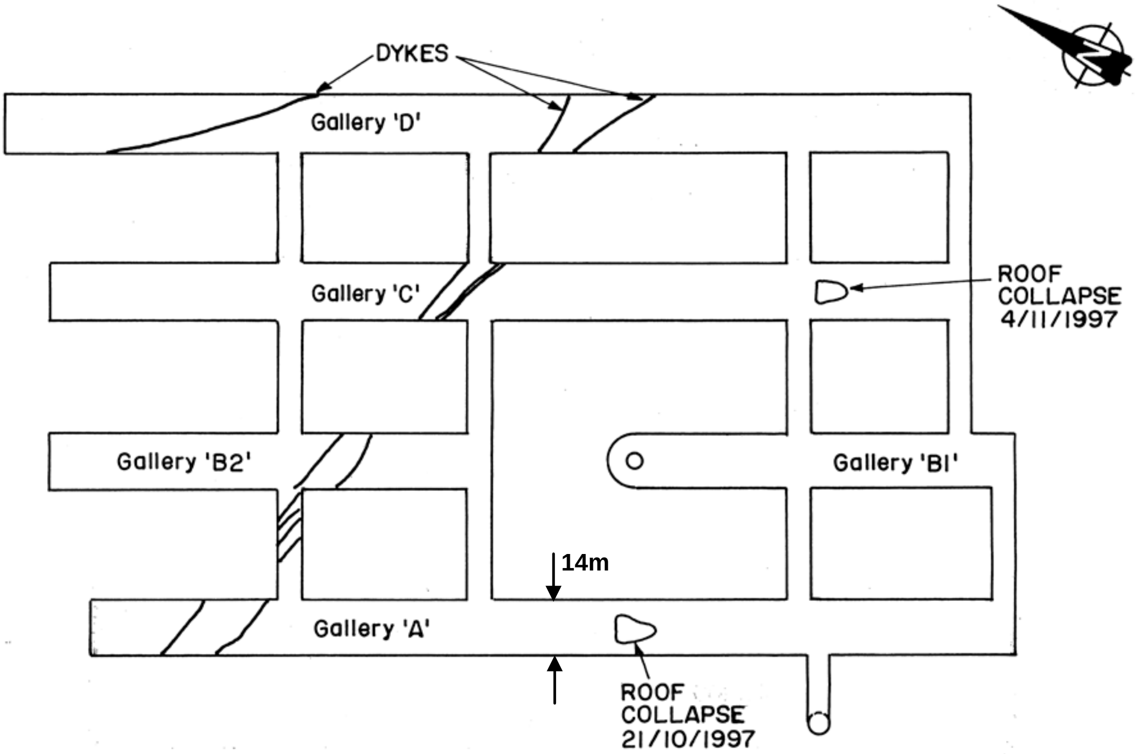

Figure 2: Gas Storage Cavern Layout

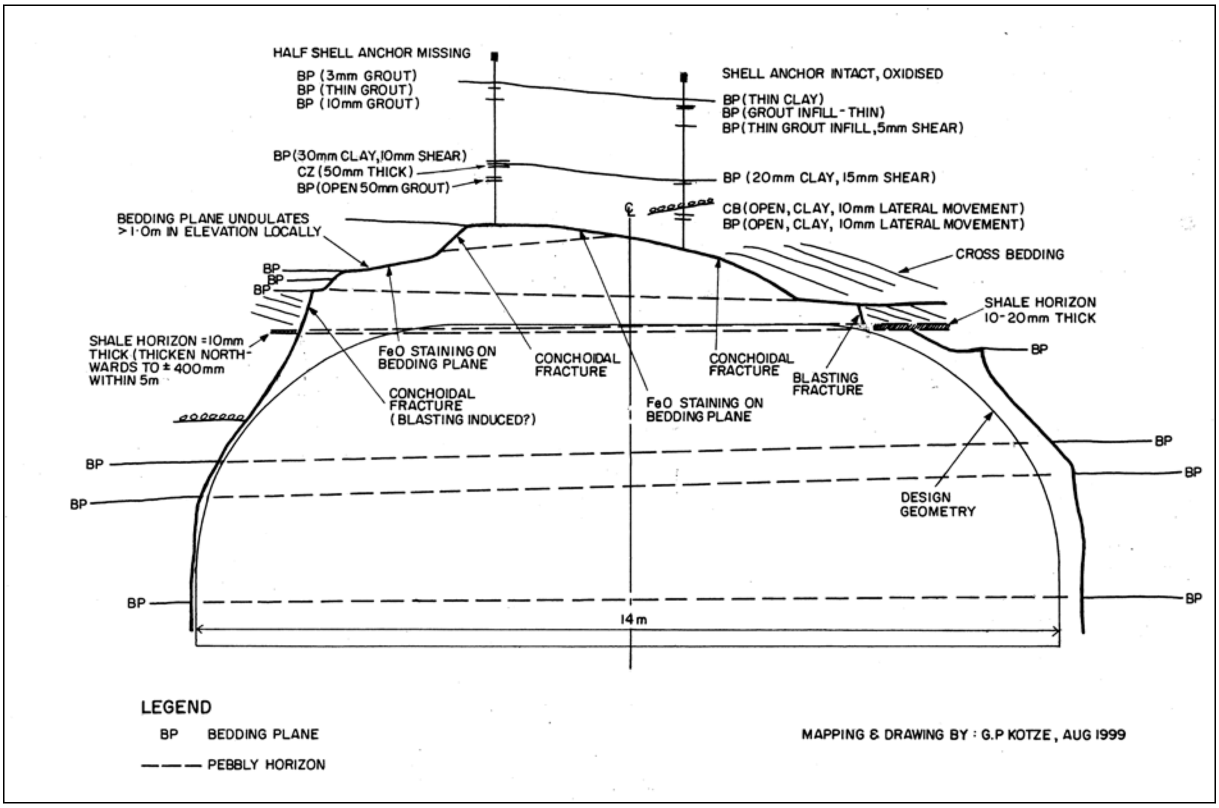

Figure 3: Roof Failure – Gas Storage Cavern

3.6 Northside Storage Tunnel

In early 2000 a major system of TBM driven tunnels was completed on the north side of Sydney Harbour to store peak sewage flows. The scheme included about 6.5 km of 3.8m diameter tunnel, 7.3 km of 6.0m to 6.3m diameter tunnel. All the tunnels were in Hawkesbury Sandstone, with depths of cover ranging from about 20m to about 80m. The initial primary support, comprising rockbolts and mesh, was designed using the Q-system [17]. The actual density of rock bolting which proved necessary to install, following inadequate performance of the initial design, ranged between 5 and 9 times the initial design densities. The differences between prediction and reality are shown starkly in Figure 4.

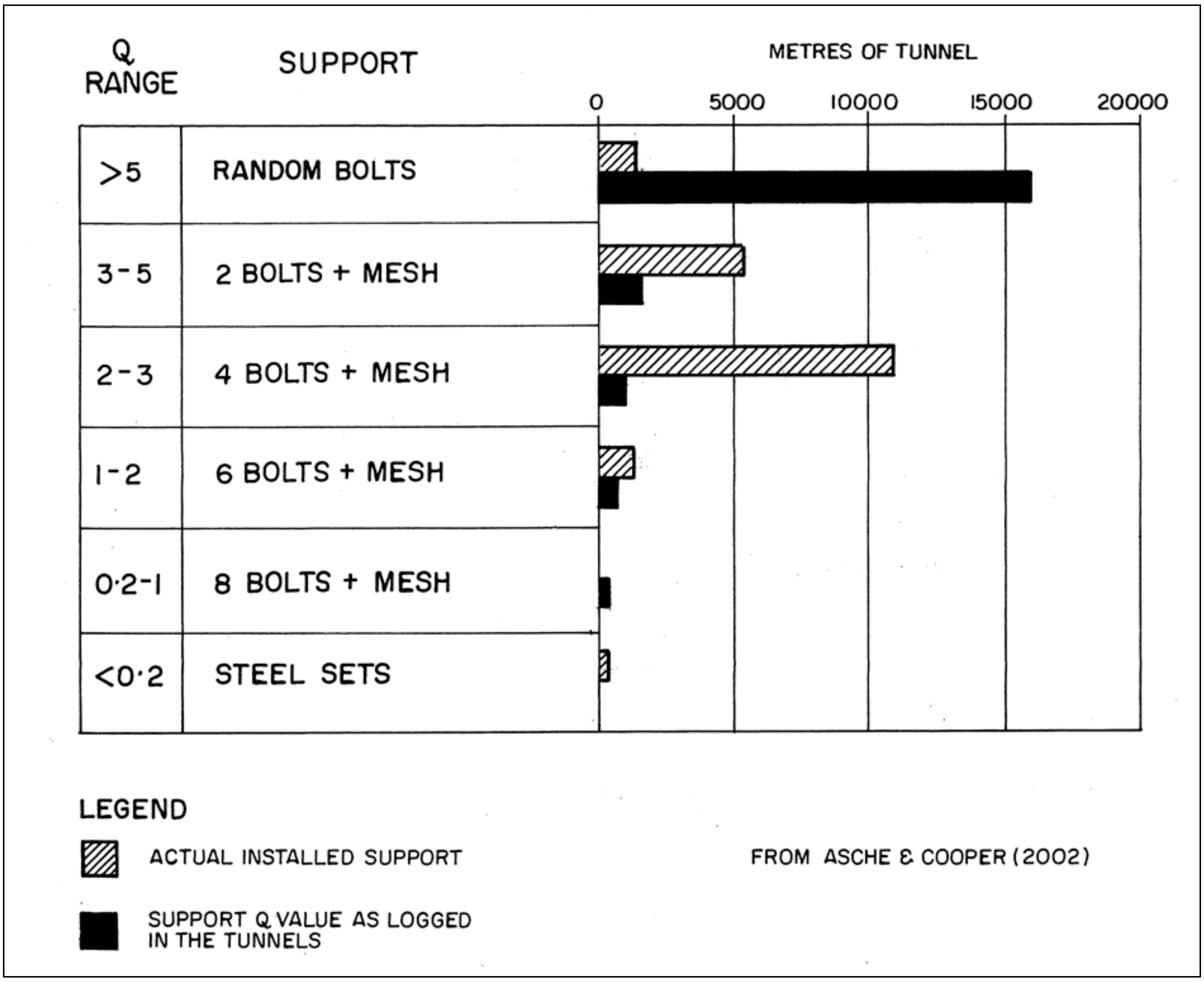

Figure 4: Support in the Northside Storage Project [20]

3.7 The M5 East Tunnel

This tollway tunnel system comprises two, 4km long, twin lane tunnels with 8.6m spans, excavated entirely in Hawkesbury Sandstone [16]. Overburden cover along most of the tunnel ranges between 15m and about 70m. The tunnels were excavated by roadheaders.

Tunnel support was designed by a combination of analytical and empirical methods and comprised; 3m long, 200 kN yield, rockbolts; and 50 mm to 100 mm thick SFRS. Support systems were designed for three types of rock, with Q-values as follows:

Type 1	Q = 4.7 to 75 (47% of tunnels)
Type 2	Q = 0.9 to 17.5 (50% of tunnels)
Type 3	Faults and dykes (3% of tunnels)

The Q-system recommended bolt length for Types 1 and 2 is 2.8m, which is essentially the same as the 3m actually used. The differences between the actual support and that predicted by the Q-system were in the number of rockbolts and the quantity of shotcrete (see Table 5).

It should be noted that even with the support actually used there were some roof falls during excavation one which unfortunately injured a person.

TABLE 5
M5 TUNNEL – COMPARATIVE SUPPORT QUANTITIES

Item	Q - Predicted Quantity	Actual	Actual / Predicted %
Rockbolts	12300	14000	114%
Shotcrete	2400m^3	5850m^3	244%

3.8 Epping – Chatswood Rail Link

The project comprises twin 14km long 7m diameter rail tunnels and 4 underground stations caverns. The caverns are not included in this study.

The temporary support of the TBM tunnels was designed analytically and modified in accordance with the encountered geology. Permanent support comprises a formed concrete lining.

Figure 5 has been developed from the project database. It shows the relationship between the recorded Q-values and the primary support actually installed. It can be seen that there is no correlation between the Q-values and the installed support. From the purely scientific viewpoint this may not prove that the Q-system was not appropriate, it could mean that the various tunnelling teams, and the designers, had no real idea of what support was really required. However, given the international credentials of those involved in the design and construction, this view is not really tenable.

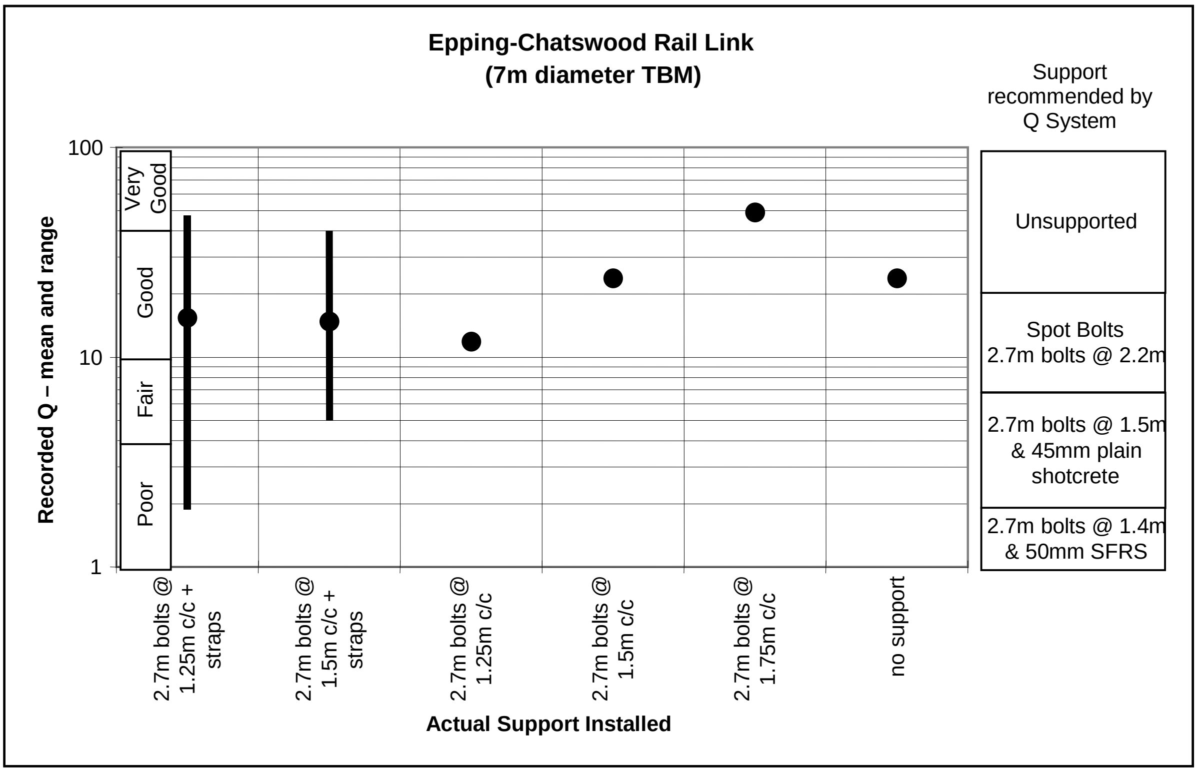

Figure 5: Epping to Chatswood Rail Link Comparison of Q recommended support with the actual support installed

4. DISCUSSION AND CONCLUSIONS

From the viewpoint of rock mass classification, the Q-system discriminates well between the different grades of Hawkesbury Sandstone and therefore is of value in communicating rock mass quality. However, the Q-system predicts significantly lesser levels of support for tunnels and caverns in these sandstones than has been proven to be necessary in practice. In seven of the nine Sydney case studies presented herein the design support was, from the outset of the projects, substantially heavier than indicated by the Q-system. No failures occurred in these seven cases so it is not possible to know whether the actual support, designed using principles of applied mechanics, was possibly conservative. However, in the remaining two cases the initial support was as per the Q-system, failures occurred, and the degree of support had to be increased substantially.

Two conclusions are drawn from this work.

1. The design correlations published in the various papers on the Q and RMR systems should be used with great caution in geological environments significantly different from those comprising the original case studies.

2. Cognisance must be taken of the fact that use of the general classification design approach is contrary to normal engineering design processes. There are no applied mechanics calculations of stress or displacement, no computations, or information, as to loads, strains and stresses in the support elements (shotcrete, rockbolts and sets), and therefore nothing against which to compare field-monitoring data. The position of the classification design approach in relation to modern limit state design is unknown and unknowable. It covers neither Ultimate nor Serviceability Limit States.

The writers are of the view that tunnel design should be done by methods of applied mechanics, like any other structural design. Classification systems are good for communication, and in some cases good for producing correlations in particular geological environments. However, on the basis of the critique by Palmstron and Broch [8] and the experience set out in this paper they should not be used as the primary tool for the design of primary support.

A final point to note is that Q and RMR values are not factual data in respect to the engineering geology of a rock mass. Firstly, they include a significant a significant degree of interpretation. Secondly, they relate to a particular structure at a particular depth. Therefore, in the writers opinions they should not appear on engineering geological logs of boreholes or on records of line mapping of excavations. These records should be restricted to data as set out in References 18, and 19.

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