

Tattersall, J.W., Tam, J.K.W., Garshol, K.F. & Lau, K.C.K. (2012). Engineering geological approach for assessment of quantities and programme for deep tunnels in Hong Kong. Proceedings of the HKIE Geotechnical Division 32nd Annual Seminar “Geotechnical Aspects of Tunnelling for Infrastructure”, pp 81-87

The Assessment Board selected this paper for the 2014 HKIE Geotechnical Paper Award, for its potential to advance local geotechnical practice and its quality of writing for the readership of practicing geotechnical engineers. It noted:

The paper Tattersall et al (2012) provides a succinct and focused account of a novel and substantial attempt to correlate ground conditions and water inflow, through analyzing a large volume of ground information in the public domain and measurements taken in the first stage of a project, for better certainty of cost and programme estimates for the second stage of the project. The effort underscores the commitment of the local geotechnical profession to improve project management in the face of geological uncertainties. The paper offers the possibility of initiating a good practice among the local profession and inspiring other uses of big datasets in the service of the construction industry. It is well illustrated with clear figures and tables and is readable even to engineers not attuned to engineering geology or familiar with tunneling.

Engineering Geological Approach for Assessment of Quantities and Programme for Deep Tunnels in Hong Kong

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ABSTRACT

Programming of tunnels in hard rocks and estimation of overall costs need to consider the sometimes great influence of the frequency and intensity of grouting that is required to limit groundwater inflow rates to pre-determined levels. This paper focuses on an engineering geological approach to assess the potential frequency of groundwater inflows and grouting effort based on a study of over 20 km of deep sewer tunnels in Hong Kong and Norwegian grouting experience. Many of the geological factors that appear to influence grouting frequency and effort are not considered or are not adequately quantified by existing rock mass classifications. Also, the geological conditions in the inevitable ‘gaps’ between drillholes can only be inferred based on indirect evidence from typical ground investigations and consideration of the overall geological setting. Notwithstanding these limitations, the range of impact that grouting may have on the programming of a project still needs to be estimated.

In an effort to meet this need for the design of the Harbour Area Treatment Scheme (HATS) Stage 2A tunnels, the engineering geological (EG) data and probing records from the HATS Stage 1 tunnels were examined. Trends in frequency and magnitude of groundwater inflows from probe holes were correlated with the engineering geological characteristics of the rock masses. This paper describes the approach adopted to facilitate estimation of costs and programme.

1 INTRODUCTION

A good geological model is essential for the geotechnical assessment of any underground construction project. The synthesized model requires expert interpretation of all relevant information including archival and project-specific investigation data. For deep tunnel construction in rock, geological and hydrogeological characterization of the ground is very important to enable realistic assessments of cost and programme and the recognition and management of geotechnical risk. Key issues for deep tunnel construction beneath intensive urban development built largely on reclamations and superficial deposits are the determination of the extent to which groundwater inflows and related groundwater draw down need to be controlled and the cost and programme implications of the mitigation works that will be required. This paper outlines the EG approach that was adopted to address these issues in connection with the design of HATS Stage 2A Sewage Conveyance System (SCS). The assessment was greatly facilitated by the lessons learnt from the construction of HATS Stage 1 and the availability of detailed records from this project on advance probing, groundwater inflows and geological conditions contained in an electronic ‘Tunnel Database Management System’ (TDMS). Detailed geological face logs were also examined to gain further insight into pertinent EG conditions that are not readily captured by rock mass classification systems originally intended for assessments of tunnel support only.

2 PROJECT BACKGROUND OF HATS STAGE 2A

HATS Stage 2A, commissioned by the Drainage Services Department (DSD), is aimed at further improving the quality of Hong Kong’s inshore marine waters. The project includes the construction of 20 km of tunnels

An outline of the overall EG approach to ground characterization and estimation of programme and quantities for the HATS Stage 2A tunnelling works is given in Figure 2 below.

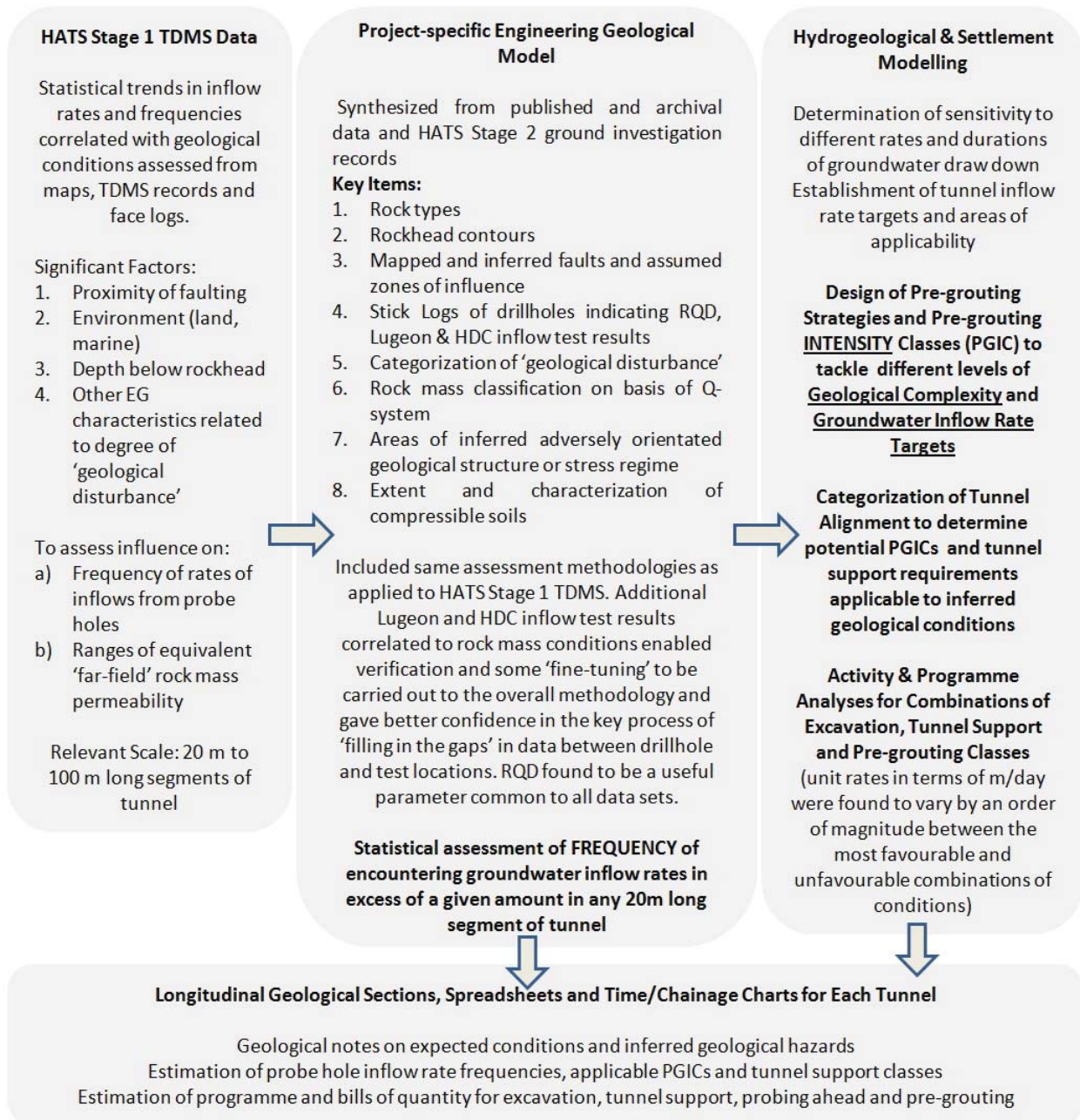


Figure 2: Overall approach to ground characterization and estimation of quantities and programme for HATS Stage 2A tunnelling works

3.2 Significant geological factors relating to frequency and rates of groundwater inflows in probe holes

Previous experience and as-built records from HATS Stage 1 were assessed to identify significant geological factors that are statistically discriminating with respect to frequency of rates of groundwater inflows encountered in probe holes drilled ahead of the face (Endicott & Tattersall, 2009; Tattersall, 2010). The relationships established are summarized in Figure 3 and Tables 1 & 2 below. The key factors indirectly reflect the inherent block size of the parent material (i.e. widely-jointed to massive granite or closely to medium-jointed volcanics), the degree to which the rock mass becomes more highly fractured and disturbed by brittle tectonic disturbance (proximity of faulting) or stress relief (i.e. relatively thick rock cover below

land and thinner rock cover under marine conditions) and frequency of persistent or inter-connecting features of higher hydraulic conductivity (e.g. closely jointed dykes and veins or joint infills of hard, crystalline materials such as pegmatite, quartz or calcite which frequently contain voids).

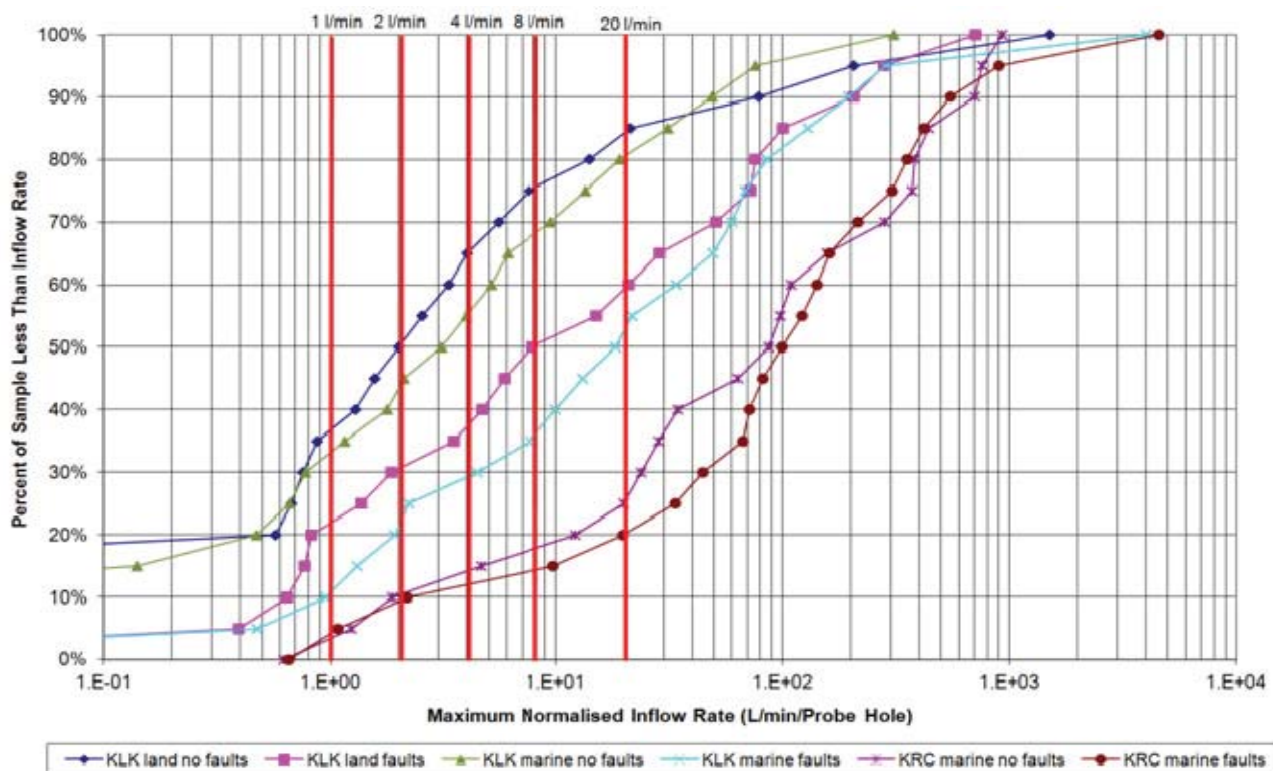


Figure 3: Variation in probe hole inflow distributions with rock type, environment and proximity to faults
 Note: KLK: Kowloon granite. KRC: closely-to medium-jointed, volcanic Che Kwu Shan Formation,
 ‘Faults’: within 25 m of a minor fault or within 75 m of a major fault.

Table 1: Classes of geological disturbance for probe hole or drillhole assessments

Class	Condition
E	Fault
D	Dykes and absence of Class E conditions
C	Frequent crystalline veins and absence of Class D and E conditions
B	Frequent crystalline joint infills with RQD < 80 or no infills with RQD <40 and absence of Class C, D and E conditions
A	Absence of Classes B, C, D and E conditions

Table 2: Probe/grout fan intensities and inflow frequencies related to geological disturbance

Disturbance Class	Klk Land		Klk Marine		Krc Marine	
	Average No. of holes per fan	% fans with inflow >20 litres/min	Average No. of holes per fan	% fans with inflow >20 litres/min	Average No. of holes per fan	% fans with inflow >20 litres/min
E	5.1	29	7.8	65	7.6	90
D	2.8	0	5.3	37	7.7	83
C	2.9	40	4.3	31	3.6	70
B	3	30	5.3	58	2.5	76
A	2.7	16	3.7	18	2.6	37

As can be seen from Figure 3, proximity of faults has a larger effect on groundwater inflow distributions in the inherently less jointed granite than in the inherently more jointed and more frequently highly transmissive volcanic rock. The factors identified in Figure 3 are more readily amenable to spatial application within a GIS-based geological model. However, the classes of geological disturbance in Tables 1 & 2 can be applied to direct evidence from drillholes and can also be used to identify likely zones of high hydraulic conductivity where drillhole information exists.

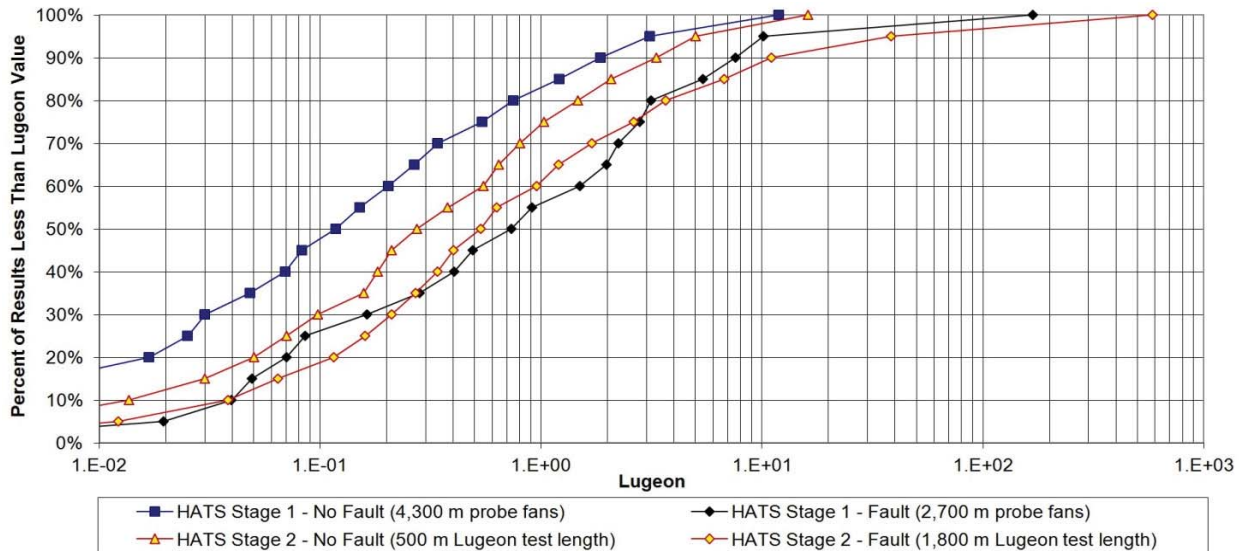


Figure 4: Hydraulic conductivity distributions for Klk (marine) from probe hole and Lugeon test data

Figure 4 shows the marine HATS Stage 1 data for Klk (probe hole inflows converted to equivalent Lugeon values) and the marine HATS Stage 2 Lugeon test data for Klk plotted on the same distribution chart. Very similar distributions are evident for the rock masses affected by faults. For Klk outside the influence of faults, the distribution from the HATS Stage 2 Lugeon testing appears more adverse than indicated by the HATS Stage 1 results. However, the HATS Stage 1 data represent about 4,300 m of near-continuous probe drilling (no selective bias), whereas the sample length for HATS Stage 2 is considerably smaller and is not continuous. Endicott & Tattersall (2009) discuss the limitations on applicability of isolated Lugeon testing and highlight the potential skewing that can occur when tests are targeted towards the more obviously jointed sections of a drillhole. In more closely fractured rocks, e.g. Klk affected by faults, there would appear to be less scope for selective sampling and the hydraulic conductivity distributions are similar. Comparisons were also made between the HATS Stage 1 probe hole data for closely to medium-jointed Che Kwu Shan Formation and the HATS Stage 2 Lugeon test data for the similarly jointed Ap Lei Chau Formation. The distributions for both 'Fault' and 'No Fault' categories were also found to be very similar.

3.3 Application to HATS Stage 2 EG model for assessment of tunnel support quantities and the need to carry out dedicated fans of PEG

Based on the similarities between the HATS Stage 1 data and HATS Stage 2 test data, the tunnels of HATS Stage 2 were categorized in terms of likely 'typical' hydraulic conductivity using the three criteria of rock type, proximity of faults and depth below rockhead in addition to direct, local evidence from drillholes. Data from both HATS Stages 1 and 2 and over 60 km of previous drillhole logging and as-built tunnel records for other projects also indicate good statistical correlations between the same three criteria and trends in RQD, block size and rock mass Q-values (Tattersall, 2010).

Application to the EG model for HATS Stage 2 helped to assess the hydrogeological characteristics and rock mass quality within the large 'gaps' in-between drillholes. The primary purpose was to aid assessment of the frequency of occurrence of different ranges of rock mass quality and hydraulic conductivity and hence facilitate estimation of tunnel support quantities and the frequency of the need to carry out PEG in dedicated

grouting fans to reduce residual groundwater inflows in the tunnels to less than or equal to the targets established on the basis of groundwater draw down and settlement modelling.

3.4 Estimations of grouting quantities and tunnel construction programme

Assessing the frequency of the need to grout is not sufficient on its own to derive realistic assessments of quantity and impact of grouting works on the tunnel construction programmes. This is because the quantities of grout holes, materials and time required are heavily dependent on the grouting difficulty and effort to achieve a given residual tunnel inflow target. In this respect, the hydraulic conductivity of the rock mass or measured magnitude of groundwater inflow from probe holes may not be a major factor in determining the required pre-grouting intensity since large inflows from a few joints of large aperture may be satisfactorily pre-grouted far more easily than smaller, well-distributed inflows from many joints of variable condition.

Scandinavian experience suggests that the required intensity of grouting is primarily dependent on the complexity of geological conditions, residual inflow rate targets and groundwater head. Table 3 below shows an outline of a matrix that was referenced when interpreting the overall EG model to provide crude estimates of ‘Pre-grouting Intensity Class’ (PGIC) to help determine Bills of Quantity and programme. The matrix is based on previous work by Scandinavian experts (Beitnes, 2009) adapted to Hong Kong conditions. The PGICs for estimating purposes range from ‘I’ for the least intensive to ‘VI’ for the most intensive. When considered in combination with tunnel support requirements, the range in estimated construction progress rate was found to vary by an order of magnitude between the best and the worst combinations of conditions.

Table 3: EG conditions affecting range of PGICs assumed for estimating purposes

Engineering Geological Conditions	PGIC I	PGIC II	PGIC III	PGIC IV	PGIC V	PGIC VI
Massive Rock with few joints or RQD = 100	←→					
3 joint sets with variable apertures or RQD = 70 – 100		←→				
Complex, multiple joint sets and joint conditions or RQD = 25 – 70			←→			
Weakness Zones of Bedrock > 2.5 m thick with RQD <25				←→		
Mixed Ground or Soil > 2.5 m thick					←→	
Hydrostatic Pressure <5 Bar: Reduce grouting pressure as necessary. Assume upgrading of PGIC I-V by one class.						
Highly anisotropic transmissivity favouring discontinuities sub-parallel to tunnel axis: May require multiple injections of different grouts and grouting pressure may need to be reduced to limit excessive ‘travel’. Assume upgrading of PGIC I-V by one class.						

Note: Arrows indicate approx. influence of range of applicable residual inflow targets (left to right: least stringent to most stringent)

4 CONCLUSIONS

The statistical EG/hydrogeological relationships found from examination of HATS Stage 1 data helped to gain greater insight into key indicators that can be practicably applied to assess rock mass hydraulic conductivity on a statistical basis. The relationships were tested against project-specific Lugeon test data and were found to be discriminating. However, it should not be expected that relationships assessed for one geological unit can be directly applied to other geological units subjected to different geological conditions over time – although general principles and overall trends are likely to be similar.

The same key indicators used to assess frequency of the need for dedicated fans of PEG can also be referenced to obtain estimates of tunnel support requirements based on past experience in Hong Kong.

Prognoses of grouting intensity which are necessary to give crude, preliminary estimates of quantity and programme are notoriously fraught with uncertainty due to local variations in the combined influence of a large number of factors that are almost impossible to adequately assess using current ground investigation practice. Much EG interpretation, judgment and reliance on previous experience are necessary. Consideration and extrapolation of only the EG conditions listed in Table 3 and their implicit connotations is very much a simplified but pragmatic approach.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Director of Drainage Services Department, the Government of the Hong Kong Special Administrative Region for permission to publish this paper.

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