Appropriate support selection

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The selection of support has a considerable impact on the safety, cost, excavation progress, risk and critical path of a complex project. Three case histories provide examples of various criteria for support selection.

It is not uncommon for controversy to be associated with tunnel support selection, particularly when it comes to quantity overruns. In North America, contract and design documents have assigned specific responsibility for tunnel safety, and thereby the choice of support, to the contractor. Historically, that responsibility was delegated to the foreman at the heading. Challenges to the selection of support type and quantities occurred in association with quantity overruns only after support had been installed, and never at the heading. These challenges were usually financial and seldom addressed technical issues, efficiency or safety.

Development of ground classification schemes as the basis for support selection have become more common. However, they are invariably applied at the design stage and less commonly at the heading. In some cases, the selection of support is highly technical and based on deformations or geotechnical measurements at the heading. In other systems support selection is based on observed quantitative geotechnical conditions at the heading; these require a geologist or an engineer to be present at all times during support selection.

For the first example, Hunter Tunnel II – Completion Contract in Colorado, the temporary tunnel support was specified in the bill of quantities (Table 1) and the contract drawings. Soon after tunnel excavation was under way, it became apparent that more extensive steel rib support was being installed in the tunnel than was anticipated either by the owner or contractor. Although tunnel crews maintained excavation rates in excess of those anticipated in minimally supported ground, the overabundance of ground requiring support slowed down overall excavation below anticipated as well as possible average rates.

The contractor was paid for all installed steel rib support; however, the owner initially declined to compensate the contractor for delay by claiming that not all the steel rib support was necessary. The delay in this case was substantial. Both parties agreed that all support in shear zones was justified. The need for the remainder of the steel ribs was under dispute, and no agreement was forthcoming. Discussions with the tunnel superintendent confirmed that the shifters at the face of the tunnel directed installation of steel based on observations and judgements which were consistent with rock mechanics principles. Only the language and expression of opinion were different.

In its frustration, the contractor retained the services of yet another independent consultant, who confirmed, at various locations in the tunnel, that "the use of steel ribs was obviously necessary". It was not, however, obvious to the owner and the impasse continued.

Analysis of installed supports

The owner's geologist had mapped the tunnel on a scale of 1in = 10ft; consequently, analytical data were available. However, what to do with it all? Was the use of steel support in all instances justified? How to show that the steel was necessary? It was impractical to analyse 50 000 data points by hand.

Encountered geology portrayed on tunnel logs was quantified and entered into a computer. Initially, separate histograms for all the geological conditions and associated support were prepared. It became apparent, at least intuitively, that installed support (not justified by shear zones) was necessary because various geotechnical conditions acted in concert to cause instability. This was consistent with the intuitive response of the foreman at the heading.

Attempts were made to use various rock classification schemes to investigate if steel rib support could be justified by a combination of adverse geological features. This was unsuccessful. The problem was that available data were not in a form that would be discriminating enough to result in demonstrable variations using any particular rock mass characterisation scheme with the data available.

Consequently, a unique scheme was developed that utilised available data and was consistent with geotechnical principles and their effect on support requirements. The scheme was called 'Geotechnical Severity' and its definition is not essential for the purpose of this paper. The relationship between Geotechnical Severity and degree (type) of support installed was consistent with geotechnical conditions, support requirements, and the human reaction at the tunnel heading.

Support of shear zone, Hunter Tunnel.

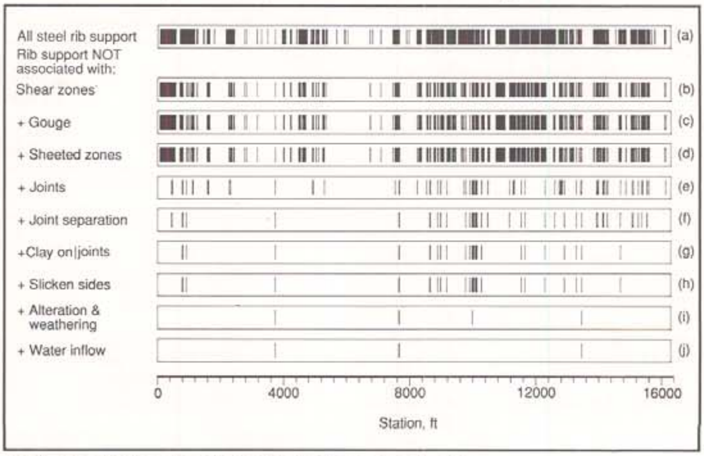

Fig 1. Justification of steel support for the Hunter Tunnel.

For the second stage of the analysis, steel ribs were plotted as shown in Fig 1a. In each subsequent line (Figs 1b to 1j), steel sets associated with (justified by) various geological features were eliminated. The remaining steel sets (not justified by any of the features listed) are shown in Figs 1e to 1j.

The extensive analyses and graphic illustrations showed insight into the relationship between geotechnical conditions, support requirements and the human element at the heading. The results were multifold: first, the contractor was compensated by the owner. Second, the owner became a loyal client, and third, a great deal about the realities and practicalities of rock mechanics in tunnel excavation and human nature came to light.

Geology encountered in Hunter Tunnel II indicated a remarkable correlation between Geotechnical Severity and the supports used. For example, as Geotechnical Severity varied, it was reflected by the degree of support installed.

It became obvious that a direct and precise relationship between Geotechnical Severity and Degree of Support did not exist. However, the Degree of Support generally (and not always) lagged behind Geotechnical Severity. In other words, as conditions become more severe, a reaction time (or length of tunnel) was evident before support was used or made heavier. Similarly, as conditions improved, the support was generally carried beyond where theoretically necessary. This illustrates the reality of the human intuitive factor involved in support selection.

The human factor, apart from its intuitive aspect, became more apparent when conditions varied suddenly, radically or cyclically. For example, where ground conditions went from unsupported to supported then back to unsupported again several times in succession, the support tended to be maintained further and further into ground not requiring support. This may be due to pessimism, conditioning or expectation of more adverse ground conditions.

Occasionally, the Geotechnical Severity was high and yet little or no support was placed. Again, this exemplifies the human factor in support selection in that observed geological conditions may be inconsistent with observed behaviour.

Figs 1e to 1j illustrate that there are in fact steel sets which were not associated with or justified by shears or even a combination of major adverse geotechnical features. A detailed review of the records indicates that these steel ribs are generally found at the beginning and end of adverse ground conditions requiring support. In other cases, the unjustified support was continued between adjacent sections of blocky ground. These phenomena are consistent with the human element in selecting and installing support at the heading.

Tunnel support selection at the design stage is common. One such example is Tunnel de los Rosales, in Bogota, Colombia, where four categories of support were specified for drill + blast excavation as summarised in Table 2.

The ground characterisations, delineation of tunnel zones and associated support systems were selected at the design stage. However, is there a guarantee that the ground types will fit into these categories or that the worst ground conditions could effectively be dealt with by support type 4 in all cases? Such technical and restrictive selection of ground behaviour:

1. May not adequately account for the behaviour of natural materials;
2. May not allow for more adverse and unanticipated conditions;
3. Neglects the impact of support installation on construction progress; and
4. Places the risk of delays entirely on the contractor.

In addition, variations in ground behaviour that require changes in support may simply be impractical, especially in a long tunnel. The contractor recognised:

1. The insurmountable risk with drill + blast excavation in the conditions as depicted in the geotechnical report;
2. The possibility of reducing the required amount of ground support by using TBM excavation; and
3. The potential for high excavation rates by TBM.

The contractor proposed TBM excavation using a support system as outlined in Table 2. Instead of using various combinations of rock bolts, shotcrete and steel ribs, the contractor substituted pre-cast concrete segments (Type B) for original ground Types 2, 3, and 4.

The contractor's alternative support system was responsible for timely completion of excavation while traversing some of the most difficult geological conditions recently encountered. Had

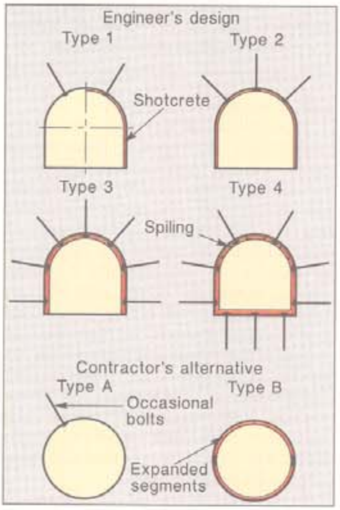

Fig 2. Support specification, Los Rosales.

Table 1: Tunnel support quantities (Hunter Tunnel).

Support category	Support type	Anticipated quantities	Encountered quantities
1	Unsupported with random rock bolts	13 749	8127
2	Steel sets	1405	7847
3	Shotcrete	920	100
Total		16 074	16 074

Table 2: Designed/actual support (Tunel de los Rosales).

Engineer designed (for drill + blast)		Contractor proposed (for TBM)	Contractor encountered (with TBM)			
Category	Support type	Design quantities (m)	Category	Support type	Anticipated quantities (m)	Encountered quantities (m)
1	Sporadic shotcrete/bolts for safety	3245	A	Unsupported	3245	2461
2	Shotcrete and bolts in the crown	4008	B	Segments	5835	6619
3	Steel rib arches; shotcrete, & bolts in crown & side walls	978				
4	Steel rib arches with curved invert struts; shotcrete & bolts in crown, side walls, & invert	849				
TOTAL		9080			9080	9080

drill+blast excavation and recommended support systems been utilised, the tunnel might not yet have been completed, certainly not within the anticipated or actual time and costs.

The unanticipated geotechnical variations in this tunnel were substantial, as the 'hard sandstone' turned out to be sand that even 'flowed', through grout holes of pre-cast segments, filling the tunnel with as much as 5 to $6m^3$ at a time. In one section of tunnel, an unanticipated 500 litre/s flow from the invert would have had more severe consequences than sustained by the shielded TBM and the fully segmentally lined tunnel. Could the flowing sand and the 500 litre/s flow have been traversed successfully by any of the original categories of support? Anyone visiting the tunnel during the time of these difficulties could only conclude not.

Support selection during the design stage may have undesirable consequences such as eliminating cost-saving options, innovative flexibility and the possibility of producing record excavation performance despite adverse conditions encountered.

An example of support selection (established at the design stage) based on measured deformations at the heading is provided by the Pinglin Tunnel of the Taipei-Ilan Expressway in Taiwan. Six categories of support were designed in detail and specified for both drill+blast and TBM excavation of the pilot tunnel. Support categories for TBM excavation are summarised in Table 3. The supports were designed for conditions based on perceptions of ground behaviour during the basic design stage. Further evaluation will be necessary to ensure full consideration of:

1. All possible variations of ground behaviour at the excavation front and around the TBM;
2. Experiences in similar and extremely adverse ground conditions encountered on various tunnelling projects in Taiwan;
3. Possible impact of various support systems on excavation progress; and
4. Encountering adverse and potentially difficult excavation of main bores, shafts and ancillary structures.

The impact of difficulties associated which other excavation could only be mitigated effectively and economically by excavation of the pilot tunnel well ahead of schedule.

There is a variety of adverse anticipated conditions for which too many alternative support methods may be costly, impractical or both. For example, the tunnel alignment will traverse under high cover (700m), through altered, crushed, highly fractured and blocky rock, and through waterbearing crushed, faulted and sheared zones. Faulted zones in quartzitic sandstones consist of rock fragments the size of railroad ballast or smaller. Such material serves as a conduit and reservoir of water having heads as high as 700m, and drainage must be allowed. When argillite is faulted it typically alters to clay and deforms freely under overburden weight, thereby requiring full support.

Table 3: Technical support selection (Pinglin Tunnel).

Category	Type	Capacity $KN/m^2/mm$ of displacement
A	Unsupported, spot bolts	
B	2×2×2.5m rock bolt pattern	10.3
C	2×1.5×2.5m rock bolt pattern 50-100mm shotcrete in crown	57.1
D	2×1.5×2.5m rock bolt pattern 100mm shotcrete	100.5
E	Steel ribs @ 1.25m spacing @ 1.00m spacing @ 0.75m spacing	61.3 76.6 102.1
F	180mm precast segments (grouted)	312.4

Note: pre-cast invert will be used throughout tunnel

Shaft excavation will have to be accomplished through rock having RQD = 0 in one case and artesian water having a head in excess of 200m above the collar of the shaft in another. These shafts are in remote locations and previous experience has resulted in extensive delays when encountering water. Consequently, excavation of shafts at three separate locations, 13km of pilot tunnel, and two 13km, 12m diameter highway tunnels will not be without uncertainty, surprises, setbacks or delays. Assurance of successful and timely excavation of underground structures will require alternative plans, redundancies and alternative techniques to be incorporated in the design of the excavation system.

Effect of support on progress

Support selection based on measured deformation at the heading is acutely scientific and will require an engineer at the heading. The use of six categories of support will be complex and will likely result in delays. An overrun of steel ribs and precast segments is likely since they are simpler to install and conservative. Steel rib support in a TBM-excavated tunnel has historically resulted in delay.

With space limitations typical in a bored tunnel, it is unlikely that six types of support (as specified) can be stored at the heading. Any changes in support type will require transport from the outside stockpile, resulting in further delay.

The use of shotcrete, although possible as indicated by successful case histories in Europe, is generally undesirable around a working TBM and its backup system. Spraying of shotcrete is not recommended within 100-200m of the face when high excavation rates are desirable. A call for shotcrete will result in more substantial delays at the heading, increasing with distance from the portal.

The most consistent and largest delay will be generated by constant variations between six support types, variation of installation methods, calling for support materials from outside the tunnel, and lack of continuity of operation. Such delays may be as much as 25 to 50% of all available time according to experience.

Categories suggested are unsupported; pre cast segments; and ribs and corrugated sheets. Alternative supports are consistent with and encourage high excavation rates. The reduction of support categories to only three simplifies heading operation, change in schemes, and reduces probable downtime. The use of ribs and corrugated/perforated sheets is provided in case drainage of waterbearing ground is desirable. Since the tunnel may be used to pressurise the emergency cross-passages in case of fire, the segmental lining may also serve as a final lining.

A time study comparing installation of steel ribs and lagging with installation of segments was conclusive. The best time for erection of a ring of steel with lagging has been 15 minutes, whereas an equivalent pre-cast concrete ring can be installed in an average of only eight minutes. Average times for steel support are at least double that required for segments.

The greatest benefit of a pilot tunnel is the alternative access (to shafts, chambers, associated structures, and pre-treatment of fault and waterbearing zones) that permits mitigation of impacts from unanticipated ground behaviour, loss of excavation progress and other possible delays. Without the completed pilot tunnel excavated ahead of schedule, delays are more likely to be crucial to scheduled project completion. Consequently, higher costs incurred in using a pre-cast segmental lining in the pilot tunnel may be miniscule compared to the more costly risks and delays for the main bores and the entire expressway.

The single most effective opportunity to provide redundancy, alternatives and safety is the earliest possible completion of the pilot tunnel. Since high penetration rates are possible, TBM utilisation will control and have the major impact on daily excavation rates. Utilisation is a function of various categories of downtime. Downtime for support installation may be as high as 25%. Elimination of such downtime, at penetration rates of 4m/h, can effectively double the average daily rates.

The purpose of the proposed excavation of a 13km pilot tunnel was:

1. The investigation of ground behaviour under adverse and encountered conditions;
2. To pre-drain waterbearing zones;
3. To allow pre-treatment of waterbearing and weak zones ahead of the main bores; and
4. To serve as emergency pre-drainage and access for three deep ventilation shafts traversing difficult conditions.

Use of standard practices form the foundation of science and engineering. However, their inflexible application can be counterproductive and detrimental to the project objectives. Independent observation and thorough, practical contemplation of the consequences of the selection of methods for excavation, stabilisation and construction result in a more cost-effective, less risky and a shorter completion path. In conclusion, the following questions are offered as an aid in selecting support methods:

- What is the best method for support selection?
- What are the shortcomings of selecting support at the design stage?
- What are the shortcomings of selecting support at the heading?
- What are the disadvantages of limiting the contractor's alternatives for excavation, support and project execution?
- Should support selection include the consideration of its impact on cost, excavation progress and other factors? What might be the consequences of not considering these factors?
- What is the cost of tunnel completion delay when it impacts the project critical path in comparison to more expensive yet less risky methods?
- Why should the Engineer be concerned about the selection of temporary support beyond the safety and stability during the life of the construction?
- What is the intention of the project in terms of life (completion) and space (alignment, conditions, methods, etc)?
- What is the order of priorities? □

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