North American Tunneling Journal

Engineering Geology as Applied to Tunneling Projects

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Engineering Geologists who are asked to assist with tunnel project design would normally be working in one way or another for the project Owner and are asked to provide input on project planning, the subsurface investigation, preparation of the Contract Document, and the provision of field observations during construction. For design-build and other alternative procurement methods, they may also provide similar input to a Contractor. Interestingly, there are two basic types of individuals who are qualified to participate in this endeavor: geologists who know a lot about tunnel design and construction, and tunnel designers who know a lot about geology; especially the type and/or specific host geology anticipated for a particular project.

In general, and for the remainder of this paper, both of these types of individuals will be referred to as "Engineering Geologists," although the term "Geological Engineer" would also be appropriate. In either case, these individuals are expected to help provide answers to the following four major questions:

- What types of geology (ground) and hydrogeology (groundwater) will be encountered by the tunnel and associated shafts along a proposed alignment?
- How will the ground and groundwater behave and/or react to the tunnel excavation and support means and methods being proposed for use during construction?
- What are the "design criteria" for the various structures that are needed both to excavate and support the ground during construction and for inclusion in the finished facility?
- How should all of the above information be incorporated into the Contract Document appropriate for bidding and for construction in order to provide the best chance for project success?

In order to provide answers to these four questions, the remainder of this section is divided into the following four subsections:

1. The Subsurface Investigation
2. Geological/Geotechnical Interpretation
3. The Contract Document
4. Field Observations and Monitoring

Top heading mapping in good ground – Caldecott Fourth Bore Tunnel. All article photographs by Sue Bednarz

1. The Subsurface Investigation

The subsurface investigation for a tunneling project is commonly divided into three phases; the planning effort, project design, and project construction. With respect to the planning effort, the design team will endeavor to collect as much available information as possible including existing test borings in the vicinity of the project, geologic maps, aerial photographs, and nearby and/or relevant case history studies. Having accumulated all of that information, a Phase I subsurface investigation is planned and executed with widely spaced test borings, other intensive field investigations, and a comprehensive laboratory testing program. The primary objective of the Phase I subsurface investigation is to establish a reliable understanding of a subsurface geologic model that establishes the characteristics present in the ground along the overall alignment through which the tunnel and associated shafts will be constructed.

It is during the Phase I subsurface investigation that the

services of skilled and experienced Engineering Geologists become important. Geologic specialties, such as geomorphology, structural geology, hydrogeology, and seismic characterization are indispensable in properly assessing the characteristics of large volumes of ground and for providing the geologic model about what to expect during tunneling. For instance, certain tunneling hazards, such as shear zones in metamorphic rock, reef or solution/karst features in limestone, swelling shales, regional faults, and highly stressed ground can be identified and anticipated for projects as a result of geologic studies. In addition, Engineering Geologists can use the results of test pits, geophysical investigations, and geologic mapping (sometimes at great distances from the actual project site) in order to form a reliable opinion about what types of ground conditions to expect, as well as how best to investigate those ground conditions in subsequent phases of the investigation. Upon completion of the Phase I investigation, the project planners and designers should be able to establish an informed project layout for the finished facility.

The Phase II investigation provides additional information about all aspects of the ground with particular emphasis on areas of continuing geologic uncertainty and on detailed design of both the temporary and finished structures. This phase of investigation also provides an opportunity to confirm the geological assumptions made as a result of the Phase I investigation, and to provide a detailed geologic model and subsurface profile along the proposed tunnel alignment.

For larger tunneling projects, it may be necessary to perform a Phase III investigation specifically to provide additional information to help prospective Contractors bid the project. For instance, a Phase III investigation might include test borings down the center of each shaft once their locations have been finalized, borings to investigate major geologic features such as fault zones, and/or to provide additional detail about the soil/rock interface. In the final analysis, the Owner and its Designers need to provide the Contractor with sufficient information to help select the correct means and methods for constructing the project and to provide a realistic and reliable bid for the work. The Contractor might also hire their own Engineering Geologist(s) and Designers to assist with independent verification of the geologic model and to design the temporary facilities required for the work.

2. Geological/Geotechnical Interpretation

During the past 20 years or so, it has become accepted practice for the Owner and its Designers to provide their interpretation of anticipated ground conditions and how ground and groundwater are expected to behave and/or to react to the process of tunneling. In the "old days" (i.e., 30 years ago) the Owner provided the results of the subsurface investigation to prospective Contractors, and the Contractors were then expected to make "reasonable and prudent" assumptions about both the anticipated ground and groundwater behaviors and the best methods for controlling those behaviors during construction. Experience, however, demonstrated quite clearly that this approach to tunnel procurement was not viable because of intense competition in the low-bidder environment, and because tunnel Contractors did not always consider the possibility of negative impacts to adjacent third-party structures. As a result, the responsibility for making "reasonable and prudent" decisions about anticipated ground conditions and behaviors shifted from the Contractor to the Owner and its Designers, including their Engineering Geologists.

All of the underground openings created for a tunneling project must be both safe for the workers and stable with respect to the adjacent third parties. In order to achieve that objective, tunnel Designers and Contractors can choose from a variety of tunneling methods and ground improvement technologies that can be used for that purpose. Hence, the primary objective of the interpretive effort is to aid in the selection of those tunneling methods and ground improvement technologies that are best suited to the anticipated ground conditions for each particular tunnel project, with the goal of providing the best chance for successful project completion "for no more time and no more money than is required."

3. Contract Document

Having completed the subsurface investigation and the geological/geotechnical interpretative effort, project engineers and Engineering Geologists then turn their attention to the Contract Document. Based on a strong consensus that has developed over the past 20 years, the primary goal of this effort is to produce two reports entitled the Geotechnical Data Report and the Geotechnical Baseline Report; both reports that are included in the Contract Document.

Tunnel mapping around miners setting initial support – New Irvington Tunnel

The Geotechnical Data Report (GDR) is exactly what the name implies; a collection of all of the facts that were accumulated about subsurface soil, rock and groundwater conditions during the subsurface investigation. In general, this report consists of a brief text that establishes the geologic setting and explains all

of the methodologies used to observe and accumulate field and laboratory test results, followed by voluminous appendices that contain the data resulting from those tests and observations. For instance, all of the test boring logs with core photos, field test results, laboratory test results for both soil and rock deposits, the results of geophysical tests, pumping tests, and other investigations that were performed for the subsurface investigation would be included in the appendices of the GDR. In addition, there are three important guiding principles associated with the GDR:

1. That the data provide the basis for a comprehensive description of the ground in which the tunnel will be constructed,
2. That all of the laboratory and field tests were performed exactly as described by applicable ASTM or other applicable standards, and
3. That the document not provide any interpretation of the results or geologic profiles with strata or other features depicted.

With regard specifically to the third guiding principle, the authors have encountered some GDRs that included a subsurface profile. Such a subsurface profile represents an interpretation of anticipated ground and groundwater conditions, and they should only be included in the Geotechnical Baseline Report (GBR). The principle of "keep it simple" applies to the GDR, which should provide a thorough and accurate factual description of the data collected concerning the ground and groundwater properties.

In contrast, the primary objective of the Geotechnical Baseline Report (GBR) should be to inform the Contractor about what they need to know in order to bid and then successfully construct the project in a proper manner. As stated in the 2007 edition of the ASCE book entitled Geotechnical Baseline Reports for Construction, Suggested Guidelines (referred to as "The Gold Book"), the primary purpose of the GBR is as follows:

"The principal purpose of the GBR is to set clear realistic baselines for conditions anticipated to be encountered during subsurface construction, and thereby provide all bidders with a single contractual interpretation that can be relied upon in preparing their bids. Other key objectives of the GBR include:

- ***Presentation of the geotechnical and construction considerations that formed the basis of design.***
- ***Enhancement of the contractor's understanding of the key project constraints.***
- ***Assistance to the contractor in evaluating the requirements for excavating and supporting the ground; and***
- ***Guidance to the owner in administering the contract and monitoring performance during construction."***

Although the concept and purpose of a GBR presented above are valid, it is not easy to write a "good" GBR. Preparation of a "good" GBR requires persons with extensive knowledge about geologic and hydrogeologic conditions, ground and groundwater behavior, tunneling, ground improvement technologies groundwater (and groundwater control), and tunneling contracting practices. Geotechnical Baseline Report preparation is not appropriate for persons who do not possess these requisite backgrounds, training and experience. The 2007 ASCE document referenced above is an excellent resource and should serve as a basic guideline for GBR preparation.

It is also important that the GBR establish "measurable" baselines that are clearly established and understandable within the document and are not vague or ambiguous. The inclusion of "measurable", well defined and established baselines values within the GBR serves several crucial functions for the project:

1. They set forth what conditions that the bidding Contractors are to assume to help them establish their bid for construction of the project
2. Bidding Contractors are responsible for conditions up to and including the baseline values established in the GBR document
3. Adverse conditions beyond the established GBR's measurable baseline values are the responsibility of the Owner and should not be included in Contractor's bids
4. The GBR is often the primary Contract Document used in the evaluation of Differing Site Conditions (DSC) claims during and after construction by Dispute Review Boards (DRB) or other mediators

Because of the importance placed upon the GBR document during bidding, determining appropriate means and methods, and in evaluating DSC claims, the importance of a "good" GBR cannot be understated.

4. Field Observations and Monitoring

The last, but by far not the least important responsibility provided by an Engineering Geologist for tunneling projects, is the provision of trained field observation and the monitoring of ground response during construction. During tunneling, it is important to observe ground and groundwater conditions exposed by the underground openings, and then compare those observed conditions and behaviors both with the factual information provided in the GDR and the interpretations and baselines provided in the GBR. It is particularly important to document how the ground and

Difficult tunnel mapping conditions in bad ground – New Irvington Tunnel

groundwater are behaving and/or reacting to the specified or selected tunneling methods for comparison with the interpretive information provided in the GBR. This comparison should include both the impacts on actual tunneling operations as well as the impacts on adjacent, existing third-party structures and utilities. As most persons associated with tunneling projects are well aware, it is not uncommon for allegations of damage, delay, and additional cost to be lodged as the result of a tunneling project, most commonly as a result of alleged DSCs. Complete documentation of the daily activities associated with the project is essential for the evaluation and adjudication of those types of allegations.

Engineering geology in tunnel construction

Engineering Geologists are also frequently called upon to assist Contractors during the bidding and construction phases of a tunnel project, and, in some ways, that process can be even more intensive and consequential as compared to working for the Owner. No one who has experience in underground construction can deny that a certain degree of "tension" exists between the Owner and the Contractor during the bidding and construction phases of a tunneling project, or that the eventual outcome of a tunneling project will be determined by how that tension is managed throughout the process of construction. For instance, the tunneling industry has been quite successful in using Dispute Review Boards (DRB) to help manage various types of claims, especially DSC claims, during construction with the intention of keeping the project moving forward as its primary goal.

Most of the cost of a tunnel claim has to do with project delay. Therefore, maintaining production during tunnel construction is one of the key goals of dispute resolution. Needless to say, almost every claim resolution has to do with an accurate assessment of what happened in the tunnel during construction and Engineering Geologists play a leading role in documenting construction activities and observed ground and groundwater behaviors for both the Owner and the Contractor. Hence, the remainder of this section is divided into the following three subsections:

1. The Pre-bid Investigation
2. Tunnel Construction
3. Claim Resolution

Probe drilling ahead from stabilized face – Caldecott Fourth Bore Tunnel

1. The Pre-bid Investigation

The pre-bid period of a construction project is without a doubt one of the most important parts of project success. It is during this period that the Contractor and its team of experts performs a totally independent and crucial review of all of the information provided in the Contract Document. Many Owners and Designers sometimes do not fully appreciate how difficult it is to provide a reliable cost estimate for a project taking place underground, especially projects in urban areas, and that will take several years and possibly many hundreds of millions of dollars to construct. When Engineering Geologists become involved in a pre-bid investigation for a tunneling project, they will usually be asked to provide answers to the following three questions:

- Based on an intensive analysis of the GDR, what types of geologic and hydrogeologic conditions will be encountered by the tunnel and shafts along the proposed alignment and how will the ground and groundwater behave and/or react to the tunneling means and methods described in the Contract Document?
- What types of temporary structures, ground improvement, and groundwater management technologies will be required to construct the proposed shafts and tunnels compared to what is specified in the Contract Document?
- Does the Contract Document provide a truly consistent picture of what needs to be accomplished during tunnel construction, and does the GBR provide "reasonable and prudent" recommendations and baselines for accomplishing that work?

It is difficult to explain exactly how this process unfolds for each project, but in general the Engineering Geologist begins with the actual project data and assists the Contractor in deciding how long it will take and how much it will cost to actually construct the project. Once that number is estimated, then the Contractor must also assign various contingencies and allowances, many of which have to do with anticipated ground and groundwater behavior, in order to come up with a final bid for the work.

Pre-bid studies for tunneling projects are intense, challenging,

time-sensitive, and crucial to the successful outcome of a project, and Engineering Geologists who become involved in this process must have the requisite background, knowledge, and experience, as explained herein, to provide meaningful contributions to this activity. What is extremely important, and hopefully equally rewarding, is the fact that if your client (Contractor) becomes the low bidder, then many of your comments and suggestions will actually be put to the test during construction. In many ways, helping Contractors with pre-bid studies is both one of the most challenging and rewarding activities for Engineering Geologists who become involved with tunneling.

2. Tunnel Construction

During tunnel construction, Engineering Geologists are often called upon to provide field observation and documentation of ground and groundwater conditions that are encountered and, more importantly, to observe and document how the ground is reacting to tunnel construction. The cost and time for sinking shafts and building tunnels is largely dependent on how the ground is behaving in comparison to what was anticipated in the Contract Document.

Both the Contractor and the Owner need thorough and accurate records of what is happening in the field on a day to day basis. This is especially true if the Contractor believes that the work is not proceeding as anticipated and files a DSC claim. Many Owners view DSC claims with great trepidation and become extremely defensive in the face of such a claim, but both the Contract itself and many years of legal precedents are available to help with the resolution of DSC claims. Astute Owners understand the inherent uncertainty involved with subsurface interpretations based on sampling and testing only a very small percentage of the volume of the ground that will be encountered during tunnel and shaft construction. In addition, these Owners should carry appropriate contingencies to cover some degree of variation that could be encountered during underground construction.

Most importantly, and as pointed out within this paper, is the fact that Engineering Geologists working for both the Contractor and the Owner will be front-and-center in dealing with DSC claims, as all of the observations and project records produced by on-site Engineering Geologists become an integral part of the dispute resolution procedures. This fact alone establishes the critical importance of Engineering Geology to the successful outcome of an underground project.

3. Claim Resolution

As stated previously, it is rather common for allegations of DSC occurrences and also defective specifications to be lodged by the Contractor during underground construction, and it is imperative for the Contract Document to provide a method for evaluating and resolving those claims as expeditiously as possible. The input of Engineering Geologists is an integral part of that process. For most of these claims, the eventual resolution revolves around answers to the following two basic questions:

1. What was indicated about ground and groundwater conditions and behaviors in the Contract Document?
2. What ground and groundwater conditions were actually encountered during construction, compared with those Contract indications?

Fortunately for the tunneling industry, the use of DRBs has become common practice for tunneling contracts. In general, DRBs are formed at the beginning of construction, and the DRB members are, as a consequence, able to observe and to evaluate the procedures used during all phases of the construction process. Hence, when a claim is made, the DRB members are familiar with the project conditions and are able to respond quickly to all of the information collected by both parties during construction. Although DRB opinions are normally not binding on the parties, experience has shown that, more often than not, the DRB opinion forms the basis upon which a resolution of the dispute is possible. Having participated in this process on many occasions, it is possible for the authors of this paper to affirm the important role that Engineering Geologists play in assisting the DRBs in fully understanding both the types of ground and groundwater conditions that were encountered and how that ground reacted to the construction procedures in use on the project. If the DRB process is not successful, then the level of effort that will be required by tunnel engineers and Engineering Geologists participating in ligation will be exceedingly more difficult and more expensive relative to dispute resolution by a DRB.

Summary and Conclusions

The four most important functions associated with the successful design and construction of tunneling projects are the subsurface investigation, an evaluation of anticipated ground and groundwater behaviors, the preparation of a useful and beneficial Contract Document, and the observation, monitoring, and documentation of construction activities and conditions by geotechnical professionals, including Engineering Geologists. The majority of the cost and risks for a tunneling project are associated with the excavation and initial support of the underground openings, inside of which a finished facility will be built. It is also important to note that 100 percent of that design and construction takes place within the ground and is dependent upon a knowledge of existing ground and groundwater conditions and behaviors. Tunnels are long, linear structures, the construction of which is wholly dependent upon successfully anticipating ground and groundwater behavior in order to keep moving forward and making the anticipated progress required to successfully complete a job on time and within the budget. There is no substitute for the successful application of geological and geotechnical knowledge and experience when it comes to achieving successful tunneling projects, and Engineering Geologists are key players in such success.