PLANNING AND SITE INVESTIGATION IN TUNNELLING

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Abstract - The importance of geology in the planning of tunnels is stressed, as is the significance of the vast uncertainty and risk that exist in underground projects. Fortunately, in spite of the inherent uncertainty and risk, geotechnical investigations for tunnels are largely successful. Geotechnical information can be invaluable in both the decision of the general corridor and the specific alignment of a tunnel project. An overall perspective and broad guidelines are given for planning and conducting geotechnical investigations for tunnels. Guidelines are given for determining the scope of a geotechnical investigation depending on the complexity of the geology and the project itself.

Key Words - Tunnel; Geotechnical; Planning

ROLE OF GEOTECHNOLOGY IN PLANNING

Each tunnel project is unique! This paper provides broad-based guidelines for the conduct and use of site investigations for planning and design of tunnels. It provides an overall approach or perspective rather than cookbook solutions. Inflexible rules or cookbook solutions often work for some situations in design of civil works but not in geotechnical investigations. This paper, which is intended for owners, as well as the planners, engineers and contractors, concentrates primarily on the aspects of geotechnical issues and investigative methods, which are important to tunnelling. Much of this paper is based on tunnelling practice in the United States but the concepts and procedures are applicable worldwide with appropriate modifications for local conditions and methods.

For the tunnel designer and builder, the rock or soil surrounding a tunnel is effectively a construction material. Think of it this way; when the excavation is made, the strength of the surrounding ground keeps the hole open until the tunnel supports are installed. Moreover, even after the supports are in place, the ground, through arching, continues to provide a substantial percentage of the total load-carrying capacity.

The geology along a tunnel alignment plays a dominant role in many of the major decisions that must be made in planning, designing, and constructing a tunnel. Geology dominates the feasibility, behavior, and cost of any tunnel. Although difficult to appreciate, the engineering properties of the geologic medium and the variations of these properties are as important as the properties of the concrete or steel used to construct the tunnel structure. In a tunnel, the ground acts not only as the loading mechanism, but also as the primary supporting medium. Thus, it is vital that the most appropriate geotechnical investigation is conducted early in the planning process for any tunnel.

It has been shown many times that those tunnels that have been investigated more thoroughly have fewer cost overruns and fewer disputes during construction. The unanticipated problems are those that can create costly delays and disputes during tunnel construction. Explorations help evaluate the feasibility, safety, design, and economics of a tunnel project.

GENERAL PRINCIPLES OF GEOTECHNICAL INVESTIGATIONS

Geotechnical Information is needed from the very moment planning begins on any tunnel project. The earlier that definitive exploration is made, the greater freedom the owner and designer can have in their selection of alignment and construction methods, and, thus, the greater the potential cost savings. Geotechnical information can be invaluable in the selection of the general corridor as well as the detailed alignment of a tunnel project. Very often, the final alignment of major tunnel projects is not the alignment established at the time the initial boring program is laid out. Although once sufficient, the determination of stratigraphy and the elevation of the groundwater table alone are no longer sufficient for a tunnel project. Rather, these descriptions are just the beginning of what is needed from investigation programs.

CHALLENGES OF THE UNDERGROUND

The underground poses some formidable, but not impossible, challenges to the geotechnical and tunnel design teams. The good news is that, in spite of these challenges, geotechnical explorations are largely successful. However, the owner and designer must appreciate this imprecise nature of geotechnical predictions. At the same time, the geotechnical engineer must appreciate the fact that such imprecision is contrary to the customary data precision a designer, particularly its structural engineers, deal with unless they are well-experienced in tunnelling.

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It is important that this uncertainty, and its associated risk, be fully appreciated by all parties, especially the management and legal staff of the owner. Some of the numerous challenges are listed in Table 1 and are briefly discussed below.

Table 1 - Selected Challenges of the Underground

- Underground projects have vast uncertainty
- The cost, and indeed feasibility, of the project is dominated by geology
- Every aspect of the geologic investigation for tunnels is more demanding than investigations for traditional foundation engineering projects
- Regional geology and hydrogeology must be understood
- Groundwater is the most difficult condition/parameter to predict and the most troublesome during construction
- The range of permeability is significantly greater than the range of any other engineering parameter (roughly 10^{-7} to 10^{+3} a factor of 10,000,000,000)
- Even comprehensive exploration programs recover a relatively minuscule drill core volume that is less than 0.0005 percent of the future excavated volume of the tunnel
- Engineering properties change with a wide range of conditions, such as time, seasons, rate and direction of loading, etc.; sometimes drastically
- It is guaranteed that the actual stratigraphy, groundwater flow, and behavior observed during construction will be compared to your predictions.

Owners and designers are beginning to evaluate risk in terms of cost and potential schedule delays earlier in the planning process and much more comprehensively. Preparation for this work should begin in the planning stage. Identification of the potential risks at this stage is important because it gives time for planners and decision makers to understand the uncertainties associated with the project.

IMPORTANCE OF GEOLOGY

From the moment a tunnel is envisioned, geology strongly affects almost every major decision that must be made in the planning, design, and construction of a tunnel. Geology determines the cost, and even the behavior of the completed structure. The relationship between geology and cost is so dominant that all parties involved in the planning and design of tunnels must give serious consideration to the geology and hydrogeology of the site. Decisions such as the general alignment and depth affect numerous decisions and issues because they may place the tunnel in or out of an adverse geological feature. This not only determines construction cost, but also can affect long-term maintenance problems, such as groundwater leakage.

Finally, geology provides a rational means of correlating particular tunneling conditions, types of ground, and case histories. It can provide an understanding of potential problems as well as their solutions and a means for predicting tunnel behavior in similar geologic materials. This can be very beneficial to the owner if it is done during the initial segment of a major undertaking, such as a subway system that will be developed in stages.

WHEN TO CONDUCT GEOTECHNICAL INVESTIGATIONS

The sooner that geotechnical information is obtained and evaluated, the greater the potential for optimization of the alignment and profile and for greater cost savings. The abundant geotechnical uncertainty requires tunnel exploration and design to be iterative. Without reliable geological information, planning decisions may be incorrect. The author is aware of numerous cases where tunnel projects benefited because either the horizontal or vertical alignment was dramatically changed as a result of geotechnical information.

The planning of each exploration phase should be based on the results of the previous phase. Most importantly, the geotechnical exploration, including evaluation and report, must be available to the decision makers on the design team in a timely manner.

Significant geotechnical work will be necessary during the early portions of preliminary and of final design interspersed with relatively low levels of effort. During the latter stages of final design when contract documents are finalized, there should be a significant geotechnical effort to support the preparation of the Geotechnical Baseline Report (GBR) and the rest of the contract documents. A genuine need for geotechnical input then extends into the bidding, construction, and post-construction phases.

Many owners think that using a Design-Build contracting method will allow them to limit, and possibly even avoid, geotechnical investigations merely by shifting the responsibility to the Design-Builder. This is not true! Design-Build may even pose greater demands to the geotechnical investigation than the traditional Design-Bid-Build. Design-Build requires that a hopefully-realistic fixed cost be agreed upon by the two parties at a very early stage of the project and at a time when most projects have too little definitive geotechnical information. Thus, there could be greater risk to the owner and greater chance for claims if the “assumptions” about geology that are made during the negotiation period are not correct. To avoid this, the author knows of at least one Design-Build project where essentially the full final geotechnical investigation was conducted early in the project so that the negotiations with the Design-Builder could be made on factual data rather than guesses and so that the cost estimates agreed upon between the two parties could be as reliable as practical.

GEOTECHNICAL SCOPE ISSUES

Owners, planners, and designers who have little experience in underground projects frequently do not appreciate the vital importance of geotechnical services to underground projects. It is well documented that insufficient investigation can result in misleading information and can substantially increase the risk of not finding hazards and unknown conditions that can seriously delay or stop construction, with costly consequences.

One of the most difficult and controversial aspects of any geotechnical investigation is deciding how much exploration to do. Among other things, the controversy results from the fact that geotechnical engineering for tunnels is mostly an art, or, at best, an inexact science. There is no guarantee that any given geotechnical task or procedure will provide sufficient information for tunnel design, even if properly planned and executed. In fact, one of the purposes of exploration is to determine whether any conditions exist that may warrant further investigation, and the phased-exploration concept is based on this premise.

Each phase must be planned, taking into account the results of the previous phase. Each phase should have a finite life or at least have milestones or checkpoints where the results are carefully reviewed and a conscious decision made as to what further work needs to be done in the next phase. In this way, budgets are easier to rationalize, justify, and to control.

The nature of the project also plays a major role in determining the scope and cost of the geotechnical investigation. Conventional projects in uniform geology might require less investigation but complex projects in adverse geology might require much more investigation than the average. These more complex projects can benefit by use of the newer, more promising geotechnical investigative techniques being developed. These might include use of large-diameter sonic coring for qualitative geologic studies, tomography, full-scale test shafts or pilot tunnels, and even risk/probability analyses.

Past Practices in Tunnel Geologic Investigations

Currently (2004), there is no accepted standard for the number of borings, their spacing, depths, etc. Each project must be evaluated on its own merits. With respect to depth, final design borings generally extend a few tunnel diameters beneath the anticipated invert but experience shows this could be inadequate in some cases. The number and spacing of borings is just as controversial.

Generally, more investigation is warranted for major projects in urban areas than smaller projects or remote sites, especially with difficult access. The cost of geotechnical investigations reported in the literature generally ranges from 1/2 to 3 percent of the total cost of the project although some up to 8 % have been reported. The guidelines given in this paper do not apply to projects in contaminated ground or nuclear waste projects, which are in a class of their own.

In 1984, a subcommittee of the U.S. National Committee on Tunneling Technology (USNC/TT) made a comprehensive study of exploration practices in the United States to determine if a greater level of geotechnical investigation effort could reduce the final constructed cost of tunnel projects. It was found that claims for unexpected subsurface conditions were a significant part of the total cost of a tunnel. Claims payments averaged nearly 12% of the original basic construction cost. Some as-completed costs were 50% over the engineer's estimate.

The subcommittee's conclusions and recommendations, given in Table 2, convey a philosophy of genuine desire to get a job done right the first time while being fair to both the contractor and the owner. Additional discussion of these and other geotechnical investigation issues are described in more detail by Parker, 1996.

Table 2 - Selected USNC/TT Conclusions & Recommendations for Site Investigations

- Expenditures for geotechnical site exploration should be increased to an average of 3.0 percent of estimated project cost, for better overall results.
- The level of exploratory borings should be increased to an average of 1.5 linear feet of borehole per route foot of tunnel alignment, for better overall results.
- It is in the owner's best interests to conduct an effective and thorough site investigation and then to make a complete disclosure of it to bidder.
- Disclaimers in contract documents are generally ineffective as a matter of law, as well as being inequitable and inexcusable in most circumstances.
- The owner should make all his geotechnical information available to bidders, while at the same time eliminating disclaimers regarding the accuracy of the data or the interpretations.
- All geologic reports should be incorporated as part of the contract documents.
- Designers of mined tunnels should compile a "Geotechnical Design Report," which should be bound into the specification and be available for use by bidders, the eventual contractor, and the resident engineer.

- Monitoring of ambient conditions prior to construction should be undertaken to establish a baseline of information for comparison during and after construction.
- Pre-bid conferences and site tours should be conducted to ensure that all bidders have access to the maximum amount of project information.
- Geologic information from preconstruction explorations and as-built tunnel mapping and construction procedures should be compiled in a report detailing project completion.
- Investigation methods and predictions should be improved for three specific conditions: in-situ stress, stand-up time, and groundwater.
- Improved horizontal drilling techniques should be developed that can recover rock core and penetrate long distances without wandering from line and grade.

It should be noted that these recommendations are aggressive and it is often difficult to convince owners that the recommended amount (and cost) of exploration is warranted. However, the study was carefully and comprehensively carried out by a distinguished blue-ribbon panel and their recommendations deserve serious consideration, particularly on major projects.

It is well documented that special investigative programs developed specifically to reduce such contingencies have been instrumental in reducing the bid costs by more than ten (10) times the cost of the additional exploration. Even greater savings are accrued to the owner because such exploration can lead to minimization of construction delays and of potential conflicts and claims from contractors. Savings in the bid price have been achieved on the order of 5 to 15 times the cost of exploration. That is to say that if you spend a million dollars more doing the right type of exploration, the savings in bid price could be 5 to 15 million dollars or more.

HOW MUCH TO DO, WHEN TO STOP

Guidelines for all Projects

The amount of exploration done on any given project is usually determined by experience and budgetary concerns. Since there are no standards and no "handbook solutions" to the amount of investigation that should be done, one approach and recommended course of action to follow is given in the following sections. Other approaches, such as guidelines for boring spacing, are also appropriate and generally should also be used to complement the recommendations given in this paper.

Since major or complex projects demand a greater level of geotechnical effort, the first step is to determine whether your project is either 1) a major or complex project, or 2) a smaller or conventional project. This will determine whether the project will likely require a high level or lower relative level of geotechnical effort. Naturally, some aspects of geotechnical investigations are similar for all sizes of projects. General guidelines that are independent of tunnel size are given in Table 3.

Table 3- Guidelines for Level of Geotechnical Effort; Regardless of Project Magnitude

- Determine all general and specific needs for geotechnical exploration, analysis, and design;
    - Determine geotechnical parameters needed; prioritize them
- Use geologic expertise to the maximum extent possible
- Conduct exploration in at least two phases
    - The initial exploration phase should be well-funded so that sufficient geologic data is developed to confidently select the alignment, and to provide an initial estimate of the likely construction methods, lining and cost
- Plan on using non-traditional techniques such as geophysics if they can be used cost-effectively
- Have a fixed budget for each exploration phase as well as a contingency fund
- Have contingency borings and other exploration techniques readily funded and ready to be approved to pre-determined criteria in a timely manner to answer technical questions resulting from initial boring program
- Do not use any more contingency than necessary.
- Get more information than needed for design. Get enough data to be able to estimate how the ground will behave under the contemplated construction methods (i.e., if excavated by TBM or by Drill and Blast techniques)
- Get enough data to minimize uncertainty.
- Don't do any exploration unless it specifically fills a genuine need;
    - Sometimes, reduction of uncertainty (just to be sure) is a genuine need but one must be very careful to be realistic about the likely cost & benefits.
- Conduct a "Supplementary Cost Exploration Phase" after the alignment is fixed to:
    - Confirm the design, and
    - Get information the contractor needs to estimate such factors as the rate of advance, etc., to estimate the costs and to bid the job. The bidder should feel confident that he can reliably select construction techniques and confidently estimate construction costs.

Major projects include subway systems, large sewer systems, long aqueducts, large-diameter tunnels, or caverns etc. Projects of 4 meters in excavated diameter or larger diameter or tunnels longer than 300 meters are candidates to be considered as major projects. Guidelines for determining the additional level of geotechnical effort for major or complex projects are given in Table 4.

Table 4 - Guidelines for Level of Geotechnical Effort for Major or Complex Tunnel Projects

- Develop multi-phased program to fill actual needs.
- Plan on using non-traditional techniques such as geophysics, shafts, adits, pilot tunnels, pump tests, etc., as appropriate provided they can be shown to add significantly to the database and will reduce uncertainty.
- For all phases of design, budget and fund between 1/2 to 3/4 of the USNC/TT guidelines (i.e., boring length ranging from 0.75 to 1.2 times route length and geotechnical costs ranging from 1.5 to 2.25 percent of construction cost).
- Have a contingency budget up to full USNC/TT guidelines of 3.0 percent of construction cost.
    - Have contingency borings and other exploration techniques readily funded and ready to be approved in a timely manner to answer technical questions resulting from initial boring program. Ideally, additional borings, deeper borings, or other tests could be approved while the rigs are still on the site saving the cost of remobilization.

When to Do Less or More Investigation

Sometimes there are reasons why less exploration should be conducted. Sometimes, a prominent river embankment, highway cut or other exposure provides a rock exposure that is far better than any boring program could ever provide. At other times, the cost of borings is so expensive (because of difficult terrain that might require helicopter mobilization, etc.) that borings are neither practical nor cost-effective and might result in misleading information (a little knowledge is a dangerous thing).

It should be noted that there also are cases where there are compelling reasons for a comprehensive investigation even though there is abundant nearby data. Note that some very complex projects in complex geology have required a geotechnical scope equal to or greater than 8 percent of the construction cost. Investigations for contaminated ground or nuclear waste disposal are not within the scope of this paper.

CONCLUSION

The geology along a tunnel alignment plays a dominant role in many of the major decisions that must be made in planning, designing, and constructing a tunnel. Geotechnical services, data collection, and evaluation should begin very early in the conceptual planning of any project and should continue through construction and even after construction to document the as-built conditions and the behavior of the tunnel in service.

There is a fundamental difference between the ways geotechnical investigations are conducted for underground construction than for any other project. This is related to the fact that, in order to predict costs, the geotechnical engineer must estimate the behavior of the tunnel under several anticipated excavation and lining scenarios. Thus, the investigative program must be directed toward the goal of predicting behavior and estimating costs.

Geotechnical investigations should be carefully planned to take into account the significance of geology as well as the vast uncertainty associated with underground design and construction. There is wide latitude for determining what should be done during an investigation. Each project is unique; there is no fixed standard or check-off list that can be used to determine the scope and how to do geotechnical investigations. Past practices in the United States resulted in the cost of geotechnical investigations being on the order of one percent of the total cost of the tunnel. USNC/TT recommended that the cost of geotechnical investigations be increased to 3% of the total cost of the tunnel. However, some investigations, especially those involving hazardous waste have been as high as 8% or more in the case of nuclear waste. No matter what the final magnitude of cost, there is a need to fund more geotechnical investigative work at earlier stages of a project.

Moreover, the investigation must ultimately give the contractor the information needed to predict the equipment and procedures as well as the rates of advance, etc needed to estimate productivity and costs. This usually requires special attention to conducting investigations in such a way that it will give the contractor the needed information. Often the information obtained for design is not sufficient for the contractor's bid. Thus, it is desirable to conduct a final phase of exploration that obtains the information needed by the contractor.

Guidelines are given in this paper for selecting the scope of geotechnical investigations reflecting these recommendations in a phased excavation approach. Additional detail on these guidelines are contained in Parker, 1996, together with investigation techniques and guidelines on the selection of the geotechnical scope of work, considering factors such as the purpose of the tunnel, geology, type of anticipated construction, size of excavation, etc. Often, the more complex projects can benefit by use of the newer, more promising geotechnical investigative techniques now being developed.

REFERENCES

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