Geologic Exploration and Risk Reduction in Underground Construction

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Abstract: Geologic uncertainty in underground construction promotes design and construction conservatism and has a significant effect on project cost. Site investigation can reduce this uncertainty and decrease costs by reducing the contingency amounts included in bids. This paper presents research findings that provide a better understanding of how subsurface exploration and improved contractual risk sharing can decrease the cost of underground projects. Issues discussed include: the methodology used by tunneling contractors to estimate geologic profiles given a set of available geologic information; the geologic classification methods used to associate the expected profile with acceptable construction alternatives; the spatial prediction of ground classes and the extents over which different excavation and support methods will be necessary; the factors involved in selecting the initial support, the excavation round length and the estimation of the advance rate; the relationship between exploration, risk allocation, and bidding behavior; the impact of changed conditions clauses in underground construction contracts; the merits of using well-defined geologic conditions as a basis in unit price contracts; and the magnitude of bid contingencies that are actually used in practice.

Introduction

Planning and estimating decisions for underground construction are strongly influenced by the quality and quantity of geologic information available during the bidding phase. This information has a significant impact on the accuracy of the cost estimate for the work, and determines the amounts of contingencies included in construction bids and the resulting total cost of the project to the owner.

Very little has been written about how contractors use the geologic information available during the bidding phase to make construction planning, estimating, and bidding decisions, and how these decisions are affected by the allocation of risks between the contractor and the owner through the construction contract. The purpose of this paper is to present the contractors' opinions and positions in relation to these issues and to provide a better understanding of how subsurface exploration and improved contractual risk-sharing can decrease the cost of underground projects. The main issues examined can be summarized as follows:

- The nature and the relative importance of geologic parameters and descriptors for describing the geology from a contractor's perspective.
- The methodology used by contractors to estimate a geologic profile for a tunneling project, given a set of available geologic information.
- The geologic classification methods employed by contractors to associate the expected geologic profile with acceptable tunnel excavation and support alternatives.

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- The spatial prediction of ground classes and the assessment of the extents over which different excavation and support methods will be necessary.
- The factors involved in selecting the initial support, the excavation round length, and the estimation of the advance rate.
- The relationship between exploration, risk allocation, and bidding behavior.
- The effect and importance of changed conditions clauses in underground construction contracts.
- The merits of using well-defined geologic conditions that serve as reference in unit price contracts.
- The magnitude of bid contingencies that are actually used in practice.

The findings presented in this paper were compiled from the information provided by tunneling contractors through personal interviews and their responses to a 33-page questionnaire (Ioannou 1984). Contractors were selected on the basis of having significant first-hand experience with the planning and estimating (but not necessarily with the construction) or urban or transmountain projects. Both successful and unsuccessful bidders were included in order to insure a representative spectrum of opinions. Comments, statements, and opinions presented here are not associated with specific individuals and reflect the experience and geographic diversity of the group of participants who are listed at the end of this paper.

Geologic Parameters and Descriptors

The ground characteristics influencing the design and construction of tunneling projects are typically described by a set of geologic parameters that are measured or estimated during the course of subsurface exploration. Contractors, however, claim that exploration programs have in many cases been configured in order to serve the needs of design, without focusing enough attention on satisfying the needs of construction. Furthermore, there is no clear understanding among geotechnical engineers as to what kind of geologic information is most valuable to contractors.

One of the primary objectives of this research was to identify a set of geologic parameters and descriptors that are considered important for underground construction planning and estimating from a contractor's perspective. Contractors were asked to identify all the parameters that belong to this set and to rank them according to their importance. The results of their responses are shown in Table 1.

This table illustrates the contractors' definition of a sufficient set of geologic parameters and descriptors (a "wish list") that provides all the geologic information necessary for construction planning and estimating. The overall importance of these parameters is shown in column 3. Columns 4–6 provide an indication of each parameter's importance for the specific tasks of selecting the excavation method, determining the required support, and estimating the advance rate. The most important parameters in each column are shown using the number 1. Dashes indicate that the corresponding parameters were explicitly identified as being unnecessary or of little value. Blanks indicate that no mention of the corresponding parameter was made.

Even though the identification of these parameters provides a better understanding of the contractors' geologic information needs, the ranking of

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TABLE 1. Geologic Parameter Ranking

Number (1)	Geologic parameter (2)	Parameter Rank: Overall (3)	Excavation (4)	Support (5)	Advance rate (6)
1	Rock type (hardness, compressive strength., etc.)	1	1	2	1
2	Joint density (RQD)	2	3	1	2
3	Fault characteristics	3	1	3	3
4	Joint appearance	5	–	4	5
5	Degree of weathering	6	–	6	7
6	Ground water inflow	4	1	7	4
7	Ground water pressure	7	–	8	6
8	In situ stresses	9	–	9	9
9	Joint orientation	8	–	5	8
10	Abrasiveness	10	2		
11	Bedding planes	10			

the parameters as shown in Table 1 is only a rough indicator of their relative importance. The actual importance of each variable is also dependent on its expected state, the expected states of other related parameters, and the impact of parameter state combinations on construction methods and cost. For example, the water pressure parameter may very well be the most important variable if water pressure is expected to be extremely high, thus controlling all major construction decisions and cost outcomes. Furthermore, the fault characteristics and water pressure parameters have very different meanings when viewed independently than they might when weighed simultaneously. Given that a severe fault exists, the probability of encountering major water inflow and pressure problems increases, as does the expected economic significance of treating the resulting water problems. Consequently, the importance of the parameters describing the water conditions increases considerably.

Geologic Prediction

The values (states) of each geologic parameter change as a function of location along the length of an underground project. For example, the expected value of RQD varies along the tunnel axis depending on the encountered geologic formation. Since these changes are not known with certainty prior to the start of construction, they may be considered as state transitions of a random process in space. The geologic variability in an underground project can thus be described by a sequence of variable-length segments within which the state of a geologic parameter can be assumed constant and equal to an average value. Each segment is characterized by its length (extent) and the associated geologic parameter state.

At a particular location there also exists variability from one point to the next because of the way a parameter is defined or measured. For example, two adjacent samples will probably yield two slightly different values of RQD. As long as this variability is relatively small, it may be considered

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as noise around an average RQD value. The length of the project within which the average value of a parameter can be assumed constant depends on the variability of the geology and the required modeling accuracy.

Geologic prediction for underground construction projects involves the estimation of each parameter's states and extents, given a limited set of imperfect observations. This problem can be tackled by probabilistic models that use statistical estimates of the distribution parameters of the assumed underlying random process to predict the actual sequence of geologic parameter states as they exist at the site (Ioannou 1987). The intricacies of these models, however, lie beyond the analytical capabilities of most contractors.

The most popular alternative adopted in practice is to produce a directly estimated conservative envelope that bounds the states of each geologic parameter at each location, based on subjective expert judgment and the available geologic observations. The estimation of points on the envelope as a function of location is similar to the choice of a confidence level in standard one-sided interval estimation. The degree of conservatism in establishing the envelope is measured by the probability that the true state at each point is worse than anticipated.

The subjective encoding of an acceptable envelope is affected by several factors, such as the amount of general information describing the regional geology, the contractor's past experience in the area, the number and quality of the observations available, the reliability of the exploration methods used, the homogeneity of the geology, and the size and location of the project. In addition, the conservatism in geologic prediction is not only a function of information about the geologic risk, but is also a function of the perceived magnitude of the economic consequences of misjudging the true geologic states. As a result, the estimation of the envelope depends on the magnitude of the risk outcomes and on the risk-sharing arrangement between the owner and the contractor. These consequences are a function of the type of the project, its use, size, and location, and the contract type and clauses.

For example, an expected 50-ft (15 m) fault zone perpendicular to the project axis will have a much larger bearing on the overall construction of the project if the project is a cavern that is 100 ft (30 m) high, 60 ft (18 m) wide, and 200 ft (60 m) long, as opposed to a 25 (7.5 m) ft horseshoe tunnel that is 20,000 ft (6,000 m) long. Furthermore, the economic significance of the fault depends on whether the contract is lump-sum or unit price, and on whether it includes a comprehensive changed conditions clause.

Geologic Classification

The estimation of the spatial variability of each geologic parameter along the length of the project provides a geologic profile that serves as a basis for selecting the appropriate excavation methods and determining the necessary support requirements. These decisions are interrelated and depend on the joint consideration of the states and extents of all geologic parameters, and on the length and cross-sectional size of the tunnel.

The term "ground classes" has been used to represent the sets of geologic parameter state combinations that require the same excavation and support methods. The joint consideration of geologic parameter states can be accomplished by using empirical classification methods that relate parameter state combinations with appropriate construction methods. Thus, empirical classification systems use ground classes as a mechanism for transforming the given state of information about the geology to a set of potential excavation and support alternatives. Examples of empirical classification systems used by contractors, as well as designers, are the following:

- Deere's Rock Quality Designation (RQD) System.
- Terzaghi's Rock Load System.
- Norwegian Geotechnical Institute (NGI) "Q" System.
- Bieniawski's Rock Mass Rating (RMR) System.
- Bischoff and Smart Equivalent Rock Reinforcement Analysis.
- Jacobs Associates Rock Structure Rating.
- Heuer's Shotcrete Design Analysis.

Of the above methods, Deere's RQD system is probably the most popular. It must be pointed out, however, that rock masses are so variable in nature that the chance of ever finding a common set of parameters and a common set of constitutive equations valid for all rock masses is quite remote. Simplified engineering-geological classifications as well as sophisticated mathematical formulations can be valuable tools in assessing rock mass behavior. However, they are often given a validity that is too general, both in literature and in practice, even though there are situations in which they are highly inadequate, both from the view of restrictive assumptions and from the point of view of the variability of the rock masses (Brekke 1972).

Consequently, experienced contractors tend to rely on their own experience and classification criteria for decision-making purposes. Some even argue that this is what makes tunneling an entrepreneurial undertaking that provides experienced contractors with an edge over newcomers in the field.

The inability of classification methods to incorporate all the factors necessary for decision-making is also evidenced by the fact that contractors often use different methods for determining the advance rate, the excavation method, and the initial support requirements. The decision on which classification method is the most applicable depends on the nature and size of the project, the regional geology, and the dominance that certain extreme parameter states may have over the others.

Ground Class Prediction

An interesting statement made by many contractors is that the greatest uncertainty does not lie in the point estimation of a ground class, but rather in the extent over which a ground class persists. It is interesting to notice that a similar statement was not made with respect to the individual parameter extents.

There are two reasons for this statement. The first is that each ground class includes many combinations of geologic parameter states. This has a dampening effect on the required accuracy for the prediction of geologic parameter states, because deviations in the predicted states of individual geologic parameters do not necessarily translate into a change in the predicted ground class.

Second, the association of geologic parameter states with construction methods (i.e., the definition of ground classes) depends on the classification

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method being used and the experience of the contractor making the assessment. Consequently, the prediction of extents for the individual geologic parameters and the prediction of extents over which excavation and support combinations will be adequate do not present the same degree of estimating difficulty. The definition of ground classes and their correspondence to construction methods involves a certain amount of conservatism, especially when certain geologic parameter combinations lie in the "gray" area between two different classes. Obviously, the safer approach is to include such vectors in the more conservative ground class, except where the contractor has evidence to the contrary from past experience.

Similar observations have also been made by other researchers. An example is the following statement concerning the estimation of the required support for a subway station:

> Although subjectivity seems to be largely excluded from support predictions, one has to be aware that this is mostly due to the dampening of parameter differences, when relating parameters (rock classes) to supports. Where the effect of subjectivity did not disappear is in the spatial fluctuation of rock class predictions. These fluctuations, which indicate the length over which a construction procedure would be used, are important in longer tunnels. (Einstein et al. 1983).

The association of geologic conditions with construction methods is similar to a regression problem where the definition of ground classes is the transformation mechanism for relating the states of the geologic parameters chosen as the explanatory variables to the adequacy of the construction methods. It is obvious that the accuracy of predicting whether a certain construction method is adequate depends on which parameters are used as explanatory variables, and the adopted transformation model (i.e., the relative weighting of parameter importance and the association of ground classes with construction methods). In simpler terms, the transformation from a state of information about the geology to a state of information about the adequacy of potential construction methods is uncertain in itself, and this uncertainty is the cause of the aforementioned difficulty in establishing ground class extents, because it is not clear when a more conservative construction method can safely be replaced by a less conservative one. The problem that contrators face is to estimate the least conservative absolute location of the interface between segments that require different construction methods.

The previous observations are fundamental in understanding how contractors make construction planning and estimating decisions. A popular approach adopted in practice is similar to the statistical method of hypothesis testing. An experienced individual within the contractor's organization proposes an initial conservative position (the null hypothesis), based on his or her perception and interpretation of the available geologic information and drawing on past construction experience in a subjective manner. Consequently, the development of the initial position is strongly dependent upon the geologic and construction related information on which it is based, as well as on the subjective judgment involved. The assumptions, interpretations, and strategies of the initial position are subsequently put to the test by either the same person or other personnel assigned to the project, by scrutinizing and revising the grounds on which it was based.

- Other persons may have additional information that was not originally considered. Equivalently, the contractor may acquire additional information after the development of the original assessment.
- Drawing from their own backgrounds and experience, other individuals may propose a different interpretation of the information available.
- New what-if scenarios about the effect of the decision at hand on the overall construction of the project may change the acceptable likelihood of the null hypothesis being wrong (i.e., the significance level).

Thus, decisions concerning the project's geology and the selection of the construction approach to be adopted are typically made collectively by all personnel involved in a particular project. Assumptions, interpretations, and strategies are evaluated and revised until everybody agrees.

Estimating Initial Support

The ground support system includes various components, such as initial ground control, type of support required, method of installation, logistics, cost of support members, and adaptability to the excavation method being used. These are some of the factors that must be considered and evaluated in order to determine a safe, efficient, and economical ground-support system with little or no reduction in the potential rate of advance. To achieve the goal of rapid excavation it is essential that the requirements for such a support system be determined prior to the start of construction.

The selection of the initial support is primarily the contractor's responsibility because of its direct impact on the stability of the rock, the safety of personnel and equipment working underground, and its effect on nearby structures. The relative importance of geologic parameters with respect to determining the initial support are shown in column 5 of Table 1. As explained earlier, the importance of these parameters also depends on the regional geology, the type of the project, the states of the parameters themselves, etc.

The decision concerning tunnel support, however, are not always based on geologic considerations. The support method preferred by the contractor may be based on a favorable unit price for steel sets as compared to rockbolts, or the lack of adequate equipment for the rapid placement of either sets or rockbolts. The preference for steel sets in the first place may be based on an overcautious safety program, or excess rockbolts may be needed because the rock is unnecessarily loosened by improper blasting in an effort to break the rock into small fragments and expedite mucking. Large-diameter drill holes with modern jumbos may also lead to overloading of blasting charges, because the column charge density of dynamite increases rapidly with drill-hole diameter, while the total number of drill holes in the face may remain about the same (Merritt 1972).

Although a tunnel support system could be considered as an engineered structure, it cannot be compared to the theoretical or standardized design of a bridge or a building. The practical implications of handling and installing the support and the resulting effect on daily advance rates oftentimes more than offsets any advantage of savings that may be indicated by a theoretically correct design. Continued increase in the cost of labor and equipment directly related to the advance rate is expected to amplify this situation.

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Contractors suggest several technical, institutional, and contractual factors that may be equally important for determining tunnel support. They are the following:

- Tunnel use, location, size, and length.
- Type of final lining and specification requirements.
- Contractor-crew familiarity. (Contractors may have to employ local labor due to contract or other regulatory requirements.)
- Safety of labor and equipment.
- Equipment, labor, and material cost and availability.
- Excavation method.
- Contract considerations. (The type of contract, the intent of the contract clauses, the procedure for justifying the necessary support, the wording of the changed conditions clause, bid prices versus "owner-plugged" bid prices for excess support items, etc.)
- Predicted quantities of different types of support (i.e., economies of scale).
- Consequences of support inadequacy (damage to the project and to other, adjacent structures).

Depending on the contract adopted by the owner, the actual choice of the support during construction may also be based on a bid-unbalancing strategy. This strategy is sometimes adopted if the contractor believes that the engineer has underestimated the initial support requirements, or equivalently, that the contractor will be relatively unconstrained in using large quantities of excess support. The contractor can unbalance and lower his bid by overpricing the underestimated excess support items and underpricing the overestimated "expected" support quantities. Not only does this strategy increase the probability of the contractor being the low bidder, but it also increases his expected profit margin.

To avoid this potential problem, some owners do not let the contractors set their own prices for excess quantity items; instead, the owner provides his own "plugged prices" for these items, an approach that, if done equitably, is also supported by most contractors. Owners also have the right to disqualify any tender if there is sufficient reason to believe that prices are unbalanced. In reality, however, such a claim is quite difficult to prove and enforce, even though it represents a desirable course of action. This is evidenced by the following comment made by a participating contractor:

> The contractor can use the amount of support placed as a means of making money by unbalancing his bid. High unit prices for support items induce the heavy use of support during construction (in the name of safety). Such unit prices (e.g., $/lb of steel) should be within a reasonable limit; otherwise, the bid should not be accepted. In other words, owners should control unbalancing as much as possible.

Finally, the actual configuration of the support placed during construction (the support type and the extents over which each type is necessary) depends on the degree of uncertainty about the actual geologic conditions and the expected ground-structure interaction prior to construction, the aforementioned economic, contractual, and institutional factors, the geologic conditions and rock behavior actually encountered, and the interpretation and implementation of the contract during construction.

Excavation Round Length

An important factor in establishing the advance rate and hence the cost of each possible excavation-support strategy is the determination of the round length. The round length is the basic measure of progress along the alignment of the tunnel that can be achieved in each construction cycle, including excavation (drill-shoot-muck), support, and the extension of necessary tunneling services.

The selection of the round length is primarily determined by the length of tunnel that can remain unsupported (from blasting the rock to installing the support), the required distance from the support to the face, and the equipment limitations. The basic variables influencing this selection are the following:

- The prevailing geologic conditions,
- the shape and size of the project,
- the excavation method and its impact on the stability of the rock,
- the desired rock movement before the installation of the support to invoke the rock arch effect,
- the type and spacing of the support, and
- the speed of support placement.

All of these factors determine the stand-up time, which relates the time an opening can remain unsupported, for different ground classes, to the opening's active span.

The length of each round and the distance of the support to the face are also important in estimating the loads that the initial support and/or the final lining have to bear. As a result, the determination of these variables is not only of interest to the contractor but also to the designer. The designer often prescribes maximum values for both the length of each round and the distance of the support to the face in order to assure that the final loads will not exceed the ones assumed during design.

In general, contractors believe that the maximum round length suggested by the designer (if at all) is usually on the high side and often applies to the project as a whole. As a result, contractors rarely use the designer's estimate as the basis for construction planning and estimating. Typically, a contractor undertakes his own analysis of the project's geologic conditions and stability, and uses these results to estimate the round length as a function of location.

Alternatively, the designer can specify the maximum allowable rock deformation (a measure of performance) and leave the decisions concerning the round length and support placement up to the contractor. This arrangement permits experienced contractors to take full advantage of their expertise and resources in determining the most efficient excavation-support sequence. In addition, the contractor would be forced to instrument and monitor the support's performance in order to prove its adherence to the specifications, a task that will inevitably lead to some form of construction adaptation based on feedback. This approach has been suggested as a first step in making

U.S. contractors more comfortable with adaptable tunneling.

Not all contractors, however, find this procedure attractive. On the positive side, some contractors would prefer to be given performance measures rather than to be constrained on exactly how they operate. Their basic argument is that it would be more efficient to leave construction-related decisions to the contractor's discretion. Others, however, believe that such an arrangement would not necessarily be advantageous because it shifts too much responsibility to the contractor. Instead, they propose that rock deformation should be analyzed by the designer (the one most familar with the project conditions) and that its impact should be reflected in the design and suggested construction staging.

Estimating Advance Rate

Production performance in tunneling is expressed by the advance rate, which measures the length of overall construction progress (including excavation, mucking, support placement, and the extension of tunneling services) per unit of time. Thus, the advance rate is equal to the inverse of the total time spent for the construction of each round.

The estimation of the advance rate is a function of the geology, the excavation-support method, the size of the project, and the productivity of labor and equipment. For a particular excavation and support combination, the advance rate is the most important factor influencing the time-dependent variable cost of a project.

The estimation of the advance rate for a given construction method is a function of the following:

- The expected geologic conditions that influence the initial selection of the excavation-support methods, and the changes that may need to be made dynamically during construction.
- The behavior of the rock in response to excavation and support methods, including the amount of overbreak, the amount of muck swelling, and the placement timing, type, and amount of support that is actually necessary.
- The productivity of labor and equipment, for a given geologic profile.

The ranking of the most important geologic parameters for estimating the advance rate is shown in column 6 of Table 1.

Exploration, Risk Allocation, and Bidding Behavior

The marginal value of geologic exploration, irrespective of the method used for collecting information, is strongly dependent on two parameters, namely, the amount of geologic information that already exists, and the perceived consequence of geologic uncertainty.

Even though the existing amount of geologic uncertainty is certainly of fundamental importance when evaluating new information from a statistical standpoint, the economic value of this information is largely dependent on the consequences of the risks' outcomes. In other words, the way the geologic risk is shared between the owner, the designer, and the contractor determines the risk premiums to be required by each party and thus influences the value of information about the likelihood of the risk's outcomes.

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The allocation of risk between the owner and the contractor is primarily determined by the type of the construction contract and the wording and intent of the contract clauses. Under a reimbursable cost plus fixed-free contract, for example, the owner assumes almost complete responsibility for the financial-risk of constructing the project. As a result, little value, if any, can be attributed to geologic exploration from a contractor's point of view. In this case, it is the owner who values exploration the most, because it can help the designer and the contractor select the best possible construction alternatives and thus help decrease the project's cost.

On the other hand, a fixed-price lump-sum contract allocates most construction risks to the contractor, who in turn protects himself from the unexpected by including contingencies in his bid. The amount of these contingencies is in direct relationship with the perceived level of uncertainty about the project's geology and its subsequent behavior in response to the adopted construction process. Most contractors place a high value on exploration in this case. The major reason for this is the fact that contractors cannot inflate their bids to an absolutely secure level and at the same time remain competitive. The possibility that the included contingencies will be inadequate is seldom eliminated and the contractor always stands the chance of losing a significant amount of money. According to a contractor the probability of losing money on a job, given that the bid must be competitive, is around 10%, which means that, on the average, the contractor loses money on one out of every ten jobs that he undertakes.

It is therefore obvious that the value of exploration is strongly influenced by the type of the construction contract and the implied risk liabilities of each party. In particular, the allocation of risk and the subsequent value of risk reduction in the typical case of a unit price contract are primarily dependent on two factors. They are the existence, wording, and interpretation of the changed conditions clause, and the definition of the bidding schedule (the association of excavation and support items with a specific set of geologic conditions).

Changed Conditions Clause

Changed conditions clauses are employed by owners as an attempt to reduce contingency costs that are added to responsible contractors' bids for geologic unknowns. For this benefit, they accept the additional responsibility for increased costs due to geologic conditions that differ from the ones expected given the available information. From the contractor's viewpoint, the clause provides insurance, or relief, if conditions different from those that could have been anticipated develop and cause increased costs. When properly interpreted, the clause allows the contractor to recover increased costs, plus markup and profit, for those geologic conditions that were not reasonably anticipated.

The changed conditions clause is of such importance in protecting the contractor from a major economic loss that many contractors have adopted the company policy not to bid a project if this clause is not part of the contract. Even though other contractors are less absolute on this issue, they nevertheless point out that if a bid were to be submitted, the absence of a changed conditions clause would certainly have a considerable impact on the

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amount of contingencies they would require. The impact of this clause's absence on the contractor's strategy depends upon circumstances:

- Past history of work experience with the owner and/or the engineer.
- The reliability and completeness of geologic information.
- The project size and scope.
- The possible risks of differing site conditions.
- The desirability of the project.
- The availability of other work.
- The existence of current or backlog work.
- The availability of labor and equipment, etc.

All of these play a factor in making the decision to bid. The end result varies from weighing the addition of a contingency to the bid to not submitting a bid at all.

Even though owners have accused contractors of misusing and taking advantage of this clause, most owners today include a changed conditions clause as part of the contract documents in order to attract a large number of bidders. More often than not, however, the intent of this clause is marred by the existence of exculpatory clauses in the contract and "the myth that contractors always make money." Considering current contractual practices, and with reservations as to the interpretation and use of changed conditions clauses, contractors argue that owners violate the intent of this clause by including clauses in many specifications that disclaim the accuracy of the geological data and its engineering interpretation, thus nullifying any reference to conditions indicated in the contract. As a result, it becomes difficult for the contractor to recover additional costs, plus markup and profit, in the event that unexpected subsurface or latent physical conditions are encountered during construction, because there is no basis for comparison in the contract documents.

Reference Geologic Conditions in Unit Price Contracts

An alternative to the current form of underground construction contracting practice is the option to prepare a bidding schedule (a quantified breakdown of the anticipated work) that is explicitly based on a particular set of expected geologic conditions. The purpose of this breakdown is to provide a well-defined basis for estimating the work, and to ease the administration of the contract and the interpretations of the changed conditions clause.

According to this approach, the owner should undertake a comprehensive exploration program and provide the contractors with all the results, including all factual data and its interpretation. The contract should then be based on a particular and well-defined interpretation of the factual geologic information available, similar to the "Reference Conditions" proposed in the United Kingdom ("Tunneling" 1978). Each item in the bidding schedule would then be priced under the assumption that the specified geologic data and interpretation are indeed true. To compensate for the unavoidable discrepancies that will eventually materialize, the schedule should also include additional work items that are priced based on other possible geologic conditions that might be encountered during construction.

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Even though contractors appreciated the merits of this approach they also expressed reservations as to its feasibility. It is generally felt that by associating the cost of the work with the actual geologic conditions most of the uncontrollable risk of geologic uncertainty is transferred away from the contractor. As a result, construction contingencies should be reduced considerably. However, the feasibility of administering such a contract under current U.S. practices is questionable. A contract that reimburses the contractor based on the actual field conditions during construction can be misused by both the owner and the contractor. The most obvious problems are the following:

- The increasing need for authoritative decision making in the field, especially on the owner's side, for determining whether the contractor's plans and methods are justified.
- The methodology for measuring and associating (pricing) the work in place relative to the existing schedule breakdown.
- The possibility of deliberately unbalanced bid prices and the excessive use of overpriced items during construction, given that short-term safety and stability of the opening are the contractor's responsibility.

The successful administration of "true unit price" contracts is heavily dependent on the equitable resolution of these problems and on the development of better contracting practices. In the meantime, this approach can certainly cause more problems than it solves, because either the owner and/or the contractor can violate the underlying objectives.

Magnitude of Contingencies

The amount of contingencies added to contractors' bids is a function of many parameters, most of which have been discussed herein. In summary, these factors are the amount of geologic uncertainty and the contractual risk-sharing approach.

Since one of the most important objectives of owners in funding exploration programs is to decrease bid contingencies, it is obvious that the value of subsurface exploration is a function of the order of magnitude of the quantity being affected (the contingency), and the accurate estimation of this quantity by an expert, other than the specific contractor.

In order to gain a better understanding of the magnitude of contingencies that might be used in practice, the writer asked the contractors participating in this research to estimate upper and lower limits on the contingency amounts that a contractor may include as part of his bid, taking into consideration the best and worst conditions they could think of. Because this assessment required the dissemination of classified information, only four contractors supplied the necessary answers. The lower bound given in three of the responses was 10%. The corresponding upper limits were 20%, 30%, and 50% or more. The fourth contractor stated that contingencies range from 50% up, and added that "anybody that says less is lying."

Unfortunately, these answers do not define a narrow cluster. Although it is not immediately clear why these estimates are in such wide disagreement, there are many possible reasons behind this disparity, such as the following:

- Contractors use different estimating procedures. Some build contingencies into the bid as they estimate each unit cost, while others add a lump sum at the end.
- The percentages do not correspond to the same quantity. Some contractors may use a combination of the aforementioned procedures and hence they may be reporting only the final lump sum amount, which is, of course, smaller.
- The contractors who have stated the smaller percentages may have underestimated the contingency range by stating a confidence interval for the average amount. This problem is quite common in subjective estimation. Many individuals have difficulty in distinguishing between the distribution of a parameter and the distribution of its average.
- Based on his or her prior experience, each contractor may have considered different contractual situations. This is a very plausible explanation, given the importance of a changed conditions clause and the methodology for determining and pricing the work in place.
- Contractors exhibit different degrees of risk aversion.

In any event, it is reasonable to argue that the responses indicate that the process for determining the contingencies to be included in a bid is highly dependent on the specifics of the situation, as well as on the contractor's personal risk preference (risk aversion). As a result, it is probably impossible to forecast with any degree of confidence what each contractor's strategy or behavior will be. In addition, the magnitude of the required contingencies, no matter which position is taken, is quite large when compared to the cost of subsurface exploration programs. One of the bidders for a subway station, for example, estimated a 10% reduction in contingency for this project because of the comprehensive exploration program undertaken, whose cost, in his opinion, was certainly less than the effected reduction in bid prices.

Conclusion

Geologic uncertainty is a multifaceted problem and the principal cause of conservatism and excessive costs in underground construction. Although the geologic conditions of a project are predetermined by nature, they are seldom known prior to the start of excavation. Even in situations were comprehensive subsurface exploration programs are undertaken, the satisfactory assessment of the spatial variability of the states and extents of geologic parameters is not sufficient for determining the optimum sequence of excavation and support sequence. Perfect knowledge about the state of the geology does not automatically translate into perfect knowledge about the effectiveness of a particular design or construction approach. The behavior of the rock and its reaction to construction methods is still unknown, and as a result, the possibility of selecting inappropriate excavation methods or overestimating/underestimating the support is never eliminated. The uncertainty in the interaction between the rock and the methods of construction is probably the major risk facing tunneling contractors today. This problem can only be addressed by introducing adaptable tunneling approaches based on extensive instrumentation, monitoring, and feedback during construction.

Given current contracting practices, geologic exploration is the most effective strategy for reducing the effects of geologic uncertainty during the

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bidding phase of underground projects. The benefits of exploration, however, cannot be fully realized unless equal attention is given to the allocation of risks among the owner, the designer, and the contractor. The levels of contingencies included in underground construction bids are large enough to indicate that considerable improvement can be achieved in this area. The most reasonable approach is to identify construction risks as either controllable or uncontrollable and assign them accordingly, realizing that risks have an incentive to perform value, if born by the controlling party.

Contractors have very little control over the geologic variability at the project site because they often have no input in the planning phase or the selection of the project site and its horizontal and vertical configuration. Furthermore, they are typically given a short amount of time (normally 60 to 90 days) within which to prepare their bid, with no guarantee that they will indeed construct the project. As a result, they cannot devote as much time as the owner or the designer can to evaluate each project's geologic conditions. Given this situation, it stands to reason that owners and designers should perform a benefit-cost analysis and provide contractors with the appropriate level of geologic information pertinent to the size and location of the project, while reducing the contrators' risk exposure through better contracts.

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Appendix. References

Brekke, T. L., and Howard, T. R. (1972). "Stability problems caused by seams and faults." *Proc., North Amer. Rapid Excavation and Tunneling Conf.*, Amer. Inst. of Mining, Metallurgical, and Petroleum Engrs., 1, 25–41.

Einstein, H. H., et al. (1983). "Comparison of five empirical tunnel classification methods—Accuracy, effect of subjectivity, and available information." *Proc., 5th Int. Cong. of the Int. Soc. for Rock Mech.*, Melbourne, Apr., Balkema Publishers, Rotterdam, the Netherlands.

Ioannou, P. G. (1984). "The economic value of geologic exploration as a risk reduction strategy in underground construction." Thesis presented to the Massachusetts Institute of Technology, at Cambridge, Mass., in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 414–446.

Ioannou, P. G. (1987). "Geologic prediction model for tunneling." *J. Constr. Engrg. and Mgmt.*, ASCE, 113(4), 569–590.

Merritt, A. H. (1972). "Geologic predictions for underground excavations." *Proc., North Amer. Rapid Excavation and Tunneling Conf.*, Amer. Inst. of Mining, Metallurgical, and Petroleum Engrs., 1, 115–132.

Parker, A. D. (1970). *Planning and estimating underground construction*. McGraw-Hill, New York, N.Y.

Robinson, C. S. (1972). "Prediction of geology for tunnel design and construction." *Proc., North Amer. Rapid Excavation and Tunneling Conf.*, Amer. Inst. of Min-

ing, Metallurgical and Petroleum Engrs., 1, 105–114.
Stasiewicz, P. H. (1981). "Improving the contractual aspects of underground construction." Thesis presented to the Massachusetts Institute of Technology, at Cambridge, Mass., in partial fulfillment of the requirements for the degree of Civil Engineer.
"Tunneling: Improved contract practices." (1978). *Rept.* 79, British Construction Industry Res. and Information Assoc., London, U.K., May, 60–63.