Pilot Tunnels: Contractor's Position

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Abstract: Geologic uncertainty in underground construction promotes design and construction conservatism and has a significant impact on project cost. Site investigation can reduce this uncertainty and decrease the contingency amounts included in bids. Pilot tunnels are one of the best geologic exploration methods, but they are also one of the most expensive. This paper presents the contractor's view concerning the usefulness of constructing a pilot tunnel as part of the site investigation program and offers guidelines for evaluating its benefits. These benefits can be realized both prior to and during construction. They include furnishing information about the geology and its behavior, and facilitating design development and construction operations. Pilot tunnels are generally most useful in large projects with limited surface access, and where the geologic conditions are unfavorable. Depending on project conditions, the construction of a pilot tunnel can reduce bid contingencies up to 20% of the project cost.

Introduction

Planning and estimating decisions in 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 thus influences the contingency amounts built into construction bids and the resulting total cost to the owner.

The investment of funds in subsurface exploration early in the design phase is one of the most effective strategies for reducing design conservatism and construction contingencies, thereby lowering the project cost. Pilot tunnels have been traditionally considered one of the most complete and versatile subsurface exploration methods. However, they are also one of the most expensive. As a result, their economic value has been the subject of debate within the tunneling industry, because it is not clear when and if the information provided by a pilot tunnel is worth the associated time and cost for its construction and separate contract administration.

This paper presents the views and opinions of a group of contractors that participated in a research project investigating this issue (Ioannou 1984). The contractors were selected on the basis of experience with underground construction projects whose geologic exploration programs included the construction of a pilot tunnel. In order to capture as wide a spectrum of opinions as possible, both successful and unsuccessful bidders were included in the set of participants. The findings presented in the following were compiled from personal interviews and from the contractors' responses to a 33-page questionnaire. Quotations of the contractors' opinions given here are not associated with specific individuals. A partial list of participants appears at the end of this article.

Overview of Geologic Exploration Methods

Geologic exploration programs include several methods, e.g., surface outcrop observations and geologic mapping, various geophysical methods,

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trenching, boreholes (core drilling), and exploratory bores such as shafts and pilot tunnels. A brief description of these methods follows.

Surface observation methods are relatively inexpensive compared to geophysical investigations, trenching, or core drilling, the last being the most expensive. Ideally, geologic mapping and interpretation of the surface over the tunnel line should be based on an accurate topographic base using aerial photography and remote sensing such as infrared or radar scanning.

The application of geophysical methods, such as seismic and resistivity methods, has been limited mainly to acquiring data for geologic prediction between surface observations and, to a lesser extent, to determining conditions at depth. As a result, these methods are primarily used for locating and defining the attitude and width of major faults and shear zones and for evaluating groundwater conditions.

Trenching is generally limited to portal areas to expose the geologic conditions affecting the design of portals where only short projections in width and depth are required.

Boreholes are the most widely used physical exploration method, and with the exception of sinking exploratory shafts, they are the best method for collecting geologic data in the vertical direction. Generally, the core recovered from borehole drilling represents a unoriented sample of the geology at various points along a vertical line. Techniques for the orientation of cores have been developed but are not widely used. Geophysical and visual probes for drill holes increase the amount of data and the significant radius of the data around a borehole.

The location of drill holes along a proposed tunnel line are usually based on geologic area mapping. In areas of abundant outcrop, boreholes are typically used to test for major faults, caverns, groundwater, or hazardous gasses. In areas of limited or no surface observations, they are drilled to determine rock type and structure. The number of holes and their depth is most commonly determined by the geology and the available funds. The accuracy of geologic prediction between boreholes and surface observations, or between one borehole and another, depends on the density and quality of the information available and on the experience and capabilities of the geologist.

Pilot tunnels are typically small-diameter tunnels driven parallel to the axis of a much larger project to provide geologic information during the design phase. Pilot tunnels may be located near the crown, center, invert, or outside the future opening at various elevations. The cross-section shape, size, location, and length of pilot tunnels depend on the specific design and construction purposes for which they are constructed.

These purposes are numerous and may include collecting information about the nature and behavior of the geology during the design phase, validating design assumptions, experimenting with excavation and support procedures, treating or supporting the rock prior to construction, dewatering the rock mass, providing access to critical locations, providing additional excavation surfaces or otherwise facilitating the main excavation, carrying services during construction, etc.

The decision to construct a pilot tunnel depends on the expected geology, the cross-section size and length of the project, the type of project, its accessibility from the surface and the relative cost of other exploration methods, the cost and time required for its construction, the value of its benefits during design and construction, and the available funds. Pilot tunnels are

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generally considered to be one of the best and most expensive exploration methods (Stasiewicz 1981).

Reliability of Pilot Tunnels versus Boreholes

Pilot tunnels differ from boreholes and other exploration methods in several ways. Boreholes provide location-specific information about the encountered geologic conditions in the vertical direction, and can be extended, at least theoretically, to any required depth. In contrast, pilot tunnels provide continuous three-dimensional information along their axis but do not allow observations outside their cross section.

In comparing the effectiveness and reliability of geologic prediction using a pilot tunnel versus using boreholes, it is necessary to distinguish between the prediction of states (or values) of the geologic parameters of interest and the prediction of a state's persistence (extent) along the main axis of the project. The effectiveness of each method depends on the quantity being estimated and the characteristics of the actual geologic formation. Since by definition neither method covers the whole volume of the main opening, it is obvious that neither method can be generally assumed to provide perfect geologic information.

If the project is located in a horizontally bedded formation that is highly variable in the vertical direction (the tunnel lies completely in "mixed face" conditions), then a pilot tunnel can be a very poor predictor of both geologic parameter states and extents. Boreholes can at least furnish information about all the encountered strata. In contrast, if the formation is highly variable in the horizontal direction, then the situation is the opposite. As a result, it is practically impossible to compare the effectiveness of each method without taking into account the nature of the geology.

The problem becomes even more complicated when one considers that the construction of a pilot tunnel is almost always complemented by a comprehensive exploration program using boreholes whenever possible. In this case, one must consider the incremental value of the pilot tunnel observations, an issue that can easily become quite controversial since most individuals cannot discriminate between (or agree upon) what was really known before and after the construction of the pilot tunnel.

Given these observations, the contractors participating in this research were not able to provide general conclusions that would have universal applicability. The only exception is the linear density of boreholes that, in general, should provide a contractor with the same amount of information as a pilot tunnel. A horizontal spacing of boreholes between 50–200 ft (15–16 m), depending on the project's geology, should be enough to make the two methods equivalent. This conclusion, however, applies only to tunnels and does not apply to subway stations, cross passages, vent areas, or other major caverns.

Contractors also point out that it is not sufficient to compare pilot tunnels to other exploration methods by solely considering each method's theoretical or potential capabilities. It is equally important to consider the form and completeness of the information as presented to the contractor in practice. In this respect, there is unanimous agreement that a pilot tunnel provides the most complete and reliable information because a contractor can see for himself what "the rock looks like and how it behaves." In all other cases, the contractor must rely on information provided by the owner or the designer.

Even though the owner and the designer try to anticipate the contractor's needs as much as possible, this information may not always be as complete and easy to understand, or interpret, as the contractor would like. Furthermore, the contractor is typically given a limited amount of time (normally 60–90 days) within which to prepare his bid, and since he has no guarantee that he will indeed construct the project, he cannot devote as much time to evaluating each project's geologic conditions as the owner or the designer can.

As a result, contractors believe that the major advantage of a pilot tunnel, besides its use as an integral part of the design and construction process, is that it provides each prospective bidder with a "quick and reliable means of determining what he should plan for." Although the amount of published material may expand with the construction of a pilot tunnel, most contractors feel more comfortable in relating the pilot tunnel field observations to the actual project conditions, as opposed to using only published information.

However, this does not mean that the use of a pilot tunnel for the sole purpose of geologic exploration is always an economically justifiable option: "If a contractor does his 'homework' properly then there is no need for a pilot tunnel; it is just too expensive as compared to other (equally effective) exploration methods."

In general, opinions as to the economic value of a pilot tunnel vary, depending on the contractor's assumptions about the project conditions and the contractor's resources and time constraints for collecting and interpreting his own geologic information.

Groundwater Conditions—Dewatering

In certain types of projects, the rate of water flow and the total quantity of water can present a severe handicap to the work. Small flows of water in a tunnel that is being driven downward, or in a vertical shaft, can impede progress severely. In a large tunnel driven upward, fairly large flows may be drained by gravity, while in a small tunnel, the same flows might have to be pumped because there is no room for drainage ditches.

Unless there is past experience in a given area and in the same geologic formation, it is impossible to predict with reasonable accuracy the rates of flow or the total quantity of water that might be encountered. It is equally difficult, under such circumstances, to predict the measures that might be successful in handling it. In those projects in which the total quantity or the rate of flow of groundwater is a real contingency, it is recommended that the contract provide bid items related to its control and handling.

Regardless of the actual quantity or rate of flow, the mere presence of water may adversely affect the progress of the work. In rock tunnels, even small quantities of water can lubricate joints and shear planes, causing a loss of ground stability. Furthermore, small quantities of water under pressure can sometimes wash materials from gouge zones or other weak strata, causing cleanup and equipment maintenance problems, as well as ground instability.

Most contractors agree that the reliability of the prediction of the true water conditions to be encountered during construction is strongly affected by the available information on the regional geology. Depending on the sit-

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uation, the prediction of the true water conditions from either boreholes or a pilot tunnel can be anywhere from very good to very unreliable. Furthermore, the reliability of the findings in a relatively short tunnel (cavern) in very homogeneous material that is explored using a full-length pilot tunnel is considerably different from that obtained from another pilot tunnel used in a similar project that is located in cavernous limestone. In relative terms, however, the general rule for most geologic formations is that "a pilot tunnel is expected to reveal the true water conditions, whereas boreholes are not."

An interesting issue concerning pilot tunnels is their effect in dewatering the rock mass and relieving some of these problems. If there is a sufficient time lag between the completion of a pilot tunnel and the commencement of excavation for the main opening, the pilot tunnel can serve as a dewatering system for the surrounding rock, acting as a buffer against the impact of excessive water flow or pressure. The contractor can take notice of this effect and plan accordingly. In addition, the dewatering effect can help the contractor reduce his estimate of dewatering costs considerably. This is particularly true for the costs related to pump operation and maintenance which, in fact, represent the bulk of dewatering costs. The general guideline with respect to equipment selection is that the contractor should still use pumps that are able to handle the maximum capacity, since this adds marginally to the project cost.

Tunnel Support

The ground support system includes various components, e.g., initial ground control, the type of support required, the method of installation, materials handling, the cost of support members, and the adaptability of the support system to the excavation method being used. The determination of a safe, efficient, and economical ground support system that optimizes the construction rate of advance requires that these factors be considered and resolved prior to the start of excavation.

Contractors agree that, in general, a pilot tunnel can provide a reliable estimate of the initial support requirements for the main opening. The reliability of this prediction depends on the regional geology, the pilot tunnel size, its length and location relative to the main opening, the size and length of the main cavern (tunnel), and the perceived similarities between the geologic conditions in the pilot tunnel and the main project.

The principal advantages of a pilot tunnel in determining the type and extent of the required support, as compared to other exploration methods, can be summarized as follows: (1) It allows visual inspection; (2) it provides an integrated picture of the geologic conditions; and (3) it permits instrumentation and monitoring of the rock behavior over space and time. A fairly good determination of the required support can be made based on the observed rock type and its characteristics and the support requirements of the pilot tunnel. It must be pointed out, however, that one must be very careful in making visual observations in the pilot tunnel. Critical areas may not be evident due to the use of temporary supports, such as shotcrete and rockbolts. Furthermore, rock movement cannot be easily determined with the naked eye. Instrument data must also be provided.

The decisions concerning the support of a tunnel, however, are not always based on geologic considerations and the observations provided by subsur-

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face exploration programs. 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 using steel sets may be based on an overcautious safety program or contractual requirements. 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 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).

In summary, contractors suggest several technical, institutional, and contractual factors that influence the selection of tunnel support:

- 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.
- Contractual 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 choice of support during construction may also be determined by 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 also increases his expected profit margin. 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. 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. Even though such a claim is quite difficult to prove and enforce, most contractors believe that owners should try and control unbalancing as much as possible.

In conclusion, the actual configuration of the support placed during construction (the support type and the extents over which each type is necessary) is a function of several variables that may be grouped as follows: (1) The degree of uncertainty about the actual geologic conditions and the expected ground-structure interaction prior to construction; (2) the economic, contractual, and institutional factors previously presented; (3) the geologic conditions and rock behavior actually encountered; and (4) the interpretation and implementation of the contract during construction.

Estimating Advance Rate

Progress in tunneling is measured by the advance rate (ft/shift). For a particular excavation and support combination, the advance rate is the most important factor influencing the time-dependent variable cost of a project, such as labor and equipment costs. The estimation of the advance rate for a given construction method is a function of the expected geologic conditions and of the productivity of labor and equipment given a certain geologic profile.

In contrast to other exploration methods, pilot tunnels provide information about both the nature and the behavior of the geology, and the performance of different excavation and support processes. Performance data from the construction of a pilot tunnel are made available to all prospective bidders and can serve as a basis for estimating the advance rate for the construction of the main opening. Table 1 shows a typical list of performance data from the construction of a pilot tunnel and the contractors' ranking of their importance in estimating the advance rate for the main project.

The value of this information depends on the expected similarities between the construction of the pilot tunnel and the main opening. For example, in many cases the equipment used to drive the pilot tunnel is different from that used in the main project. As a result, some contractors discount most of the equipment-dependent data as meaningless, while others argue that a considerable amount of correlation still exists.

Because of the possible lack of similarity, most contractors consider the data describing the behavior of the rock and the performance of individual processes much more useful than the reported overall production rates for the construction of the pilot tunnel. This phenomenon is clearly evidenced by the ranking of information in Table 1. However, these data may be used as a check for the contractors' estimates. In the event of a large discrepancy

TABLE 1. Information for Estimating Advance Rate

Number (1)	Pilot tunnel construction information (2)	Rank (3)
1	Overbreak characteristics	1
2	Rock breaking and muck swelling characteristics	2
3	Rock stand-up time characteristics	2
4	Dewatering requirements	2
5	Rock drillability data (drill force-penetration rates)	2
6	Performance of different drilling and blasting patterns	3
7	Average excavation and support rates (ft/shift)	4
8	Average cycle times (shifts/round)	4
9	Blasting vibrations for different blasting setups	5

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between the production estimated and the one reported for the pilot tunnel, the estimate is usually repeated to identify the cause of disagreement. In such cases, contractors tend to assign higher credibility to the pilot tunnel construction information, provided that they believe that they are applicable to the conditions in the main opening.

In addition to the issue of similarity, the reliability of the pilot tunnel construction information is also dependent on who has undertaken its construction. Most contractors feel that the reliability of this information is much higher if the work was done by a reputable contractor, and even more so if it was done by their own firm: "first-hand information is always better than second-hand information."

Pilot Tunnel Location and Size

There are few widely accepted rules concerning the location, shape, size, and length of a pilot tunnel. These decisions vary from project to project depending on: (1) The regional geology; (2) the size of the project (cross section and length); and (3) the primary use of the pilot tunnel (geologic exploration, experimentation with design and construction approaches, ground treatment or reinforcement, instrumentation and monitoring, etc.).

Contractors agree that, in general, a pilot tunnel is most beneficial if it is located in the crown of the future opening. Some even claim that they cannot think of situations where the pilot tunnel would serve its cause better if located at any other elevation. Others, however, point out that while the crown is probably the most advantageous location, there are cases in which the specific project conditions may favor a different configuration. For example, one contractor offers the guidelines given in Table 2.

A more detailed consideration of the possible conditions favoring a particular configuration must be based on the characteristics of each individual project.

The minimum cross section for a pilot tunnel is basically dictated by the need to have labor and equipment functioning as efficiently as possible during its construction. A minimum of 6×6 ft (1.8×1.8 m) is considered reasonable, even though a cross section of 8×8 ft (2.5×2.5 m) would be just as economical, while providing more working room.

The cross section of the main project must be large enough to justify the separate excavation of a pilot tunnel. The minimum diameter suggested by contractors is in the order of 30 ft (9 m). It can also be larger or smaller depending on the location, accessibility, length, and use of the project. In the opinion of at least one contractor, the construction of a pilot tunnel cannot be economically justified if the diameter of the main opening is less than 50–70 ft (15–21 m).

TABLE 2. Guidelines for Location of Pilot Tunnel

Location (1)	Project conditions (2)
Crown	Large openings requiring support; instrumentation.
Center	Medium openings; favorable geologic conditions.
Invert	Drainage; sidewall support; wall plate drifts.
Below invert	Drainage; instrumentation.

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Similarly, the applicability of a pilot tunnel also depends on the length of the project, even though the influence of the project's length is weaker than that of its cross-section size. The minimum length for a cavern ranges from 50–500 ft (15–150 m) with an average value of 250 ft (75 m). The minimum length for a tunnel ranges from 200–2,000 ft (60–600 m) with a mean value of 1,000 ft (300 m). The determination of the minimum length depends on the project geology, the cross-section size, and the integration of the pilot tunnel with the construction and operation of the main opening.

TEST SECTIONS

Full-scale test sections can be considered as a special case of pilot tunnels. The term "test section" denotes a full cross-section segment of the main project that is primarily used for the development and validation of design and construction methods.

Test sections are used in cases where a conventional full-length pilot tunnel would not be justified, either because the cross section of the main project is too small, or because the main project is extremely long. Test sections are constructed when there are serious technical, functional, or economic doubts about design performance, which might call for full-scale testing (Lane 1975).

The previous discussion concerning the information value of pilot tunnels was based on the assumptions that a pilot tunnel has a smaller cross section than the main opening, and that it runs the full length of the project, or is at least as long as the portion of the project under consideration. Under these conditions, the main direction of inference is perpendicular to the project axis. In the case of a full-scale test section, however, the main direction of inference is parallel to the project axis, even though it is still necessary to estimate the geology outside the volume of the test section itself. In other words, one needs to extrapolate away from the observations made in the test section in all three dimensions.

Contractors have diverse opinions about the value of information provided by full-scale test sections. Some consider the method too expensive, primarily due to separate contract administration, and argue that generally this kind of exploration, by staging the construction process, creates more cost than it saves. Others point out that the value of this information relates directly to the degree of correlation between what has been observed in the excavated portion of the project and the remainder of the work.

This correlation can easily be established if there are borehole observations for both the constructed and the unexcavated project segments. If this correlation is high (the project geology is either highly uniform or repeats itself in cycles), then the proposed staging of construction can be of considerable value as a means of predicting not only the geology but also the required support and the expected construction performance.

In contrast, if there are few or no borehole observations in the unexcavated portion of the work (which, for example, may be the case in a transmountain tunnel where the overburden is prohibitively high), this correlation cannot be established, even if it exists. Under these conditions, a test section, or a pilot tunnel that does not run the full length of the project, loses most of its value. The observations made in a test section have little value when extrapolating in the direction of the tunnel axis, unless the geologic conditions

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are known to be highly variable in the vertical direction and homogeneous in the horizontal direction. This is the exact opposite of the situation favoring small cross-section, full-length pilot tunnels.

Advantages and Disadvantages of Pilot Tunnels

Beyond its usefulness as a subsurface exploration method, a pilot tunnel can serve several other design and construction purposes, depending on the configuration and needs of a particular project. In evaluating the decision to construct a pilot tunnel, these uses and the resulting benefits, or potential problems, must be considered explicitly, because they can outweigh the value of the information provided by the exploration method. Similarly, the construction of a pilot tunnel typically includes part of the work for the main project that must be discounted in a cost-benefit analysis.

Pilot Tunnels—Benefits

The benefits resulting from the construction of a pilot tunnel can be divided into two groups. The first group is informational in nature. Its value stems from the fact that the corresponding information is made available during the design/construction-planning phase, thus eliminating some of the uncertainty in the designer's and contractor's tasks. This set includes:

- The information on the project's geology.
- The effect of a pilot tunnel in dewatering the rock.
- The information on the behavior of the rock under different excavation and support methods (including monitoring and experimentation).
- The production rates achieved during the construction of the pilot tunnel.
- The identification of external constraints on underground construction in general.

The second set includes benefits that are realized because the pilot tunnel is used as an integral part of the construction process. In this sense, a pilot tunnel can be used for:

- Installing presupport in the main opening's crown.
- Treating the rock ahead of the face.
- Dewatering the rock during construction.
- Providing relief in blasting the rock.
- Ventilating.
- Accessing critical locations.

A pilot tunnel can also have other uses depending on the needs of the project. For example, the pilot tunnel's outline provides extra surfaces that make the excavation of the first drift by mechanized ripping of the rock much easier. In addition, the existence of the pilot tunnel allows the possibility of using a partial face tunnel boring machine that anchors itself within the pilot tunnel and pulls (rather than pushes) the cutter head towards the rock face; this approach has the advantage that the newly excavated area behind the machine is free to be supported as quickly as required.

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The main difference between the two groups, as previously defined, has to do with the timing of the realization of the corresponding benefit. For the first set, the benefit is realized before construction begins, whereas for the second set the benefit is realized afterwards. In considering the value of a pilot tunnel as an exploration alternative (i.e., before construction begins), one must still take both sets of benefits into account. This is particularly important, because in some cases the second set may be of more value than the first, or the elimination of the second (and more tangible) set may make a pilot tunnel an unattractive option.

It must be noted here that some contractors are uncomfortable with this approach because they do not believe that a pilot tunnel can be considered as the only possible source of the second group of benefits. This view is not altogether unjustifiable because some of these benefits can be achieved through other means as well; especially, in the case where the main opening will be excavated using multiple drifts, the first drift being considered equivalent, in many respects, to a pilot tunnel. Even in this case, however, one should still take into account the existence of the pilot tunnel during the construction phase and estimate the value of the potential benefits or problems thereof by analyzing the expected costs of the options with and without a pilot tunnel. In other words, one needs to look at the marginal value of the pilot tunnel benefits in comparison to the other options available.

Presupport

In cases where the main opening is quite large, or where the rock is of inadequate quality, the designer can use a pilot tunnel to install rockbolts in the opening's crown, acting as presupport for the first stage of the main project excavation. The objectives of installing the presupport are to minimize rock movement during subsequent excavation, to reinforce the natural rock arch, to decrease the required support for the main opening, and to decrease the subsequent overbreak.

Contractors have diverse opinions as to the value and usefulness of presupport. Some feel that it can be of considerable help in reinforcing the rock and speeding-up subsequent construction. Others argue that if the support is installed during the construction of the main opening and on the same basis as for the pilot tunnel (e.g., type of support, time between blasting and supporting the rock, distance of support to the face, etc.), then there should be no difference.

The main factors in comparing the two cases are the size of the pilot tunnel relative to the size of the first drift in multiple drift excavation, assuming that the first drift will be located at the crown, and the span of rock to be initially exposed at the crown.

If the size and location of the two openings is approximately the same, then it is obvious that the presupport enjoys no particular advantages if installed from a pilot tunnel. On the other hand, if the pilot tunnel is much smaller than the first drift and the rock is not of particularly good quality, then the pilot tunnel presupport should be beneficial since it minimizes rock movement and the disruption of the natural rock arch. In this case, the installation of presupport may even allow a decrease in the number of required drifts and thus help reduce the cost and time required for the construction of the main project.

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Contractors, however, point out that the installation of the necessary presupport can be much more time- and labor-consuming if done from a relatively small opening. For example, in the case of the Porter Square Station (part of the Red Line extension of the MBTA in Cambridge, Massachusetts), the initial plans called for the installation of 30-ft (9-m) rock bolts from a 12 × 12-ft (3.6 × 3.6-m) pilot tunnel as part of the main contract. This would have required that each drill and each rockbolt be spliced twice. Given the contractor's concerns about efficiency, the final presupport was subsequently changed to 10-ft (3-m) rockbolts.

The effectiveness of presupport when installed from a pilot tunnel can be affected both positively (less damage to the rock) and negatively (more expensive) by the pilot tunnel's size. An alternative that bypasses some of these difficulties is to wait until the start of excavation of the main opening and to presupport the crown by installing rock bolts from the first drift prior to blasting each round. This way the presupport extends over the length of one round ahead of the enlarged face, where it is needed the most.

In general, the benefits of presupporting the crown from a pilot tunnel is an issue that depends on the project geology and the set of available options for sequencing the excavation and support of the main opening. Most contractors do not believe that the installation of presupport can decrease the amount of overbreak to be experienced during the main excavation, while the ones who do cite a decrease of 10–20% (an indication that the effect on overbreak is also a function of the geology and other project characteristics). With respect to the advance rate, and given that the presupport has already been installed, most contractors feel that its existence can speed-up the construction of the project. The increase in the advance rate can range from insignificant, to 5%, or even 10%, depending on the situation.

Blasting Considerations

A common practice in hard-rock conventional (drill and shoot) tunneling is to use large-diameter burn-cut holes to furnish relief for the explosion of the rock. A burn-cut provides space for the rock to expand during blasting, and thus provides the following benefits:

- Eliminates the need for furnishing relief through short diamond-cut or V-cut holes. (Diamond-cut holes are inclined short drill holes near the center of the tunnel face, so arranged that when the first shots are exploded in the round, a diamond-shaped wedge of rock is removed; this allows relief for the remaining rock when the delay exploders set of the charges in the other drill holes. V-cut holes are a similar technique.)
- Allows each hole to be drilled the full length of the round.
- Permits long steel feeds on each drifter. (A drifter is a heavy drill for drilling nearly horizontal holes in the tunnel face, typically supported from jumbo-mounted jibs. Since the feed can be as long as the round, steel changes will not be required for individual holes. This reduces the labor requirements and decreases the actual drilling time but increases the consumption of drill steel due to breakage (Parker 197).)

Most contractors agree that a pilot tunnel, when viewed as a bore in the tunnel face, can serve the same purpose as a large burn-cut. In this capacity, a pilot tunnel can provide relief for the subsequent heading rounds, help

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reduce the blasting vibration levels, and decrease the cycle time per round. As a result, a pilot tunnel can make blasting rounds easier to design and execute. The resulting effect on the advance rate can range, depending upon circumstances, from none (as will be explained, it can even be a hindrance) to a very substantial improvement.

The existence of a crown pilot tunnel can also present problems in blasting the rock by causing it to break in a nonuniform manner. According to one contractor's experience, the existence of a pilot tunnel in the crown of a particular project altered the rock's expected reaction to blasting and caused more material to be excavated from the tunnel's crown than from the invert (excavation was full face). As a result, there was not enough room in the invert to install the already available, full-height steel sets, and too much of the crown was left unsupported. However, it is not clear whether this problem was solely due to the existence of the pilot tunnel, or whether it can be attributed to an inappropriate blasting plan.

Ventilation

Under certain conditions, a pilot tunnel may be used as a ventilation duct for the construction of the main opening. The amount of necessary ventilation is almost proportional to the amount of diesel horsepower used underground [regulatory requirements vary between 50–100 cu ft/min/diesel hp (2–4 m^3/min/kW)]. The larger and longer the tunnel, the more haulage units are required, and thus, the more horsepower; therefore, as the tunnel length increases, larger ducts and fans are typically required. In tunnels that have connecting shafts, it is possible to exhaust air through these shafts to save vent pipe.

Typically, the end of the main ventilation pipe is kept about 200 ft (60 m) from the tunnel face to prevent damaging the pipe during blasting. This results in a dead-air space between the end of the pipe and the tunnel face. To obtain proper ventilation at the face, small fans are set up on the jumbo with short sections of pipe that extend back and into the main vent pipe (secondary ventilation system).

A pilot tunnel that communicates with the open air at its end ahead of the construction face can serve as a large ventilation duct and can thus substitute for both the main and the secondary ventilation system. Hence, it can reduce the cycle time for the excavation-support sequence by eliminating the need to extend a ventilation duct in each round and by decreasing the "smoking time" portion of the cycle (due to increased flow capacity). Contractors believe that the resulting increase in the advance rate can vary from 0–12%, depending on the project's characteristics. Similarly, the ventilation cost can be reduced by 0–8%.

External Constraints

Underground construction, especially in highly congested urban areas, has a significant impact on the environment and the interests of the local community. In order to minimize the effects of construction on property, services, and operations, the affected public imposes constraints on the construction process in the form of rules and regulations to which the project must conform. Otherwise, legal action may be taken against any of the principal parties to the construction contract, an event that is clearly undesirable since, in most cases, it translates into bringing the construction process to

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a halt, at least temporarily. During the construction of a subway station, for example, the contractor was informed upon the completion of mobilization that the city prohibited the storing of explosives on site. This resulted in the contractor's loss of three working days.

The construction of a pilot tunnel can alleviate some of the externally imposed problems by identifying these constraints before the construction of the main project, thus allowing the designer and the contractor to modify their plans accordingly. The construction of a pilot tunnel, however, is no guarantee that all such problems will be identified and dealt with in time. In the case just mentioned, the construction of a pilot tunnel failed to identify any constraints on explosive materials storage. In fact, even though several other tunneling projects were being constructed in the same area, the engineers were not aware of this regulation. This example serves to indicate not so much the inability of a pilot tunnel to identify the problem, but rather the unpredictability in the nature and timing of external constraints.

Contractors agree that, in general, the construction of a pilot tunnel can help identify the environment within which they should plan to operate. Reservations are based on the fact that since the construction of a pilot tunnel is a small-scale operation, some of the problems may not surface early (as in the case stated). In addition, the value of this information depends significantly on whether "the owner, engineer, and contractor (for the main project) do their homework properly." According to contractors, the problem areas that could be identified through the construction of a pilot tunnel, include: (1) Traffic routing and disruption; (2) acceptable noise levels; (3) acceptable blasting vibration levels; (4) haulage restrictions; (5)explosives handling and storage; (6) dust suppression; (7) water discharge and treatment; and (8) safety laws and enforcement.

Any of these problems, especially those such as restrictions on acceptable blasting vibrations and noise levels that affect directly the tunnel-driving operations, can have a major impact on production and cost. For example, the contractor may not be able to do any blasting at night. According to one contractor, these constraints may increase the cost of the project by 15–20%, an amount that exceeds the typical cost of a pilot tunnel.

Discounting Part of Pilot Tunnel Cost

The decision to construct a pilot tunnel is basically a function of two variables: its perceived value and its expected cost. The discussion thus far has focused on the evaluation of a pilot tunnel's benefits, since this is by far the most difficult and controversial issue. The cost of constructing a pilot tunnel (a small underground project in itself) can generally be estimated fairly accurately.

In some cases, however, the construction of a pilot tunnel involves some of the work that would otherwise have been part of the main contract. The cost of this work should, in general, be discounted when performing a cost-benefit analysis. An example is the cost of an access shaft that is necessary for the construction of the pilot tunnel and the main opening. Contractors suggest several similar work items that may be considered unavoidable expenses, including: (1) Dewatering; (2) the provision of initial tunnel (cavern) support (presupport); (3) the provision of access to a critical location (e.g., access shafts); (4) instrumentation and monitoring; (5) rock treatment and

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reinforcement; (6) ventilation; (7) utility relocations; and (8) the preparation of dump roads and dump sites.

It should be pointed out that discounting the cost of this work may not always be appropriate. For example, the cost of an access shaft is generally independent of whether it is constructed as part of a pilot tunnel contract or as part of the main contract. However, this is true only if the location and size of the shaft does not seriously constrain the options available to the main project contractor. The size of an access shaft is a crucial decision which, if not made properly, may subsequently preclude the use of large specialized excavation and haulage equipment. If such equipment is necessary for the construction of the main opening, then the access shaft used for the pilot tunnel may be virtually useless to the main project contractor and its cost must, of course, not be discounted.

Potential Problems

In addition to the benefits already mentioned, the construction of a pilot tunnel may also be the cause of several problems, the importance and extent of which is significantly influenced by the project's geology and configuration. Most of these problems deal with the support necessary for the stability of the pilot tunnel and its impact on the construction of the final opening.

In cases where the rock is of poor quality, the construction of a pilot tunnel may require the heavy use of support: rockbolts, steel sets, shotcrete, etc. Some of this support may have to be removed during the excavation of the main opening, thus slowing down the advance rate and necessitating a more costly excavation procedure, especially if steel sets are used.

In addition, supporting, unsupporting and allowing the rock to move, and then supporting the rock again, may have an adverse effect on arch stability, resulting in more overbreak and additional support requirements when compared to a once-supported opening without a pilot tunnel. The use of steel in the pilot tunnel support can also have an adverse effect on the mucking cycle and cause damage to equipment.

Furthermore, contractors point out that the use of shotcrete as part of the pilot tunnel support defeats one of its major purposes, i.e., to allow contractors to have a look at the nature and behavior of the rock.

Another potential problem is the effect of blasting on previously grouted rock and the possibility of sudden, excessive water inflow. Even though this problem would still be present if grouting were done from the main opening instead of the pilot tunnel, it is felt that the larger free surface exposed over the full length of the pilot tunnel increases the probability of this event.

The construction of a pilot tunnel requires the commitment of significant resources (time and money). Contractors indicate that this commitment may make it very difficult for the owner of the facility to justify a change in the project's location or configuration, if the pilot tunnel proves that such action is necessary. This is particularly true if the investment in a pilot tunnel is approved because some of its cost was discounted as being part of the main project. Even though the investment in a pilot tunnel should be considered a sunk cost when evaluating the option to change the project's location, few organizations would be willing to admit that this is indeed the case, especially if the (public) owner had to go through a lengthy process to secure the pilot tunnel construction approval in the first place.

Exploration, Risk Allocation, and Bidding Behavior

The marginal value of geologic exploration, irrespective of the methods used, is highly dependent on two parameters: the amount of geologic information that already exists, and the perceived consequences of geologic uncertainty.

Even though the existing amount of geologic uncertainty is certainly one of the primary factors in evaluating new information, the economic value of this information is largely dependent on the consequences of the risk outcomes. In other words, the way the geologic risk is shared between the parties to a contract determines the risk premiums required by each party and thus influences the value of information on the likelihood of the possible outcomes.

Under a reimbursable cost plus fixed-fee contract, for example, the owner assumes complete responsibility for the 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. It is the owner that 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 places all construction risks on the contractor, who in turn must protect the company from the unexpected by including contingencies in the bid. The amount of these contingencies is in direct relationship with the perceived level of uncertainty concerning the project's geology and the rock's behavior, given a particular excavation-support process. Most contractors place a high value on exploration in this case. The major reason for this is that contractors cannot inflate their bids to an absolutely secure level and at the same time remain competitive.

Based on these observations, it becomes evident that the value of a pilot tunnel, or any other exploration method, is always a function of the type of contract and the implied risk liabilities of each party. In the typical case of a unit price contract, the allocation of risk and the subsequent value of risk reduction is very much dependent on the existence and interpretation of a changed conditions clause and the association and excavation and support items with a specific set of geologic conditions.

Changed Conditions Clause

The changed conditions clause is of such importance in protecting the contractor from a major economic loss that many contractors have established as company policy to abstain from bidding 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 contingency amounts they would require.

The impact of this clause's absence on the contractor's strategy depends upon circumstances, some of which are:

- The 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 availability of labor and equipment, etc.

All of these factors play a part in making bidding decisions. The end result varies from the inclusion of a contingency to the bid, to not submitting a bid at all.

In order to attract a large number of bidders, most owners today include a changed conditions clause as part of the contract documents. More often than not, however, the intent of this clause is marred by the existence of exculpatory clauses in the contract. The accuracy of the geological data or its interpretation is disclaimed, thus nullifying any reference to "conditions indicated in the contract." Because of this practice and "the myth that contractors always make money," contractors are not always successful in recovering additional costs, plus markup and profit.

Contractors also claim that, in some cases, one of the principal objectives behind the owner's decision to construct a pilot tunnel is to provide insurance against any changed conditions claims. Since the wording of a changed conditions clause is quite ambiguous as to what constitutes "conditions not reasonably anticipated," the construction of a pilot tunnel may be advocated as a source of "perfect information," thus nullifying the basis of any changed conditions claims. Contractors agree, however, that even though this strategy and this interpretation of a pilot tunnel's results have indeed been attempted, it has been without success. Even though a pilot tunnel can be an excellent exploration method, very rarely can the furnished observations be considered as complete or perfect information for the rest of the project. The possibility for the unexpected still remains, a fact that is usually recognized by most arbitration and legal authorities.

Potential of Pilot Tunnels in Reducing Bid Contingencies

The construction of a pilot tunnel and the associated reduction in uncertainty about the nature and the behavior of a project's geology can cause a significant reduction in the contingencies included as part of underground construction bids. Contractors estimate that the resulting reduction in contingencies can range from 0–20% of the project's estimated cost depending on: (1) The location of the pilot tunnel and the type of geology encountered; (2) the quality and quantity of the pilot tunnel information and whether this is expected to be representative of the project's conditions; and (3) the pilot tunnel's ability to identify difficulties that do, or do not exist.

The contractors' estimates for the range of the expected reduction in contingencies indicate that, under certain circumstances, a pilot tunnel can indeed be an economically viable exploration option. For example, the cost of the tunneling portion of the work for the Porter Square Station was about $20,000,000. The cost of the pilot tunnel for this project was about $1,200,000, including $400,000 for the construction of an access shaft that would have otherwise been part of the main contract. Depending on whether the cost of the shaft is included, the cost of the pilot tunnel was approximately 4% or 6% of the project's cost. This percentage is certainly in the same range with (if not less than) the expected reduction in contingencies that may have been effected by the pilot tunnel's construction. One of the bidders for this project actually attributed a 10% reduction in contingency to the comprehensive exploration program.

This does not mean, however, that the construction of a pilot tunnel is unquestionably a sound economic investment. As explained earlier, one must examine all possible exploration strategies and choose the one with the highest net benefit. Several contractors alluded to this when taking a position against the use of pilot tunnels for exploration purposes. Even though such absolute approaches are questionable, their argument is certainly valid.

General Recommendations

At the outset, one of the major objectives of this research was the assessment of a sufficient set of conditions for the use of pilot tunnels as an economically justifiable exploration alternative. It is obvious from the foregoing discussion, however, that the construction of such a set of prerequisites is far from possible. The economic evaluation of a pilot tunnel is a function of too many parameters to be cast into simplistic cause-effect rules. Furthermore, none of these parameters has a dominant effect over the others to allow the development of simplified decision rules.

As an example, consider the extreme case in which a pilot tunnel can provide perfect geologic information: the geology is variable in the longitudinal direction but perfectly homogeneous in the radial direction. Even though the parameters describing the geology may be perfectly known, the ground's behavior is still uncertain because it also depends on other variables such as the size of the project and the construction methods to be used. The estimation of geologic states is of use to the designer and the contractor primarily because it is a predictor of ground behavior. 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. This can only be achieved through full-scale experimentation and the comprehensive use of instrumentation and monitoring (an observational approach).

The development of scenarios (collective sets of specific conditions), under which the adoption of a pilot tunnel would constitute a sound investment, would also be deceiving for the following two reasons:

1. Usually, a pilot tunnel is not a single contender for the exploration funds available. Depending on the project's depth and accessibility from the surface, other methods may also be applicable. The decision as to which method to use requires the evaluation and comparison of all the options available, including combinations of methods. Contractors, for example, argue that the density of boreholes that provides the same information as a pilot tunnel can be achieved at far less cost, at least for shallow urban projects.

2. Scenarios cannot be of wide practical acceptance unless they can answer "what if" types of questions. Since no two underground projects are exactly the same, it becomes highly improbable that a real-life situation can fit a given scenario exactly. Given the tight interaction between all the parameters in tunneling, even a small deviation will necessitate individual consideration. As a result, the evaluation of a pilot tunnel can only be done on a project basis; any attempt to

generalize is futile because it can never be universally applicable.

However, it is possible to identify some of the conditions that are most likely, or unlikely, to make the construction of a pilot tunnel an attractive option. Contractors suggest several situations that favor pilot tunnels:

- When the size of the main opening is large. Large projects impose more difficulties in the prediction of excavation and support performance. Slight variations in parameters like overbreak, support type and density, the advance rate, etc., result in large changes in the expected cost because of the size effect and economies of scale.
- When there is limited surface access for the comprehensive use of other exploration methods such as in congested urban areas or inaccessible rural locations.
- When there are unfavorable geologic conditions, such as in highly variable geology, high water pressure and/or flow, faulted formations, etc., provided that the rock conditions in the pilot tunnel can be expected to be representative of the conditions in the rest of the main opening.

Similarly, the following situations are indicative that a pilot tunnel may be of very little value:

- When the size of the main opening is medium or small.
- When a comprehensive boring program is possible.
- When the geology is uniform, the geologic conditions are favorable, the project is above the water table, etc.
- When the project is in mixed face conditions (the pilot tunnel observations are not representative of the rest of the opening).

Conclusion

These suggestions as well as the overall discussion in this paper can serve as guidelines for the most likely conditions that support the economically justifiable use of pilot tunnels. Pilot tunnels serve many useful design and construction purposes, the relative importance of which depends on the project's individual needs and characteristics. Given a set of project characteristics, and before a final decision on the method and extent of subsurface exploration can be made, owners and/or designers should first review all the possible advantages or limitations of a pilot tunnel that have been presented. This thorough screening is necessary in order to make the preliminary and sometimes crucial decision as to whether a pilot tunnel should be considered (as opposed to adopted) as a possible alternative. The final decision depends on the pilot tunnel's relative merits as a subsurface exploration method and as an integral part of the project's design and construction process.

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