Engineering Decision Support of Automated Shield Tunneling

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Abstract: Construction-engineering problems in the application of automation to soft-ground tunneling, especially shield tunneling, are discussed. A concept for decision support in the selection of a type of shield-tunneling machine and of an appropriate construction technology under given site conditions is presented. Corresponding engineering problems involved in an entire tunneling project from preplanning to excavation practice are also discussed. As an illustration of the discussed issues, the history of an earth-pressure-balanced shield-tunnel project in Osaka, Japan, suggests an effective application of construction automation in similar future works.

Introduction

Although construction is the largest and one of the most important industries in most of the developed countries, it is also among the least advanced in the use of automation technology available for the performance of on-site work. Despite some progress made in the area of earth-pressure-balance technology, this is also true in soft-ground tunneling. However, due to a serious shortage of skilled labor and an imperative to improve work safety, soft-ground tunneling is currently experiencing intensive studies to automate its production process. Possible ways to implement automation in soft-ground tunneling are presented next. Also, problems involved in computer-aided preplanning of excavation and in automatic excavation systems are discussed.

Computer-Aided Planning of Soft-Ground-Tunneling Projects

Preplanning of a soft-ground tunneling project begins with an investigation of geotechnical and environmental problems. No engineering tasks can proceed without a reasonable amount of geotechnical information pertaining directly to the planned project site. Next, a feasibility study of the proposed project is performed. Without a resolution of all important engineering problems, a feasibility study and a subsequent economic evaluation of the project would lack technical merit.

Engineering problems arising after the geotechnical information becomes available can be compiled within a knowledge base for subsequent computer-aided analysis and solution. The main issues related to the design of such a knowledge base follow next.

The problem at hand is the selection of a shield-tunneling machine and of subsoil improvement strategy. Precise geotechnical and environmental

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Note. Discussion open until May 1, 1992. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 19, 1990. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 117, No. 4, December, 1991. ©ASCE, ISSN 0733-9364/91/0004-0674/$1.00 + $.15 per page. Paper No. 26437.

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information is desirable for achieving these objectives. Another typical problem in the engineering practice is the initial equipment and personnel assignment during the project planning phase at the time when little geotechnical information is available. In these conditions, contractors must also routinely determine the desired qualifications and number of engineering staff necessary for the project.

Construction planning and scheduling, as well as a need to provide detailed information for project cost estimates, constitute a strong motivation for the creation of a knowledge base for selecting tunneling equipment. With the use of such knowledge, less experienced engineers can more efficiently perform realistic planning of construction shaft layouts and the scheduling of entire tunneling projects.

A decision-support-system prototype aimed at fulfilling these goals has been designed, based on the current state of the practice of shield-tunneling operations performed by the Obayashi Corporation of Japan. The prototype has been implemented within the knowledge base system (KES) programming environment. Kakoto and Skibniewski (1989) provide a sample of the program code and show an example test run of the prototype. The following sections describe the knowledge base contained within the prototype based on the compiled information and procedures.

Selection of Type of Shield Machine

In soft-ground tunneling the selection of the type of tunnel-boring machine must be completed during the preplanning of the entire project-engineering process. This is necessary to proceed with temporary shaft planning, mobilization, and demobilization of project equipment and of other resources.

There are two basic types of appropriate equipment: open-face and closed-face shield machines. Fig. 1 shows the classification of the basic types of shield-tunneling machines. An open-face shield machine was first used in the early 20th century to bore through Thames Estuary with the use of low-pressure compressed air (Haswell and Campbell 1983). This was the first subaqueous tunneling project in the world. However, the history of open-face shield tunneling without applying compressed air is apparently older than this project, although there is currently no technical interest in earlier types of tunneling techniques. The traditional open-face shield machines utilized manual mining at the face, while modern machines of this type are equipped with various kinds of excavation units to minimize the manual work required.

Closed-face shield machines are also called by other names such as *full-face excavating shield machines*, or *mechanical-blind shield machines*. One significant difference between closed-face and open-face shield machines is that the closed-face machines may not require compressed air to proceed with the tunneling under subaqueous conditions. Closed-face machines can

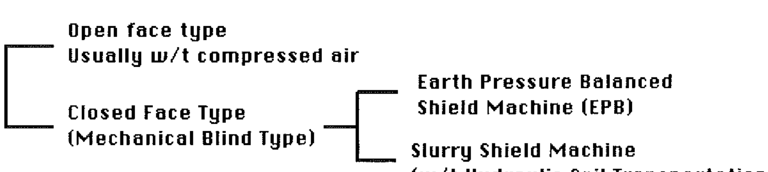

FIG. 1. Shield Machine Type Classification

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further be classified into two subtypes, earth-pressure-balanced (EPB) shield machines and slurry shield machines.

Some intermediate types of shield machines have also been developed to suit various subsoil conditions. One example is an open-face-type shield machine with a controllable opening. Another is a *mix shield machine*. This machine is designed to alter its form from open-face to closed-face or vice versa during its progress into the tunnel. However, a practical performance test has been reported on its *liquid-support face* version only (Becker 1987). Thus, there is only one tested and reliably available version of a slurry shield machine.

Subsoil Improvement

A proper selection of the type of a shield machine to deal with a given subsoil condition does not complete the preplanning of a tunneling project. Another action often considered by tunneling contractors is the use of auxiliary methods to improve the characteristics of subsoil conditions around the designed tunnel axis. Two methods to accomplish this objective exist: freezing of the ground and grouting. Both freezing and grouting can be practiced on the ground surface and at the tunnel face.

Grouting can be classified into two categories, cement grouting and chemical grouting. Cement grouting uses pressurized mortar milk as the grouting agent. Most chemical grouting methods rely on the bonding effect of silicic acid agents injected into subsoil. Fig. 2 presents the classification of these techniques. Both methods are often combined to control the hardening period and the strength of the improved ground. It is important to control the hardening effect since the tunneling machine must advance through the improved zone following the grouting. Overimprovement may cause significant drop of productivity in tunnel excavation itself or, in an extreme case, it can stop the progression of the shield machine.

Geotechnical Issues

Subsoil-Condition Feedback Loop

An entire tunneling project consists of various tasks from design to actual construction and maintenance of the completed work. Resendiz and Romo

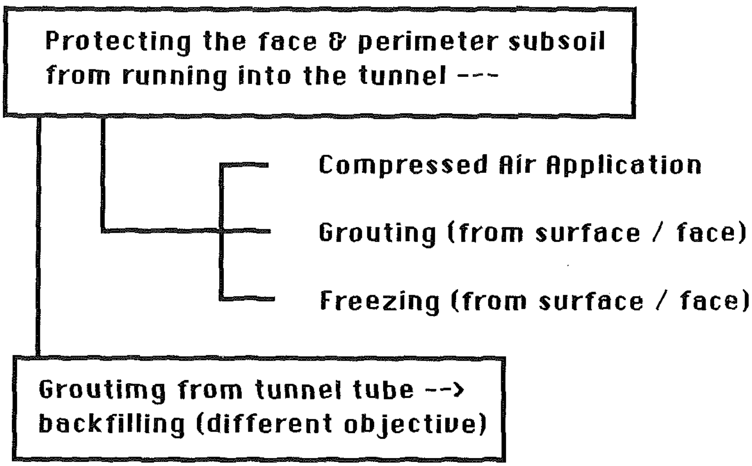

FIG. 2. Classification of Auxiliary Methods

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(1979) introduced the following classification of stages and tasks involved in soft-ground tunneling projects.

1. Characterization of underground conditions along and around the area of tunnel axis.
   a. Advance exploration, sampling, and measurement of subsoil conditions and properties.
   b. Development of a conceptual model of the character and properties of soil formations along and around the tunnel.
   c. Additional investigations and measurements during construction to fine-tune the conceptual model of the subsoil.
2. Design of the excavation against soil collapse. In order to perform the tasks involved in this stage, it is necessary to determine which variables affect tunnel stability in each type of soil formation. In addition, the quantitative relationships between those variables and the safety factor against collapse ought to be known. Much has been learned from investigations and field experience gained in the many tunneling works accomplished in the last two decades. Yet current knowledge of these qualitative and quantitative relationships leaves ample room for improvement.
   a. Selection of excavation methods and equipment.
   b. Selection of fluid (air or slurry) pressure in the excavation chamber. It is necessary to apply a fluid face support method in the case when soil strength or the combination of permeability and groundwater conditions make excavation under atmospheric pressure unacceptable.
   c. Selection of primary support characteristics and installation method.
3. Design against excessive soil displacements.
   a. Prevention of yielding of the tunnel face.
   b. Control of soil displacement due to advance of the shield.
   c. Prevention of tunnel walls displacement upon initial adjustment between soil and primary lining.
   d. Control of deflection of primary lining.
   e. Control of displacements due to reology of soil and permanent lining.
4. Construction.
   a. Implementation of design decisions.
   b. Observation of soil behavior.
   c. Feedback of conceptual model of the subsoil.
   d. Design adjustments.

Among these tasks, design of the excavation against soil collapse directly pertains to the selection of the type of tunneling machine. Construction is the final stage of the process summarized in this procedure.

Construction-Control Loops

Construction tasks involved in tunneling forms cycles of material flow and information flow. Rodriguez and Ruelas (1979) maintain that the mining procedures in both open-face and closed-face shield tunneling can be divided into two alternating procedures, advancing of the shield and setting of the temporary lining. Therefore, tasks to be executed at the face of a shield-tunneling work site can be generally described as a cycle of shield-machine jacking, excavating, and primary-lining installation.

The first cycle is formed by the movement of material coming in and

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going out carried by a conveyor, a pipeline, or mucking cars. The cars bring in primary lining material when they come into the tunnel, and bring back the excavated muck when they go out. In some cases, the productivity of the project is controlled by the mucking operation, especially when the construction length becomes large.

Mucking operation forms the first cycle of the tunneling work. The individual components of the mucking operation cycle time (CT_m) are as follows: t_1: loading time of the excavated soil at the face; t_2: hauling time to the shaft; t_3: unloading time at the shaft; t_4: lining material loading time at the shaft; t_5: hauling time to the face; and t_6: unloading time of the lining material at the face, and .

$$CT_m = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 \quad (1)$$

The second cycle reflects the flow of information between the face and the shaft. After each step of shield jacking, information regarding earth pressure, water pressure, and jack resistance is reported to the operator to determine the number and location of the jacks to be applied in the next step. At the same time, this flow of information between the face and the shaft controls the grouting operation.

The third cycle involves the flow of information pertaining to the control of location of a tunneling machine. This location directly influences the precision of the completed tunnel axis. However, it is not necessary to measure the coordinates of the machine center and its inclinations and rotations following the installation of each primary lining. In a tunneling project utilizing manual surveying methods to measure the tunneling-machine location, it is precise enough to obtain these data once every three to five cycles of the primary lining installation.

The information loops just described are presented in Fig. 3. These loops constitute integral components of the entire tunnel-excavation process.

Automation Applications

The main components of an automated tunnel guidance system include an automatic machine-position detection system and an automatic data processor. Currently, a certain number of tunneling projects in Japan, Western Europe and the United States employ some kind of an automatic guidance system. Clients, contractors, and machine manufacturers have gained major benefits in terms of safety and accuracy of their product, coupled with significant savings on project costs and time (Skibniewski 1988). New tunneling machines in which instrumental guidance is an essential and integral part of design have been introduced, and many more are under development (Skibniewski and Russell 1989).

Guidance Systems for Shield Machines

The main components of an automated guidance system in a shield-tunneling machine are transducers that gather geometric data of the machine. A conventional tunneling laser provides a datum beam, usually parallel to the desired tunnel axis. A target unit of unique design mounted on the tunneling machine receives the beam and continuously performs three independent measurements with respect to the axis of the target unit. The three independent variables include the coordinates of incidence (X,Y) and the angle of incidence (lead).

Rotations about the machine horizontal axes, referred to as *look-up* of

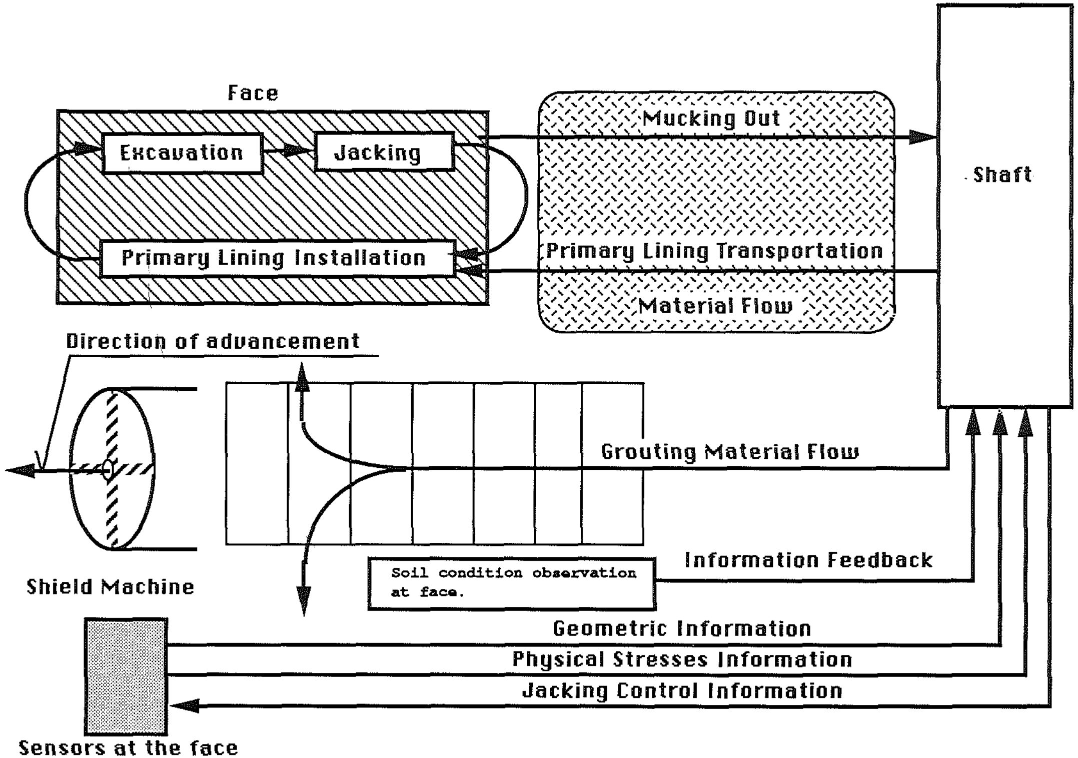

FIG. 3. Cycles of Tasks and Information

the machine face, and the rotation of the machine drum body are measured by two inclinometer units with the use of gravity. An optional distance-measuring unit measures the six independent variables determining the position of the machine along the tunnel axis, but often the inclinometers alone provide sufficient accuracy without additional instrumentation.

Subsequently, the position data are processed and analyzed. The measured positions are automatically checked for validity and transmitted to a special tunneling computer in a project engineer's site office. The engineer can thus monitor the data relative to the geometry of the tunnel, such as position of the laser beam relative to the designed tunnel axis, the position of the target unit relative to the machine axis, the required gradients, etc. From these transmitted measurement data, the position coordinates and attitude angles of the machine axis are computed. A computer program automatically compensates for all interactions (e.g., the rotation about the machine axis affects the laser-spot position as it appears on a target screen).

Finally, the computed results are displayed to the operator at the machine controls and to the engineer-surveyor at a convenient remote position in the tunnel or aboveground. The standard display device is a digital monitor unit that continuously shows the deviations of the machine axis from the designed tunnel axis, thereby indicating in a clear numerical form the actual corrections that are required (Zollman 1985).

Geometric Transformation

By using geometric transformation, the location of the center of the shield machine can be defined with respect to its previous and future locations. Basic transformations include translation, scaling, rotation, and mirror image (Chang and Wysk 1985). In tunneling, it is most frequently enough to use only translation and rotation.

Point V representing the center-point vector of the face of the shield machine in the original coordinate system (x,y,z) can be transformed into point V' in a new system (x,y,z) using the following relationship:

$$V' = V \times T \quad (2)$$

Figs. 4 and 5 depict the relations of these movements. In Fig. 4, the advancement of the shield machine is simplified by limiting it to the positive direction of the x-axis. The y-axis coordinate value indicates the horizontal drifting of the current machine center. The z-axis represents the height of the shield-machine center. The tilting of the machine can be expressed by rotation about the y-axis. The rotation of the machine can be expressed by the rotation of the x-axis. The rotation about the z-axis represents the curve direction.

Predictor Feature

A useful feature is the *predictor*, which displays on the monitor the deviation of the machine axis from the designed tunnel axis for several steps ahead at given operating conditions. The predictor ensures a smooth optimized drive of the tunneling machine, and wasteful overcorrecting can be avoided. In addition to a digital monitor, analog monitors, remote monitors, and printer units are also available on a modulus basis. The present and predicted deviations are continuously updated and displayed on the operator's monitor and at the engineer's unit. Every detail of the operation can be followed aboveground on the computer screen and automatically printed out for a permanent record (Zollman 1985). This technology provides a

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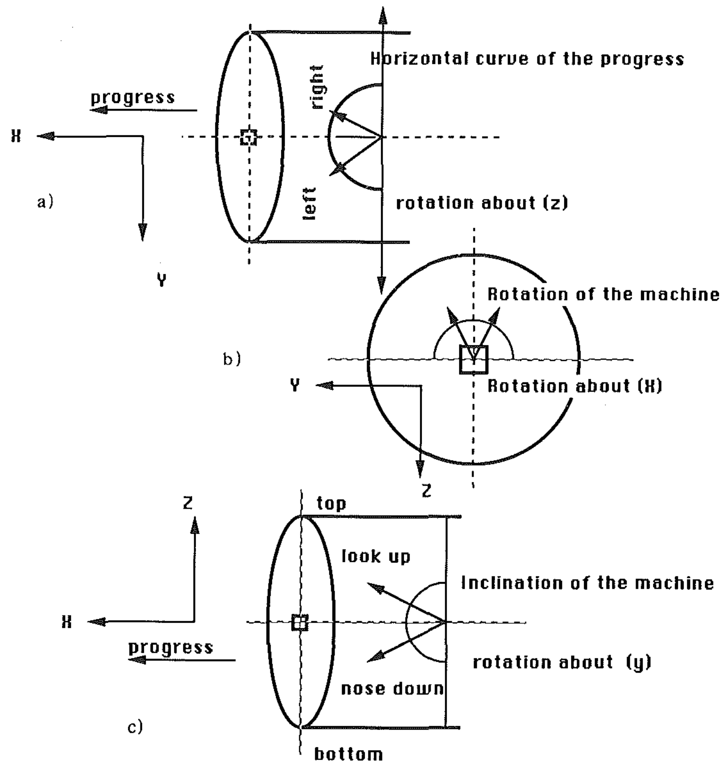


FIG. 4. Coordinate Control System of Shield Machine: (*a*) Plan of Machine Head; (*b*) Section of Machine Head; (*c*) Profile of Machine Head

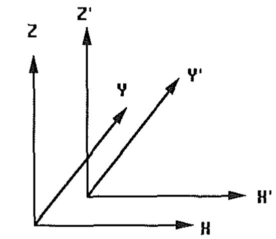
basis for feasible robotic performance of the tunneling process with only minimal feedback required from human operators.

Project Analysis

A sample project is presented next to illustrate possible productivity improvements through the implementation of some construction automation technology concepts for a tunneling process, as just presented.

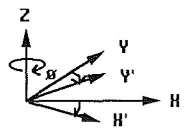
Project Outline

The Sangenya-Chisima No. 2 Sewer Main Project is a part of Osaka's, Japan's second largest city, flood prevention program. A 3.75-m internal diameter, concrete-lined 952-m long tunnel was designed to divert water from the existing No. 1 sewer main, which became overloaded due to the overdevelopment of its basin. The new tunnel axis was designed to make a shortcut to the newly planned wastewater-treatment plant. The new plant was still under construction at the same time as the tunnel. The city's department of sewerage acted as owner, designer, and engineer for the project. The contract was awarded to Obayashi Corporation through a designed competitive bidding process. The project site was located in Taishou-ku, a)



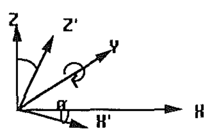
$$T_t = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -T_x & -T_y & -T_z & 1 \end{bmatrix}$$

b)



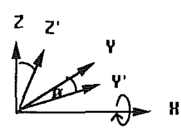
$$T_{rz} = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

c)



$$T_{ry} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ \sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

d)



$$T_{rx} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & \sin\theta & 0 \\ 0 & -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

FIG. 5. Transformation Matrix: (*a*) Translation; (*b*) Rotation about (Z); (*c*) Rotation about (Y); (*d*) Rotation about (X)

Osaka City, the bay area of the Osaka metropolis. The contract term was from October 15, 1983 to March 31, 1986, a duration of 29.5 months. Table 1 lists some basic quantities associated with that project.

Construction-Progress Record

The completion of the entire project took three years. The tunnel excavation was executed as listed in Table 2.

The first two months were devoted to perform the initial excavation. Usually, the first 40–50 m of shield-tunnel excavation are performed along with the installation of backup equipment. Therefore, the productivity at that period was lower than the standard excavation period. In this project, two groups of abandoned wooden piles on the planned tunnel route were encountered in May 1984, as was actually expected from prior site research. Thus, the productivity of the first two months of tunnel excavation was significantly low.

Tunnel progress had been suspended on September 1984 due to an encountered methane gas–contaminated layer. Necessary modifications were

TABLE 1. Sangenya-Chisima No. 2 Sewer Main Project Quantities

Item (1)	Quantity (2)
Outside diameter of shield machine	4,580 mm (15 ft)
Linear length of tunnel	952 m (3,124 ft)
Primary-lining outside-diameter—steel	4,450 mm(14 ft 7 in.)
Primary-lining thickness—steel	150 mm (6 in.)
Length of straight portion	900 mm (35 in.)
Length of curve portion	450 mm (7.5 in.)
Internal diameter of secondary lining of cast-in-place concrete (partially reinforced)	3,750 mm (12 ft 4 in.)
Thickness of secondary lining of cast-in-place concrete (partially reinforced)	200 mm (8 in.)

TABLE 2. Progression Record for Tunnel-Excavation Process

			Working days		Monthly progress (rings)		
Year (1)	Month (2)	Calendar days (3)	Single shift formation (4)	Double shift formation (5)	Straight portion, 900 mm progress per ring (6)	Curved portion, 450 mm progress per ring (7)	Monthly progress (m) (8)
1984	April	8	6	—	3	—	2.7
1984	May	25	20	—	6	85	42.2
1984	June	17	12	3	80	—	72.0
1984	July	31	1	16	112	—	100.8
1984	August	8	—	6	29	50	47.8
1984	September	—	—	—	—	—	—
1984	October	20	—	23	214	38	209.1
1984	November	30	—	23	274	—	246.6
1984	December	25	21	—	134	104	165.6
1985	January	22	17	—	13	106	57.6
1985	February	1	—	1	3	—	2.7
Total	—	196	56	93	868	383	947.1

made to the machine and back-up equipment before restarting the progress in October.

Productivity Analysis

The cycle time of the procedure is measured by the installation time of the primary lining rings. There were two types of rings, i.e., a 900-mm ring for the straight portion and a 450-mm ring for the curved portion. There was no significant difference in the time required to install one set of rings, regardless of their type.

The number of rings installed:

$$(STR) + (CUV) = 868 + 383 = 1{,}251 \text{ (rings)} \quad (3)$$

The number of shifts that performed the excavation and primary lining at the face:

$$(SS) + 2 \times (DS) = 56 + 2 \times 93 = 242 \text{ (shifts)} \quad (4)$$

Since a shift works for eight hours, the total productive hours can be calculated:

$$242 \times 8.0 = 1{,}936 \text{ (hours)} \quad (5)$$

Therefore, the cycle time for installing one ring is:

$$\frac{1{,}936}{1{,}251} = 1.55 \text{ (hours)} = 93 \text{ (min)} \quad (6)$$

The face laborers include one shield-machine operator, three tunnel laborers, and one grouting unit operator, a total of a five-man crew. The back-up unit consists of one mucking car operator, two shaft-gantry crane operators, and one grout-mixer operator, a total of a four-man crew. The total number of workers involved in a shift is thus nine laborers plus one foreman.

The total number man-hours required for the tunnel face work:

$$1{,}936 \times 10 = 19{,}360\ (M\text{-}H) \quad (7)$$

However, excluding machine problems and other delaying factors, the observed cycle time to advance the shield machine for one ring was 60 min. Thus the efficiency factor is:

$$EF = \frac{60}{93} = 0.65 \quad (8)$$

Fig. 6 presents the actual observed cycle time of two major groups of activities; first, those performed at the face of the tunnel, and second, the work cycle of a mucking car traveling between the tunnel face and the shaft. The work cycle time at the tunnel face was stable through most of the

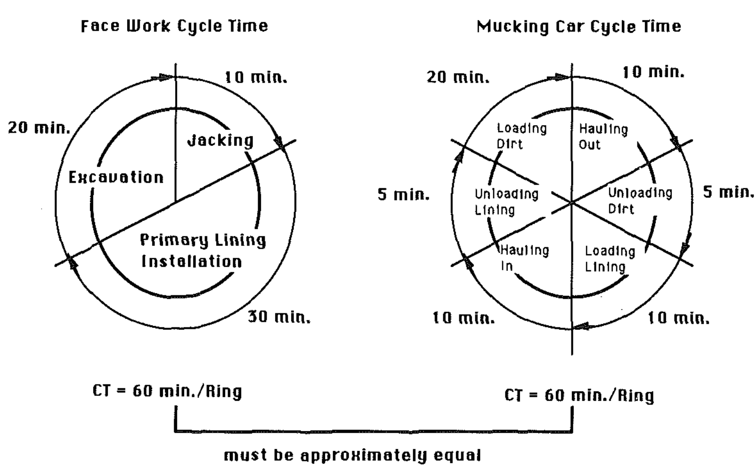


FIG. 6. Typical Cycle Time Observed in Example Tunneling Project

TABLE 3. Average Cycle Time

Activity (1)	CT_m (min) (2)	200 m (3)	400 m (4)	800 m (5)	Standard CT_m (6)
Load muck	t_1	25.0	20.0	20.0	20.0
Haul out	t_2	2.2	7.4	14.8	10.0
Unload muck	t_3	7.5	5.0	5.0	5.0
Load lining	t_4	15.0	10.0	10.0	10.0
Haul in	t_5	2.2	7.4	14.8	10.0
Unload lining	t_6	7.5	5.0	5.0	5.0
Total	CT_m	59.4	54.8	69.6	60.0

excavation period. On the contrary, the mucking-car cycle time gradually became longer as the tunnel face progressed far from the starting shaft. Table 3 summarizes the mucking-car cycle time at 200, 400, and 800 m of tunnel progress.

The hauling time t_2 and t_5 is calculated from (9):

$$t_2 = t_5 = \left(2 \times T_{Acc} + \frac{(L - L')}{V_{\max}}\right) / EF \text{ (min)} \quad (9)$$

From (8), $EF = 0.65$ and from field observation:

$$T_{Acc} = 0.5 \text{ (min)} \quad (10)$$

From safety regulations:

$$V_{\max} = 5\left(\frac{\text{km}}{\text{hr}}\right) = \frac{5 \times 1{,}000}{60} = 83.3\left(\frac{\text{m}}{\text{min}}\right) \quad (11)$$

Therefore:

$$Acc = \frac{V_{\max}}{T_{Acc}} = \frac{83.3}{0.5} = 166.6\left(\frac{\text{m}}{\text{min}^2}\right) \quad (12)$$

and

$$L' = 2 \times Acc \times (T_{Acc})^2 = 2 \times 166.6 \times (0.5)^2 = 83.3 \text{ (m)} \quad (13)$$

Thus, at $L = 200$ (m)

$$t_2 = t_5 = \frac{\left[2 \times 0.5 + \frac{(200 - 83.3)}{83.3}\right]}{0.65} = 2.2 \text{ (min)} \quad (14a)$$

at $L = 400$ (m)

$$t_2 = t_5 = \frac{\left[2 \times 0.5 + \frac{(400 - 83.3)}{83.3}\right]}{0.65} = 7.4 \text{ (min)} \quad (14b)$$

at $L = 800$ (m)

$$t_2 = t_5 = \frac{\left[2 \times 0.5 + \frac{(800 - 83.3)}{83.3}\right]}{0.65} = 14.8 \text{ (min)} \quad \ldots\ldots\ldots\ldots\ldots \quad (14c)$$

As estimated in the preplanning stage of the tunneling operation, the cycle time of the mucking work was 60 min. The cycle-time analysis indicates that it would be useless to implement automated equipment to a particular segment of tunneling operations in a fashion unbalanced with other segments. Thus, it is clear that the introduction of a superpowered shield machine does not directly guarantee the improvement of productivity in shield tunneling. As presented in Fig. 3, the balance of activities between face and shaft is crucial in improving tunneling productivity.

Each component of the cycle procedure has equal potential for improvement. It is important to evaluate the cost involved in the improvement of each segment of these activities and to determine the priority among these activities to actually develop possible improvements. Fig. 6 also indicates the time impact of each activity involved in the progression of tunnel excavation. If an improvement is to be applied to one segment of the total system, it must be well balanced so that the entire link of activities can run smoothly.

It is clear that in order to improve the entire productivity of the tunneling operation, it is necessary to improve the operation as a single organic system. Certain percentage of improvement in excavation process requires the same amount of improvement to the mucking procedure; otherwise the saved time at the face turns into mere idle time waiting for the mucking car coming back from the shaft.

One answer to resolve such problem is the development of a hydraulic mucking system that pumps out the excavated dirt to the surface. This system eliminates the cycle formation of the mucking operation, changing its form to continuous transportation of liquified soil through the piping.

Cleaning Work

Another labor-intensive task to be performed during the progress of the shield machine is the cleaning work of the completed portion of the tunnel. In this project, the backfilling of the void between the tail of the shield machine and the perimeter was important to minimize the settlement of the ground along the tunnel axis. Therefore, the mortar-mix compound material was grouted from the face at high pressure. The only way to confirm the sureness of the grouting was to observe the blow-in of the liquid material from the invert of the shield machine. The excess material had already hardened after a shift finished its work. The cleaning work had to follow after the excavation crew when the back-up equipment had progressed along the dirty section. Usually, for safety purposes, the work took place about 100 m behind the machine.

The cleaning work, however, does not form an observable cycle. It is rather a continuous monotonous work. In this project, the blow-off of excess grouting material was so immense that it was necessary to hire two teams, each having four laborers for the entire excavation period. The cleaning teams were assigned to work parallel to the excavation crew shifts. The total number of shifts for the cleaning work was 150. Thus the man-hours for the cleaning summed up to:

$$150 \text{ (shifts)} \times 8 \text{ (hours)} \times 8 \text{ (men)} = 9{,}600\ (MH) \quad \ldots\ldots\ldots\ldots\ldots (15)$$

This sums up to 50% of the main excavation work man-hour amount. It implies that there is ample potential in cleaning-operation improvement.

Two approaches are possible to improve the cleaning operation. The first method is the direct development of a cleaning robot and the second method is the improvement of the excavating system to minimize the generation of excess waste. According to preliminary estimates performed by the contractor's engineers, among these two approaches to resolve the cleaning problem, the latter method would be less expensive. However, precise measurement of grouting pressure and its real-time feedback to the pumping unit are required to accomplish any improvement.

Expert-System Applicability

An expert-system prototype designed to assist in the tunneling machine type selection and assess potential for work automation has been applied [see Kakoto and Skibniewski (1989)]. The system's utility can be illustrated on the Sangenya-Chisima No. 2 Sewer Main Project, which is being used as an illustration vehicle for issues discussed in this paper. To examine the system's applicability in the machine type selection, two cases of project performance are presented. Case 1 describes the project scenario, ignoring the wooden piles that existed along the planned tunnel axis. Case 2 considers the influence of these obstacles on the route. The data obtained from the project provides input to the system as follows.

1. Expected obstacles on the planned axis of the tunnel: none for case 1, and wooden piles for case 2.
2. Nature of the subsurface condition classified by ASTM D-2487: *SP*, poorly graded sand.
3. Stiffness of the subsurface soil: very loose.
4. Project location: Japan.
5. Length of the project: less than 2 km.
6. Internal diameter of the tunnel: 2–4 m.
7. Type of the primary lining: steel.

In this test run, under the given input conditions, the system has selected the use of an open-face-type shield machine as its first recommendation. However, the system also evaluates recommendations for other excavation methods with the use of certainty factors. Following are the scores for each method in the two site condition cases considered.

Case 1 (Obstacles on Route are Ignored)

1. Excavation methods: open-face ⟨0.82⟩, *EPB* ⟨0.81⟩, slurry shield ⟨0.79⟩.
2. Auxiliary methods: grouting ⟨0.90⟩, freezing ⟨0.55⟩, compressed air ⟨0.10⟩.
3. Driving notations: installation of 8 + 4 = 12 jacks are recommended.

Case 2 (Obstacles on Route are Considered)

1. Excavation methods: open-face ⟨0.96⟩, *EPB* ⟨0.85⟩, slurry shield ⟨0.79⟩.
2. Auxiliary methods: grouting ⟨0.90⟩, freezing ⟨0.55⟩, compressed air ⟨0.10⟩.
3. Driving notations: installation of 8 + 4 = 12 jacks are recommended.

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The test results show that for the Sangenya-Chisima No. 2 Sewer Main Project the best suited was an open-face-type shield machine, even ignoring the wooden piles on the route of planned tunnel axis. When the obstacle on the planned route is taken into account, the open-face-type shield machine is more strongly recommended.

Considering geotechnical aspects of the project, especially the subsurface ground condition classified here as very loose and poorly graded sand, these selections seem correct from an experienced project engineer's perspective. However, at the actual project site, an *EPB* excavation machine was used. The main reason for this apparently incorrect decision was the availability of a less expensive machine on market at the time of project commencement. Although a direct cost comparison between open-face type and *EPB* is difficult, since the price for an open-face-type shield machine for the project cannot be obtained retroactively, it is worthwhile to assess the potential schedule reduction and labor savings should an open-face-type shield machine have been used.

The construction record shows that it took 18 shifts for excavation and advance of the shield machine and for removing 24 wooden piles. The work-schedule breakdown was as follows:

1. Removing soil from the chamber: two shifts. This was necessary because the pile cutting was done manually from the empty chamber opening the front bulkhead of the shield machine.
2. Manual pile cutting, excavation, and advancing through the pile section: 11 shifts.
3. Normal excavation between two pile sections: five shifts.

The total duration of these tasks was 18 shifts, or nine days. In order to accomplish these procedures, intensive grouting was performed from the surface before the machine reached the section.

There are three aspects of the project that could have been improved by the introduction of an open-face shield machine. First, it would not have been necessary to stop the advancement of the machine for two shifts to remove soil from the chamber. Second, it would not have been necessary to confine the laborers into the small chamber to cut the obstacle piles manually. The space in the chamber was large enough for only two workers, thus it took 88 hours, or 11 shifts, to advance through the pile section. Because of the labor contract, the entire 10 men crew was paid for full-time work while eight of them were idle at any time during the work shift. Third, the extra grouting would not have been necessary if open-face shield machine had been used. An approximate estimate of the direct-labor cost saving in the case of an open-face shield machine had been used includes the following items:

1. Direct labor cost saving on soil removal from the chamber:

$$2 \text{ (shifts)} \times 10 \text{ (men)} \times \$150 = \$3{,}000 \qquad (16)$$

2. Direct labor cost saving on manual pile cutting:

$$11 \text{ (shifts)} \times 8 \text{ (men-idle)} \times \$150 = \$13{,}200 \qquad (17)$$

for the total $15,200.

The extra grouting was performed based on the existing lump-sum subcontract for the essential grouting, therefore the potential cost savings due to the elmination of this procedure is difficult to estimate.

The overall contract volume for the entire project was approximately \$14,000,000. The purchase price of the *EPB* machine was approximately \$600,000. Assuming that the cost of an open-face tunneling machine would have been similar, the possible direct labor cost saving due to the application of this type of tunneling equipment can be estimated as:

$$\frac{\$15{,}200}{\$600{,}000} \times 100 = 2.5\% \quad (18)$$

of the cost of the tunneling machine.

Summary and Conclusions

There are three important factors in the use of advanced technology in tunneling operations that can contribute to an overall improvement in work performance in comparison with conventional tunneling methods. All these factors are important for solving currently typical tunneling project problems.

The first factor is related to the improvement in work quality. In particular, the precision of the excavated tunnel axis is essential. Without even a fully automated system, the application of an automatic guidance system for a tunneling machine can improve the construction precision well beyond that of conventional manual surveying methods. Full application of an automatic guidance system can further minimize boring of vertical shafts for surveying purposes only. By implementing a fully effective information loop system to control the excavation equipment, it is expected that the accuracy of the machine location can be controlled with optimum precision, benefiting primarily project cost and schedule.

The second factor is related to construction cost savings, as illustrated in the example project analysis presented in this paper. The cost impact of implementing technologically advanced tunneling equipment can be shown during analysis of such work items as primary lining erection, concrete pouring, and cleaning. By minimizing the need for human labor at the face, along the tunnel, and at the shafts, significant savings can be accrued. An important positive side effect of the minimization of human involvement in tunneling labor is improved safety performance of this work. Savings arising from lower workers' compensation insurance premiums can reach 2% of the construction cost (*Improving* 1983). Considering that the average profit ratio for tunneling construction contracts in Japan is about 15%, a direct impact of 2% savings should not be underestimated as far as contractor's interest is concerned.

Third, technologically advanced tunneling equipment is expected to shorten the construction time compared to conventional manual tunnel excavation methods. The effect of minimizing the human labor is not limited to cost reduction; it can also increase the flexibility in project construction operation times. As a rule, labor cost for night shifts is substantially higher than for day shifts while energy costs, especially electricity, are often cheaper during night hours. Although no quantitative research has been performed in this aspect of cost-savings potential, advanced technology implementation can give the tunneling work operation a greater chance to expand to night work and a 24-hour consecutive operation.

Acknowledgment

Partial support from the National Science Foundation under the Presidential Young Investigator Award No. MSM-8657142 is gratefully acknowledged.

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Appendix II. Notation

The following symbols are used in this paper:

Acc = acceleration;
CUV = curved portion, 450 mm progress per ring;
DS = double shift formation;
EF = efficiency factor;
L = distance from shaft to face;
L' = traveled distance for acceleration and deceleration;
SS = single shift formation;
STR = straight portion, 900 mm progress per ring;
T_{Acc} = time needed to reach maximum speed;
$t_1, \ldots, t_6$ = same as in (1); and
$V_{\max}$ = maximum speed of the electric mucking car.

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