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1976

Monitoring Soft Ground Tunnel Construction

DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

Urban Transportation Tunneling

a handbook of
rational practices
for planners and designers

prepared for
Transportation Systems Center
by
Birger Schmidt
Parsons Brinckerhoff Quade & Douglas, Inc.
New York 10001

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16. Abstract

The objectives of the Urban Mass Transportation Administration (UMTA) Tunneling Program are to lower subway construction costs and reduce construction hazards and damage to the environment. Advances in the practice of technology of construction monitoring of soft ground tunnels and deep excavations can lead to a better control, and in some cases reductions in, transit construction costs. This handbook documents the findings of a recent UMTA construction monitoring instrumentation research project. The handbook is directed to systems managers and planners to show how to incorporate successful monitoring programs in their systems to help control and reduce costs. Recommendations are made for planning and specifying the purchase and installation of instrumentation.

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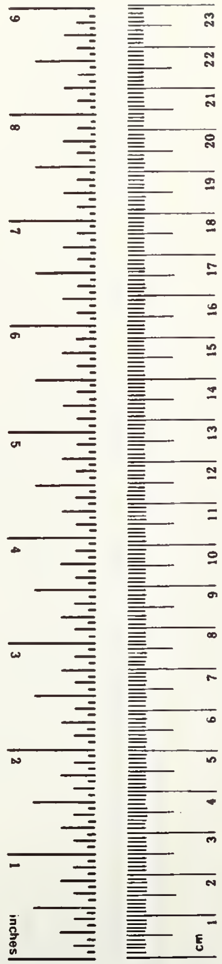
METRIC CONVERSION FACTORS

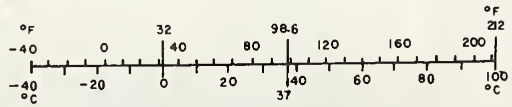
Approximate Conversions to Metric Meesures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	cantimeters	cm
ft	feet	30	centimeters	cm
yd	yerds	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	squere inchas	6.5	square centimeters	cm^2
ft^2	squere feet	0.09	square meters	m^2
yd^2	square yerds	0.8	square meters	m^2
mi^2	square miles	2.6	squara kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teespoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gel	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 321	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	squere inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	querts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius tempereture	9/5 (then add 32)	Fahrenheit tempereture	°F



Contents

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Foreword

"Benefits of monitoring are not automatic – they are managed and engineered."

– The Author

Preamble

Monitoring of tunnel construction and deep excavations can help reduce the construction cost of urban underground facilities. These efforts can also reduce construction hazards and minimize the impact of construction on existing structures and facilities, as well as on city traffic. In the long term, monitoring provides the essential information to improve design and construction methods, as well as methods of predicting and controlling ground movements and settlements, loads and stresses. In the short term, monitoring benefits the project directly by providing the essential means to make intelligent decisions during construction.

Construction Monitoring Defined

Monitoring is the intelligent observation of selected construction activities and effects for specific, identified purposes. It encompasses a number of related activities including measurements and field observations of soil and groundwater behavior and the behavior of structures, and recording of all relevant construction activities. An essential part of monitoring is the interpretation of data and the implementation of the resultant conclusions. Instrumentation is usually, but not always needed, and more often than not the simplest instruments will do the job. What is important is the intelligent planning and execution of monitoring and the conscientious and consistent implementation of its results.

Goals and Address of This Handbook

Although the principal purpose of this Handbook is to encourage and improve the use of monitoring for urban mass transit tunnels, it will also be of use for other types of tunnels and deep excavations. The Handbook is designed to demonstrate the possible and potential benefits of monitoring, and to assist in the planning and design of monitoring programs and systems.

The Handbook is directed to owners (municipalities, states, federal agencies, authorities, etc.) of public transportation systems and other underground conveyances and their system planners and engineers. Consulting and design firms who prepare plans and specifications for underground systems will also benefit. Chief designers, project managers, and specification writers will particularly benefit. It may also be useful to those engineers who execute the final design of the monitoring system, and to those who install and read monitoring instruments and interpret and implement the results.

The Handbook gives guidance to those who make policy decisions, and to those responsible for overall planning, specifications, and contract and insurance arrangements.

Handbook Organization

Those readers interested only in a brief review of the capabilities of monitoring may be satisfied by reading this Foreword and the Overview in Chapter 1. Chapter 2 describes many of the ordinary, and a few of the extraordinary, tunneling and deep excavation problems. This material serves as background for Chapter 3, which presents a treatise on the functions and purposes of monitoring, and includes a systematic approach to implementing a monitoring program.

Chapters 4 and 5 describe in greater detail the immediate and long-term benefits of monitoring. Chapter 6 shows how to select monitoring parameters and instrumentation, and Chapter 7 describes how the monitoring program is implemented through proper distribution of responsibilities, quality control, adequate specifications, and favorable contract arrangements. A Bibliography is included at the end of the Handbook.

Those who make basic decisions regarding monitoring should read at least Chapters 1 through 4; those who implement the decisions through contract documents and into the field should also read the remaining chapters. For convenience a key to the contents of the Handbook is presented on the next page.

Reader Interest					Key to Handbook Contents	
Owner and Planner	Engineer, Designer	Specification Writer	Specialist, Geotechnical & Instrumentation	Field Staff, Contractor	Topic	Chapter/ Section
X	X				Overview: Scope and Potential of Monitoring	Foreword; 1
X	X	X	X	X	Background: Problems of Tunnel Construction	2
X	X				Organization: Contract Relations and Funding	3; 5.2; 6.8; 7
X	X	X	X	X	Methodology: Objectives and Functions	3.3
X	X		X	X	Benefits and Needs: Immediate	4
X					Benefits and Needs: Long-term	5
	X		X		Methodology: Parameter and Hardware Selection	6
	X	X	X	X	Implementation: Responsibilities and Contracts	7.1 to 7.3
	X	X	X	X	Implementation: Specifications and Field Work	7.4 to 7.7

Stages of Tunnel Construction Monitoring

When monitoring is employed, its purposes must be clearly defined at the outset, whether for short- or long-term benefits, and it must be made an integral part of design and construction if it is to serve the immediate needs of the project on which it is used. Procedures for reading and recording, and interpretation and implementation must be carefully prepared during design. Many stages must be considered in a monitoring program:

- Definitions of benefits and purposes of program
- Design and project specifications to draw the full benefits of program
- Selection of monitoring parameters
- Selection of instruments and writing of specifications for procurement and installation
- Procurement and installation
- Observations, reading and maintenance of instruments
- Data storage and retrieval
- Interpretation and implementation

A systematic approach to monitoring includes at least all of these stages; with a deficiency in just one or two of these stages the whole program may falter, and the potential benefits may be lost.

Some of these stages are fairly easy to implement and may use established practices, theories and technologies. The difficult ones are those that require the bending of minds, changes in the way engineers design underground structures in soil, and those that affect the way owners pay for such facilities, and the way construction is managed, inspected, controlled, and insured.

Basic Needs

A study sponsored by the Urban Mass Transportation Administration (UMTA) disclosed that, although the art of instrumentation and monitoring is well advanced, monitoring has not nearly been used to its full potential on tunneling projects. One of the main reasons for this was found to be a lack of general procedures and guidelines, and a general lack of expertise on these subjects among those who make decisions regarding tunnel monitoring. This Handbook was commissioned by UMTA to help overcome these difficulties. Since much of its content has little written precedence in this country, the author realizes that certain ideas and procedures must be tested in actual practice; hence, this Handbook should be termed a "Working Draft." It is hoped that the implementation of procedures suggested in this text will lead to improvements that may be incorporated as revisions to this Handbook.

The Handbook is intended to stimulate discussions beyond the scope of its contents, as well as the development of new ideas and concepts that may benefit from monitoring and the intelligent use of field observations. The Handbook should inspire American engineers to excel in progressive engineering.

A companion handbook or manual, directed to design engineers, specification writers, and instrumentation and monitoring engineers is planned for issue in 1976. This handbook would treat in detail the selection of monitoring hardware, procurement and installation procedures and specifications, and related matters.

1. Overview

Construction monitoring of tunnels and deep excavations is cost-effective when properly applied. With today's state of technology, monitoring is not only possible, it is technically and economically feasible and profitable, and it is a necessary adjunct to many modern construction alternatives. When used in conjunction with appropriate design techniques and construction methods, it affords new opportunities for cost and time savings, and reduction of construction hazards and environmental impact. These premises are briefly examined in the following paragraphs.

Is It Profitable?

For a $30-million subway station and tunnel contract, the design of a monitoring program might cost $15,000 to $40,000; instrumentation might cost $50,000 to $150,000, including installation; and monitoring and implementation perhaps a similar amount. This total amounts to between one-third and one percent of the total cost, or somewhere near ten percent of the design cost, or five percent of the design plus construction supervision cost.

Another comparison is more illustrative: The cost of design and execution of a monitoring program is equivalent to a typical single building underpinning job. If monitoring can eliminate just one underpinning job, or otherwise save just one percent of the total cost, it will have paid its own way.

Is It Possible?

Instrumentation and monitoring technology has reached a stage where virtually any parameter of interest to the tunnel constructor can be measured and monitored. Improvements can be made in instrument accuracy, reliability and cost, but basically the state-of-the-art is mature. Instrumentation know-how is not particularly abundant at this time; however, guidelines, manuals, and experience should improve monitoring planning, instrument selection, and installation. The adversary relationship between owners and contractors has often made it difficult to achieve the full benefits of monitoring, but minor modifications of construction specifications will make these benefits achievable.

Is It Necessary?

As a rule, at least a minimum of monitoring is required. For example, when tunneling through granular soil below the original groundwater table, it is essential to monitor the water table; when tunneling through soil near existing structure, at least ground surface movements (settlements) must be monitored and the existing structures observed.

These measurements and observations are necessary for the safety of the work and for legal protection

Some Basic Considerations:

- Each important underground project warrants the diligent study of possible or potential benefits, either long-term or short-term, that may be derived from construction monitoring or test sections.
- Funding of a meaningful monitoring program should be a matter of course; it should be considered a fully justifiable design or construction cost. When scientific use and development requires additional data not otherwise needed, public funds may be sought.
- When monitoring only for direct benefits, consider also the likelihood that additional or better data will provide benefits for: future extensions of the monitored project, similar projects not yet underway, and increasing the general knowledge of tunneling.
- Data centers and central coordination of research efforts on a local or regional basis, and efforts to disseminate existing or new knowledge, are essential to the future success of underground design and construction projects.

of the owner or the contractor. More than a basic minimal monitoring effort is necessary, however, if monitoring is to save construction costs. For this purpose, monitoring must be structured so as to allow predictions of future ground or tunnel behavior, diagnoses of adverse behavior and, most importantly, action based on monitoring interpretation.

To many engineers, the deliberate use of monitoring in this fashion is unfamiliar or even totally foreign; they have no confidence in it. To these people, we must demonstrate that the concept works.

For this reason, and also for the development of new technology and design techniques, the accumulation of case history data of sufficient breadth and reliability is also necessary. Tunnel construction even more than other types of earthworks, eludes sophisticated theoretical analysis, and the study of empirical data is absolutely necessary for advancing design and technology, and hence, reducing the cost of the next tunnel project.

What's in the Future?

Underground construction today is expensive and often unattractive because of cost and surface disruptions. Technological advancements and improvements in contract arrangements are needed, but improvements don't just happen—they are engineered and managed.

Real technological progress comes with the observation of prototype construction. The daring use of flexibly jointed tunnel liners in London, and massive grouting in lieu of underpinning of landmarks in Paris, could not be executed except through the use of carefully engineered test sections and construction monitoring.

The progressive use of monitoring may allow development of new design and construction concepts that otherwise might not be possible; conversely, the use of new and unproven concepts require diligent monitoring and testing in pilot projects, test sections or prototype construction.

Who Can Make These Concepts Work?

Some changes in philosophy and basic approach are required to achieve the greatest benefit of monitoring. First, the decisionmakers must be made fully aware of the benefits of monitoring and the cost of alternatives, and confidence in the application of the principles must be instilled. The need for monitoring is, of course, quite apparent in most instances, but full benefit is derived only by a conscientious effort on the part of the decisionmakers.

A cost-and-risk analysis carried out by planners or designers should clearly point out to owners and decisionmakers the most probable cost benefits and intangible benefits, as well as the possible risks that may be either eliminated or incurred through properly applied monitoring practices. Such cost-and-risk analyses are often not carried out because owners do not request them and do not include them explicitly in the scope of work for which design is contracted.

Hence, the owners have an obligation to request a certain level of design effort directed toward a definition of the utility of monitoring principles.

But owners are not know-it-alls. The planners and design engineers in negotiating a design contract have the obligation to provide the proper feedback so that appropriate emphasis is placed on minimizing costs through monitoring and associated quality control.

Once the most feasible level of monitoring has been established for a given project, it is the designer's obligation to scope out and develop a complete design incorporating all necessary implements to make the monitoring program work according to intent. Contract documents are very important, and the specification writers play a significant role in this effort. Specialist consultants may be required.

Finally, the contractor's indulgence is desired, and, most importantly, the educated crew of inspecting engineers, the owner's representatives, must vigilantly recover, interpret and act on all pertinent monitoring data.

For continuity and to derive the full benefits through proper feedback, a central coordination group should have responsibility for construction monitoring for an entire transportation system. This is often best done under the auspices of a construction manager cooperating closely with the designers.

To Implement Monitoring:

- Include examination of benefits of monitoring and preparation of monitoring program in planners' and section designers' contracts with owners
- Develop organizational review, coordination, and implementation tools
- Educate engineers and specification writers
- Provide funds commensurate with expected benefits
- Develop confidence in concepts of monitoring
- Do not antagonize the contractor

Fig. 1-1. Settlement of High-Rise Building. Building on the right settled toward a deep excavation, opening the joint between the two buildings. Early detection of settlement, through monitoring, may have provided a means to prevent such an occurrence.

Who Pays and How?

Logically, the agency that stands to benefit, should pay the cost of monitoring. Where monitoring singularly benefits the project itself, clearly the cost should be borne by the owner's project funds. Where monitoring at test sections is exclusively for research, presumably a (public) research fund or grant should pay the cost, including possible costs incurred due to contractor delays or interference. Where monitoring stands to benefit further projects of a particular agency, that agency should fund it. Circumstances are, however, rarely so clear cut, and hopefully all properly executed monitoring programs will benefit all concerned.

It is expected that once monitoring is established as a meaningful, integral and beneficial (for cost, safety, and environmental protection) part of a construction project, its cost will be borne as any other necessary design or construction cost.

2. Problems of Tunneling and Deep Excavations in Soil

2.1. Planning and Design

When monitoring is done essentially for research purposes, the design of a tunnel project is not ordinarily greatly affected by the decision to perform monitoring, and minimal monitoring "for the record" does not greatly influence design decisions.

However, when monitoring is intended to benefit directly the project being monitored, the design and the contract documents must carefully consider not only the mechanical implementation of the monitoring program, but also the design aspects for which benefits are expected to accrue, and the full implementation of the results of monitoring.

Subsequently, details of design and implementation will be examined. This section describes some of the planning and design decisions that will be affected by the decision to utilize directly the benefits of monitoring.

Planning and Design Decisions/Arrangements Which Should Be Considered in order to Draw Direct Short-term Benefits from Monitoring:

- Insurance arrangements
- Distribution of responsibilities by contract
- Underpinning and other protection
- Adjacent property acquisitions and right-of-way negotiations
- Nature of field decisions to be determined
- Minimum requirements of construction methods
- Type of temporary or permanent structure
- Type of ground stabilization
- Types of geotechnical data that must be provided the contractor

Fig. 2-1. Pre-Cast Concrete Tunnel Liner (Opposite Page).

Insurance and Project Responsibility. Wrap-up insurance, by which the owner insures the contractors' work against third-party damage or accidents, is commonly used (e.g. Bay Area Rapid Transit Authority, Washington Metropolitan Area Transit Authority). The decision to employ this type of insurance is in part political, in part economical. It tends to lift some responsibilities away from those who execute the work.

Diagnostic monitoring will often indicate work details that may be improved or work items that may be alternately employed or instituted. Contractors may not be willing to react to such monitoring results without the incentive inherent in full project responsibility. This responsibility extends to the contractor's provision of his own insurance. For this and related reasons wrap-up insurance affects the working climate and the quality of parts of the work, and should affect the type of monitoring and the way it is used.

Acquisition or Protection of Adjacent Property. When little control of construction methods is exercised, directly or indirectly through proper responsibility allocation, and when the contractor's performance is not properly monitored and checked, adjacent structures within the zone of influence must usually be positively protected (by underpinning, grouting, protective walls, or similar) or acquired for demolition or later repair and resale. This is often costly. A combination of controls or incentives coupled with appropriate monitoring affords the possibility of eliminating much underpinning, protection, or acquisition of property.

Selection of Structural Elements. The design of the permanent tunnel structure is often little affected by monitoring decisions, except when temporary structural elements are to be incorporated in the permanent structure. In a bored tunnel, ground conditions and the desire to minimize ground movements could eliminate certain structural schemes from consideration and could also influence the selection of the width of tunnel lining segments, the distance between twin tunnels, or other details. In a deep cut, however, the rigidity of the temporary retaining walls, and their manner of support, may well be dictated by ground movement considerations and the desire to eliminate underpinning of adjacent structures. Often, slurry-trench tremie concrete walls, or other preformed walls selected to minimize ground movements, are incorporated as part of the final structure with significant economic advantage.

Construction Procedures and Field Decisions. The contractor for a bored tunnel spends much time and money in mobilizing tunneling equipment and in setting up his project plant. Construction materials and expendables are ordered early, and once tunneling is underway, it is difficult and costly to make significant changes in the basic construction methodology. It is, therefore, essential that the contractor prepare in advance his construction plant in anticipation of the demands on his work. To do this, he must, in the contract documents and appurtenant geotechnical reports, be given the basic philosophy of design, the expected quality of performance, the nature of any field decisions that may be required, and all appropriate geotechnical data. Equitable pay items and distribution of responsibilities must also be given. Specifications based in part on performance criteria require dependable monitoring of appropriate geotechnical or construction parameters.

For an open cut, or cut-and-cover project, there are greater possibilities for modifying construction details as construction proceeds, and implementation of monitoring results is easier. Nonetheless, the basic performance requirements must be presented to the contractor in the contract documents.

A design and construction process that involves monitoring activity will incur construction costs of a different distribution than a process not including monitoring. Some bid or unit prices or quantities will increase, and some modifications and delays may have to be paid for, while other costs—underpinning, street restoration, utilities retributions, contingencies—vanish or diminish.

Summary. Construction monitoring is not a concept that will, by itself, guarantee a full return on the investment. Monitoring is a required activity resulting from a decision to exercise a certain level of control on the contractor's performance and the results of his work, and is a representation of an adopted design philosophy that must be carried through deliberately. This design philosophy, to be productive and cost effective, must influence and permeate the affected portions of planning, design, construction, and control activities, as well as the contract documents. Monitoring as a part of design and construction should be intended and structured for significant benefit—in the short or the long term—beyond its own cost.

2.2. A Summary of Tunneling Procedures and Problems

Typical Tunneling Procedures (see Figs. 2–1 thru 2–9). Most modern transportation tunneling in

Fig. 2-2. Business End of 10-Foot Robbins Tunneling Machine. Note slant of cutting edge, crown doors for face breasting and excavator.

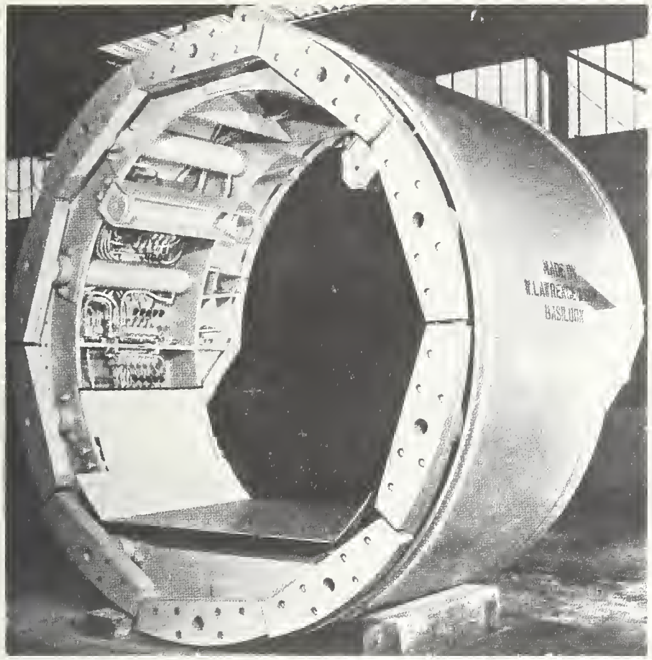
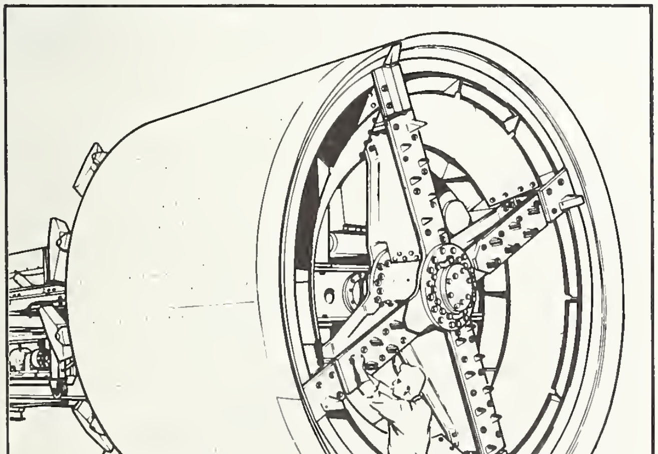


Fig. 2-3. Jack Shoes Form a Ring to Push Against the Erected Lining.

soil employs a shield which is shoved forward by jacking against the erected lining (Fig. 2–3). The shield is a steel cylinder, 12 to 18 feet long, with a vertical or slanted cutting edge in front. The forward end is often hooded, i.e., the leading top (crown) edge overhangs the bottom (invert) front edge to protect workers close to the face and to help in keeping the working face stable in granular soils.

Fig. 2-4. Rotary McAlpine Digger Shield (with Trailing Power Pack) — for Firm Soils.



Soil is excavated from the working face manually or mechanically, for example by clay spades, by a large articulated pick and hoe combination (Fig. 2-2), or by rotating (Fig. 2–4) or oscillating arms (Fig. 2–5) provided with cutting teeth or blades. Muck is removed by conveyor belts and/or muck cars, or by other means.

The face may be open (Fig. 2-6), or it may be partly or fully supported by breast boards jacked against the face (Fig. 2-2) or other similar means. Alternatively, the rotating or oscillating digger may be virtually closed to provide face support (Fig. 2-7), and the individual arms or blades may be tilted to allow muck to enter the tunnel in carefully controlled quantities as the digger wheel rotates. Face support may also be provided by pressurizing the entire tunnel with compressed air, or, in some unique tunnel machines, by placing only the isolated face under air, water or slurry pressure (Fig. 2-8).

Typically, the tunnel lining consists of a number of prefabricated segments of steel, cast iron, or concrete, erected and bolted together to form a ring inside the tail of the shield (Figs. 2-1 and 2-9). As the shield is then shoved forward by jacking against the last erected ring, a void is left between the lining and the soil. The thickness of this void is theoretically equal to the sum of the clearance between ring and tail, and the shield tail thickness. The lining may also consist of steel rings or ribs with an H-shaped cross section, with timber or steel lagging between rings. This is later followed by a permanent concrete lining. It is sometimes possible to expand a lining directly against the soil behind the tail, if the soil stand-up time is adequate. Under those circumstances, the lining is often

Fig. 2-5. Caldweld "Windshield Wiper" Digger Shield with Four Oscillating Sets of Spokes. Digger operates with a virtually sealed face in poor soil.

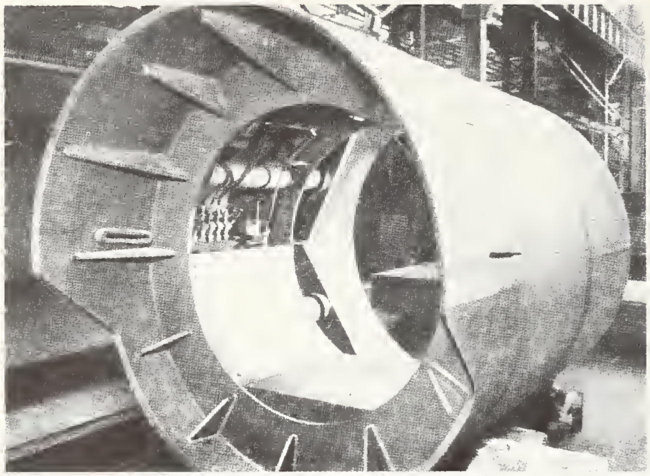


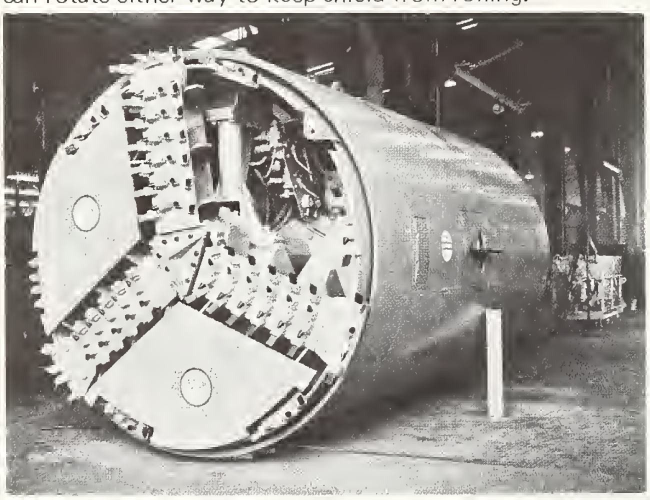
Fig. 2-6. Hooded 8-Foot Lawrence Shield. Note reinforcement of shield front. Shield is 9 feet long and is advanced by six 40-ton jacks.

left unbolted, and flexible joints are emplaced

The void usually left behind the lining must be filled, often in two stages, with pea gravel or sand followed by cement grout, or by grout alone, to prevent soil from entering the void. Sometimes, an additional stage of grouting is performed with higher grouting pressure, to ensure complete filling of all voids. The first stage of grouting can only employ relatively low grouting pressures; otherwise grout will enter the shield through the clearance between the lining and the shield tail. This clearance is notoriously difficult to seal against high pressures. In very soft squeezing or flowing ground, it may not be possible to fill the void before the soil flows in.

Settlements and Ground Movements Due to Tunneling. Ground movements depend on soil and groundwater conditions, tunnel geometry, the contractor's general procedures, details of tunneling equipment and methods, and the care with which the tunnel is built. When ground conditions are predictable and the contractor has the proper (pecuniary) incentives, ground movements can be reduced to the level of insignificance. When this incentive does not exist and when ground conditions are unpredictable, ground movements can be very large, to the point of tunnel face collapse and daylighting.

Fig. 2-7. Caldweld Rotary Digger with Closed Face. Digger can rotate either way to keep shield from rolling.



Soil moves toward the tunnel opening from above and laterally through the tunnel face, and into the tail void space (Fig. 2-10). Soil movements are also generated by the shoving of the shield whenever the shield axis and the tunnel axis do not exactly coincide. Water flows may also carry soil particles into the tunnel and, finally, the change of the soil stress conditions around the tunnel brings about elastic or elasto-plastic strains and displacements.

Soil movements caused by singular incidents or effects tend to appear abrupt when observed at or near the tunnel. The disturbance spreads as it moves up toward the ground surface and results in fairly widespread subsidence effects. For this reason, observations at or just above the tunnel (lower curve on Fig. 2–10) are much more useful for diagnostic purposes than surface settlement observations.

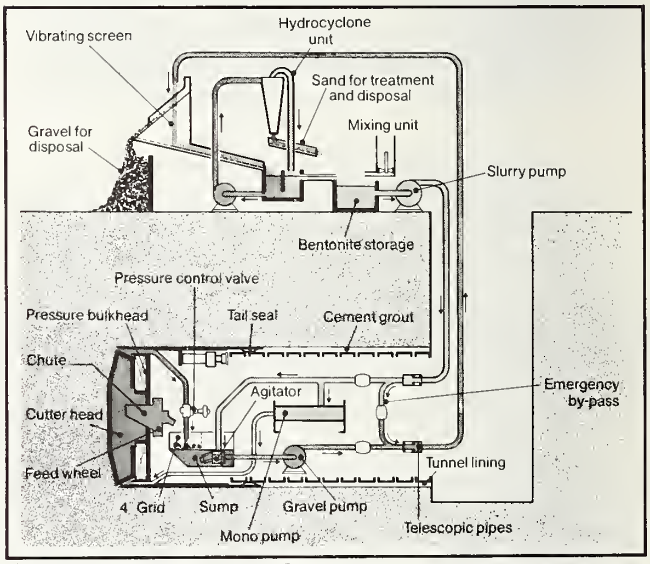


Fig. 2-8. Bentonite Under Pressure Keeps Tunnel Face Stable Without Compressed Air in Tunnel.

Settlements and horizontal displacement at and below the ground surface and stresses and strains, are all roughly proportional to the amount of soil lost during tunnel construction. This quantity of lost ground, defined as the difference between the amount of soil excavated and the theoretical tunnel volume, either as a volume per foot of tunnel or as a percentage of the theoretical tunnel volume (generally based on the outside dimensions of the shield), is unfortunately quite unpredictable.

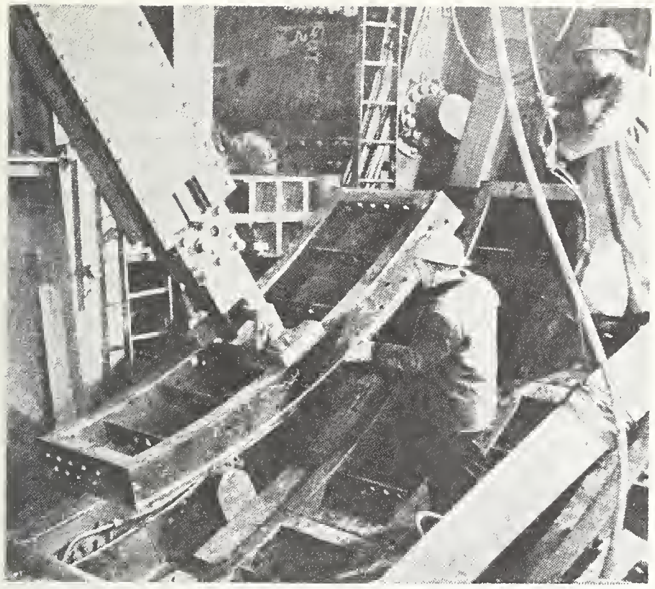
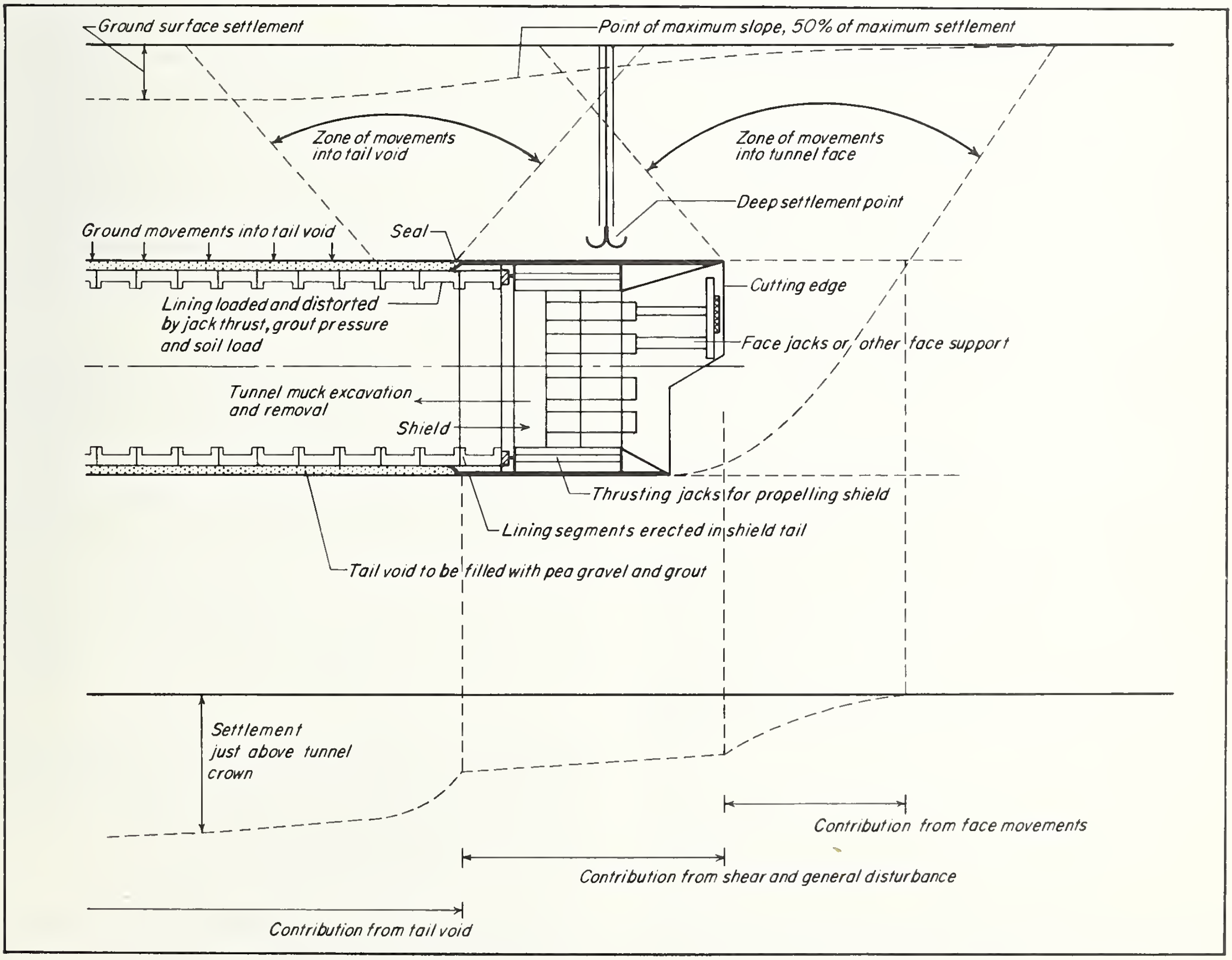


Fig. 2-9. Erector Arm Positioning 1,500-Pound Steel Ring Segment.

- *Ground Loss Due to Tail Void Encroachment.* This is often the most significant ground loss contribution. Under the assumption that the entire tail void is filled with soil collapsing into the void, an upper limit of the ground loss can be calculated. For an 18-foot diameter, shield-driven tunnel with a 3-inch tail void, the upper limit would be 5.6 percent. Even in the worst instance, however, the encroachment is usually not complete. Stability of the tail void is a particularly severe problem in cohesionless sands, where at least the upper half of the tail void may collapse, and in squeezing clay, where the entire tail void may be filled. The tail void loss evidently depends on the stand-up time of the soil, the maximum span of soil exposed in the tail void, and the measures employed to counteract the ground loss (compressed air, rapid grout application, etc.).

- *Tunnel on a Curve.* Whenever a shield negotiates a curve, overcutting occurs on one side, and compres-

Fig. 2-10. Ground Movements During Shield Tunneling.



sion of the soil occurs on the other side. This leads to an increased tail void thickness and adds to the possible tail void loss. While the tail void loss is controllable to an extent, the curvature loss is much less controllable because the added void space is first exposed behind the shield, and the soil may settle onto the shield before grouting or other measures are provided. The maximum possible ground loss in this instance can be estimated on a purely geometrical basis. With a 12-foot-long shield, 18-foot-diameter shield, an 800-foot curve could generate an additional ground loss of 0.15 percent.

- *Yaw.* Usually, it is not possible to drive the shield perfectly parallel to the theoretical tunnel axis. Irregularities in the resistance of the soil to the shield cutting edge and irregularities in the applied jack pressures will make the shield wiggle on its course in a yawing fashion. The mechanism of the resulting ground loss is similar to that of the curvature loss, but the magnitude of the loss evidently will vary greatly with soil conditions, shield details, and operator's skills.

- *Plowing.* Considerably more important in many instances is the plowing action that results from having to steer the shield at a greater or lesser inclination than the theoretical tunnel axis inclination, either because of an unfavorable weight distribution in the shield or other shield details, or because of differential soil resistance. A pitch difference of 1.0 percent is not uncommon; Hansmire and Cording (1972) report an upward differential pitch of up to 3.0 percent. This could result in a ground loss of 3.0 percent if the shield is as long as it is tall.

- *Forepoling Plates.* Where forepoling plates or other devices are attached outside the shield, they leave behind a void that cannot usually be grouted at once. There is, therefore, a possibility of significant ground loss, a loss whose maximum limit can be estimated from shield geometry details. In the case examined by Hansmire and Cording (1972), the ground loss due to forepoling plates was about 1.0 percent.

- *Bead or Relieving Bar.* In dense or hard ground it is common to use a cutting edge of slightly larger diameter than the shield itself. This protrusion has many names (bead, relieving bar) and its purposes are to reduce soil friction against the shield skin and to facilitate steering. Where the curvature of the tunnel is only in the horizontal (or vertical) direction, the relieving bar may be placed in elliptical fashion, only on the sides (or crown and invert). Where soils are loose and cohesionless, or very soft, they will fill the void behind the relieving bar, which would then serve no purpose. The relieving bar adds a small amount to the tail void and the possible ground loss.

- *Face Losses.* A variety of factors may lead to excessive face losses. In most instances, where the face is kept stable, the ground loss through the face is quite small. In cohesive sands or sands kept stable by other means, and in stiff or hard clays, the loss is usually considerably less than 1.0 percent. In softer clays, on the other hand, face losses are often significant and are a function of the ratio of overburden pressure to soil strength. The most severe ground losses through the face are those caused by running or especially flowing soil, types of instability that the contractor usually attempts to prevent but that may nonetheless occur. Other types of face ground loss occur when it becomes necessary to manually remove boulders ahead of the cutting edge, or when a cutting wheel works at an excessively low jacking pressure.

- *Delayed Ground Losses.* Depending on the type of ground and type of lining, certain other types of ground loss can occur. Losses due to lining deflection usually are small, but may be significant where ribs and lagging are used. Delayed losses may occur due to either reconsolidation of disturbed cohesive soils around the tunnel or collapse of voids inadvertently left open.

Estimating Ground Losses. When an estimate of ground losses has to be made, it is convenient to separate the estimate into three items:

- *Category 1 Losses.* Those that must be considered unavoidable under the given soil conditions and with the inherent capabilities of a selected construction method: elastic movements due to changes of stresses in the soil, nominal face losses, a percentage of the maximum possible tail void and curvature losses, and a contingency.

- *Category 2 Losses.* Category 2 movements are those that result from locally improper but controllable selection of construction details. These movements may be considered extraordinary, yet they may be expected to occur on several occasions during a project. Examples are: too low air pressure, too late application of grout filling of the tail void, overexcavation beyond the leading edge of the shield, etc. Other ground movements in this category are caused by local soil weaknesses that result in minor runs or flows or squeezing of soil into the face or the tail void, or excessive yaw or plowing.

While the Category 1 ground movements are relatively uniform with reasonably constant soil conditions, those of the second category are localized; they constitute the peaks of normally observed settlements. These peaks are, in general, considered normal but to a certain extent are avoidable.

- *Category 3 Losses.* Ground movements of the third category are those associated with major or catastrophic ground loss, primarily through the face. Most often these movements are caused by the unanticipated encounter of a permeable soil of low cohesion, that is water logged with a substantial head and reservoir of water. Less commonly, major ground loss is caused by unanticipated weaknesses in the soil (local loss of cohesion in otherwise cohesive soils, abnormally low strength of clay) or by gross misjudgment of the soil character. These gross ground movements may be widespread, or may "chimney" directly to the surface. Such movements are sometimes extremely hazardous and costly and are always greater than anticipated.

Estimating Likelihood of Ground Loss Occurrence. In addition to these estimates of ground losses, it is usually necessary to estimate the likelihood of their occurrence, with ground losses greater than or equal to Category 1 losses having a probability of one. The probability of incurring Category 2 losses in a given location or region, where an existing structure is under study, depends on the estimated frequency of their occurrence and the size of the region considered. This probability must be calculated with careful consideration of the structure under examination. The probability of experiencing Category 3 settlements must be assessed on the basis of the quality and quantity of available geotechnical data and general experience records. These estimated magnitudes and probablilities will permit informed decisionmaking regarding underpinning and other protection, and monitoring requirements.

Settlement Distribution. The loss of ground generates vertical and horizontal ground movements which reach the ground surface to form a trough roughly parallel to the tunnel axis. When the ground loss is evenly distributed over the width of the tunnel and the subsiding soil mass does not significantly change in volume, the shape of the settlement trough is similar to the Gaussian error function (Fig. 2–11). and the width of the trough can be estimated from the equation, $i/a = (z_0/2a)^{0.8}$, where i is the width parameter (the standard deviation of the error function) and $z_0/2a$ is the ratio of centerline depth to tunnel or shield diameter. This is illustrated in Fig. 2–12. Examples of actual settlement measurements are shown in Section 6.2.

Subsidence trough widths from tunnels in granular soil often deviate from the equation, for a number of reasons. For example, ground losses resulting from soil-water flows are often widespread horizontally, especially if soils above are stratified and cohesive, and the settlement trough can become wide. On the other hand, ravelling or running concentrated in the upper part of the face, or over the center of the tail void, tend to result in quite narrow troughs. A densification of a loose subsiding soil volume will increase the settlements and widen the trough, while a loosening will do the opposite.

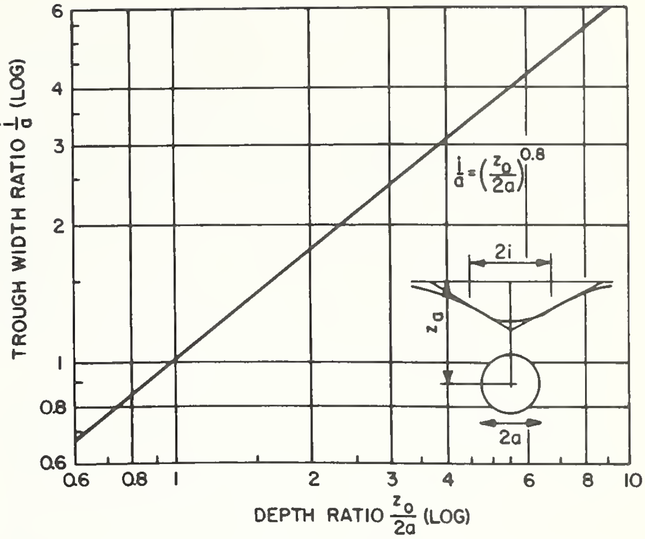
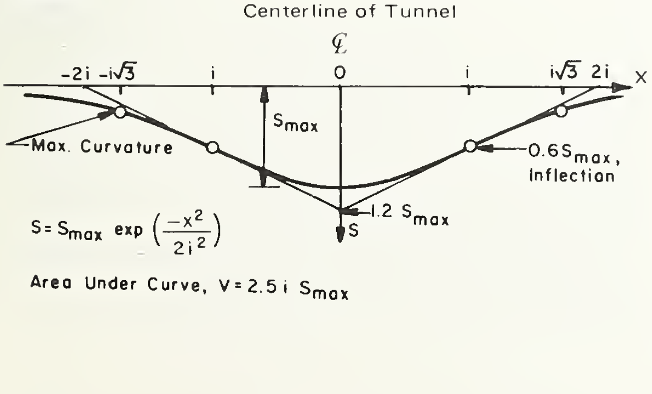


Fig. 2-12. Width of Settlement Trough – Empirical Data from Construction Monitoring Case Histories – Tunnels in Cohesive Soils

Fig. 2-11. Theoretical Shape of Settlement Trough Across Tunnel.



"It is astonishing to many inexperienced engineers, the first time they meet the phenomenon, how far the influence of bad or unsafe construction methods can extend from the source of the operation, e.g. many contractors will attempt to dig in find sand below water – convinced that they can 'bull it through.' They can't. And cracking of any building within a radius of 100 yds or more can rightly be attributed to their operations."

– H. Q. Golder, 1971

Problems of Groundwater. More tunneling problems and hazards are associated with the occurrences of groundwater than with any other single factor. Without groundwater control, otherwise manageable ground can become unstable, resulting in soil and water flows that in the extreme could bury the tunneling equipment. The gradients of water flowing toward the tunnel opening may weaken granular soils to the point where quicksand conditions occur. When an aquifer, a permeable lens or stratum filled with water, is opened up by the tunnel excavation, a sudden inflow of water may carry large quantities of soil into the tunnel. A chimney may be created to the ground surface or, if stronger cohesive soils exist above, large horizontal soil flows may occur, resulting in widespread settlements or local collapse depending on the geological conditions.

These occurrences of instability, even if not as catastrophic as indicated above, cause substantial delays in tunneling and a considerable risk to the tunnel workers. The associated ground movements can have serious effects on overlying and adjacent utilities and structures, and be a significant hazard to surface traffic.

For these reasons, tunneling below the groundwater table in granular soils or soils with aquifers must usually employ measures of groundwater control such as pre-construction dewatering, compressed air in the tunnel balancing the water pressure, or combinations, or on occasions grouting or freezing. Monitoring of groundwater pressures is employed to ascertain the need for, and the adequacy of, such control measures.

Stresses and Strains in Tunnel Liners. When a liner ring is erected in the shield tail, it is subjected only to loads from its own weight, yet it usually experiences a slight squat due in part to play in the joints. The first significant stresses come from the shield propulsion jacks. These may be more severe than any other stresses the lining will ever experience. As the shield moves forward, the lining emerges into the tail void, and the loading of the liner depends on the soil stability, the time of exposure before filling of the void, and the pressure of the grout filling. If a later secondary grouting is performed, the loading changes again. Since grouting is never performed uniformly, the loading of the lining is quite irregular. In very weak soils, the load will quickly approach a condition of relatively uniform radial pressures, approximately equal to the overburden pressure. In stiff, cohesive soils, long term reconsolidation will eventually (after months or years) also lead to relatively uniform radial loads often approximating the overburden pressure. At some depth in granular soils, the load may be somewhat smaller than the overburden pressure, controlled by construction procedures and arching of the soils above the tunnel. Load changes also take place when air pressure is returned to normal in a compressed air tunnel, or when the groundwater rises again after dewatering.

Each load change brings about changes in compressive lining stresses and in the moment distribution. However, except in occasional instances where large voids or other irregularities have been left behind the lining to produce large unbalanced loads, overstressing due to excessive moments is highly unusual. An aging process takes place in cohesive soils which causes distortion of the lining (vertical diameter decreases, horizontal diameter increases). However, except for unusual external influences, linings in granular soils generally retain their shape.

Loads and stresses in tunnel linings are often hard to measure; it is easier to monitor the accompanying distortions. Monitoring is frequently required to verify that the lining is not overloaded and that it stays within tolerances. Typical actual measurements are shown in Section 6.4.

One external influence is of significance: the driving of an adjacent tunnel. This is particularly important since most rapid transit tunnels are driven in pairs. When the two tunnels are closer than one-half to one diameter clear, the driving of the second tunnel increases the load on top of the first tunnel and at the same time removes horizontal support. Sometimes, for this reason, the first tunnel is temporarily supported with braces or tierods. Monitoring of tunnel distortions is required to determine the need for such temporary supports.

2.3. Shafts and Cut-and-Cover Construction

Open excavations produce ground movements somewhat similar to those produced by tunneling. While a reduction of settlements due to tunneling is often difficult and uncertain, there are many options available for reducing ground movements produced by open excavations. Loads and stresses in the supporting structural members in an open cut are more significant than those in tunnel liners.

One method of excavation (Fig. 2–13) begins with the installation of soldier piles (H-piles driven or placed in pre-bored holes to a depth below the excavation floor or socketed into rock). Utilities crossing the line of the soldier piles are usually exposed and relocated as needed before the placement of the piles. As excavation proceeds, timber lagging is placed between the soldiers to retain the earth, and when excavation has reached a point beneath the level for the first strut, walers and struts or anchors are placed. These supports may be prestressed to minimize ground movements. Before they can be placed, however, the cantilevered wall will move toward the opening. This movement is associated with a relaxation of the original soil pressures on the back, and ground settlements. The movement is generally unavoidable but can be minimzied by: (1) using very stiff soldier piles or a heavy, slurry-trench tremie concrete wall, (2) placing the first support very high, and (3) prestressing. The primary functions of prestressing are to eliminate the play in the connections and to eliminate the movements caused by elastic shortening of the strut.

As excavation proceeds to below the next level of supports, additional stress redistributions occur on

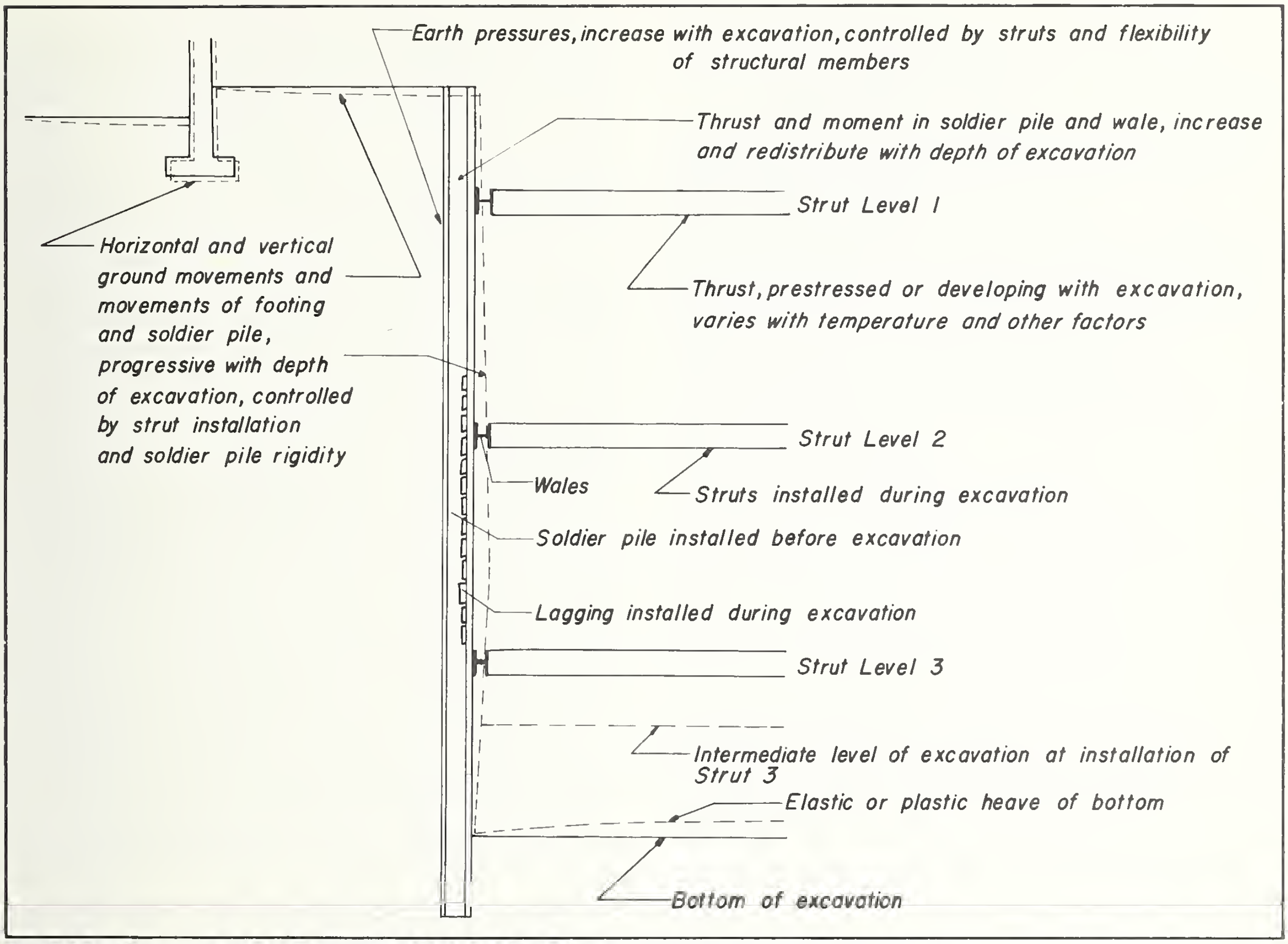


Fig. 2-13. Processes in Cut Excavation With Soldier Piles.

the back of the wall, before these struts can be placed. The piles tend to bend inward, but are restrained by the upper strut and the earth below. Vertical and horizontal ground movements occur, moments develop in the soldier piles and walers, and the strut load changes. A prestressing of the lower strut will change loads and stresses throughout, but cannot generally be counted on to reverse movements that have already occurred. Excavation below the second strut will repeat these processes at a deeper level. The horizontal extent of movements increases with the depth of excavation.

The bottom of the excavation tends to heave slightly due to the removal of overburden. In competent soils this rebound heave is elastic and nominal; in cohesive soils, the heave may be subject to a time delay. In softer cohesive soils, where the ratio of overburden pressure to shear strength is high, plastic displacements occur, and there is a risk of plastic bottom failure for very high overburden/strength ratios. These bottom heaves contribute to settlements behind the wall.

If the groundwater level is not lowered, waterflow through the timber lagging may erode the soil, leaving local voids and contributing to settlements. Without groundwater control, there is a risk of creating quicksand conditions, boils, or similar problems as the bottom of the excavation proceeds below the groundwater table. The factors controlling these effects are similar to those controlling face stability in tunnels. The groundwater level is usually drawn down by dewatering, unless soft strata exist in the environment which would compress intolerably due to dewatering.

A watertight wall, consisting for example of steel sheets or a slurry wall, is often employed where extensive dewatering cannot be performed. These walls must, of course, be designed to withstand the water pressure. Where settlements cannot be tolerated close to the wall, a rigid slurry-trench tremie concrete wall is often used.

It is often economically advantageous to eliminate cross-lot bracing, thereby allowing much easier access and more working room within the excavation. Instead of struts, earth or rock anchors are used. Interaction with the wall and the soil is then similar to that of the struts, except that the supporting force is inclined, and the support is generated by stressing soil materials in the anchor zone, far behind the wall.

2.4. Safety Hazards

"In the present state of technique, adequately planned field observations can be expected to reduce the risk of accident by surprise to a small fraction of the risk in former days."

– Terzaghi & Peck, 1967

A study of accident statistics for heavy construction and tunneling shows that more than 80 percent of all accidents are due to errors in judgment or carelessness, rather than to adverse conditions. In tunnels, a large proportion of accidents is associated with muck handling. In deep excavations, a large proportion is due to materials handling. Accidents caused by adverse geotechnical conditions, however, are frequently severe and costly, primarily because they are often associated with severe construction delays.

In soil tunnels, the most frequent accidents generated by adverse or unsafe conditions are associated with face and roof instability. Such accidents include those caused by boulders or blocks of soil falling from a temporarily unsupported roof or the upper part of the face. The severity and occurrence rate of these incidents increase with the tunnel diameter. The risk is significantly increased when it is necessary to work manually in front of the excavator, in particular when excavation in front of the protective shield is required. For example, this may be necessary to remove boulders or other obstructions (piles, rubble, etc.) that cannot be handled by the excavator and mucking equipment.

Face instability due to excessive hydrostatic head or groundwater flow is quite common, but fortunately in most instances is not dangerous to the workers. However, if a severe face blow does occur, the consequences can be severe. On infrequent occasions, a face blow can inundate and bury the entire tunnel excavator and shield and several hundred feet of tunnel or more in a matter of minutes; the hazard to tunnel workers is obvious. To guard against instability caused by groundwater, a monitoring program of the water table and the dewatering process and related observations must be maintained.

Whenever face instability results in major ground loss, there is a possibility of burial of equipment and workers, but other effects are also severe. Utilities above may, and frequently will, rupture, resulting in various communication losses. The rupture of water, sewer or gas lines severely aggravates the problem. Chimneying to the ground surface creates a severe hazard to surface traffic, and widespread settlements associated with major ground loss may severely impair existing structures within the zone of influence. Although major and catastrophic face or roof instability, ground loss, or face collapse are relatively rare occurrences, whenever they do occur they are extremely hazardous and costly for the tunnel workers and the tunneling operation, as well as for the surface and subsurface environment.

Another relatively rare type of accident is explosion due to accumulation of natural gas, or utility gas from leading or ruptured gas mains. The most recent severe gas explosion accidents occurred in a sewer tunnel under Lake Erie at Port Huron (Michigan) and in a water tunnel at Sylmar (California), where 39 tunnel workers lost their lives. Another occurred in a 9-foot sewer tunnel in Green Bay, Wisconsin where a methane gas explosion reportedly trapped four workers. Such accidents, though rare, are extremely costly. The occurrence of natural gas is geologically determined, and usually local experience will indicate the likelihood or risk of encountering gas. Gas is potentially more hazardous in tunnels that are unlined or lined with pervious liners than in tunnels lined with tight segments; hence, they are more hazardous in rock than in most soil tunnels, where the gas can only enter at the face. In a compressed-air-filled tunnel, the air overpressure tends to displace the gas away from the tunnel. It is often prudent to monitor the presence of gasses in tunnels using automatic devices.

In braced, open cuts, severe accidents are occasionally caused by boulders or soil falling out of the excavation wall, or by bottom instability. The occasions are rare, but such incidents can be bothersome and cause significant delays. More often, severe accidents are caused by buckling of struts, pull-out of anchors or kick-in of the toe of the wall. There is almost always an inherent risk built into the support system of an open excavation. Struts are loaded in compression, and buckling failure caused by excessive strut loads may occur with little or no warning. Moreover, the system is without redundancy; if one strut buckles, or one earth anchor snaps, loads are distributed to adjacent members that are not usually capable of carrying these extra loads. The failure is, therefore, often progressive, and an entire wall can collapse if just one strut or anchor fails.

Excessive strut loads are sometimes caused by faulty design or overly optimistic earth pressure assumptions, but just as often are caused by the buildup of water pressures that exceed design parameters. Kick-out of the toe of the wall may be caused by insufficient embedment of the wall below the excavation, in conjunction with a long vertical lower span of the wall. This is usually the result of careless design. On occasions, toe kick-out is caused by a loss of available passive pressure against the toe, due for example to upward water gradients (quicksand-like conditions). A relatively common kick-out failure occurs when a wall socketed into rock above the excavation floor is not properly tied back. The rock cannot usually be counted on to provide holdback or end bearing in this situation without assistance from rock anchors or similar means.

2.5. Effects of Settlements on Existing Structures

"....... for most structures, deformation is a more important concept than settlement."

– H. Q. Golder, 1971

Fig. 2-14. Settlement Trough is Revealed by Shadow Across Center of Photo.

Settlements and horizontal displacements caused by tunneling and deep excavations are generally unavoidable, but can be minimized by proper construction procedures and care during construction. Typical surface expressions of underground construction are shown in Figs. 2–14 through 2–18. The ground movements can be classified in three categories of increasing severity in accordance with their general magnitude and their basic causes (see Estimating Ground Losses).

During the design process for an urban tunnel, the designer must estimate the likely settlements along the tunnel centerline, and the likely range of discernible or significant settlements, considering first the settlements of the first category. To do this, the designer must know the pertinent soil conditions and anticipate the contractor's procedures. On the same basis, an estimate must be made of the magnitude of the second category, peak settlements and their likely frequency. Considerable experience is required for such estimates, and recorded case histories resulting from intelligent construction monitoring form the most valuable source of experience data. Settlements of the third category are generally to be avoided, but the designer must assess the risk of experiencing such extraordinary settlements and weigh the possible con-

Fig. 2-15. Cracks and Sidewalk Settlement Caused by Tunneling.

Typical Construction Effects:

- Tilting of buildings
- Shear of buildings, causing architectural or structural distress
- Bending of buildings, causing architectural or structural distress
- Vibration settlement and associated damage
- Dust nuisance
- Noise and vibration nuisance
- Accidents by construction equipment
- Dislocation or disruption of utilities
- Drop of groundwater table
- Traffic disruption

sequences against the cost of fully insuring against such risks.

Structures and utilities directly above the tunnel are subjected to several types of distress during the process of tunneling. Utilities that are roughly parallel to the tunnel are first subjected to extension, beginning several tens of feet in front of the shield's leading edge; then, as the shield moves by, to recompression, as the soil settles. With uniform longitudinal settlements, the utility eventually is unstressed, but moved vertically downward. An additional lateral movement occurs when the utility is off the centerline of the tunnel.

In the same situation, a building structure is also affected by the longitudinal curvature of the settlement profile. A building of appreciable length along the centerline will first tend to split open at the top as it rides the hump of the settlement profile, but soon after, the tendency will be to close such cracks. The building will finally become essentially unstressed but settled. The extent to which a building or utility withstands such massaging depends on the relative size of the structure, its flexibility and ductility, and its strength in shear and horizontal tension.

Utilities running across the tunnel are subjected to permanent extension along the flanks of the settlement trough, and compression over the center of the tunnel. In addition, a permanent sag occurs following the settlement trough profile, as well as possibly some temporary or permanent lateral movements.

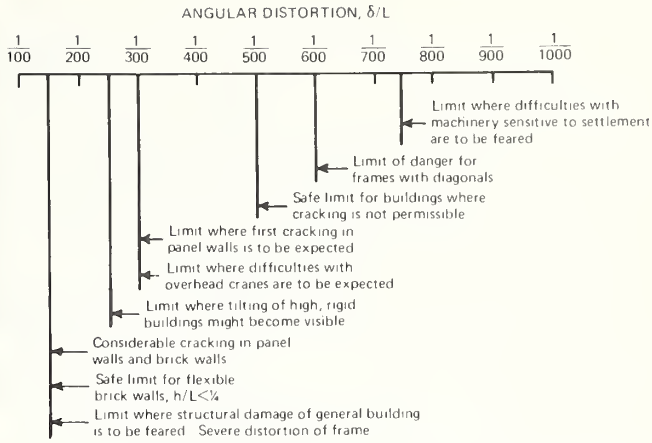
Building structures are typically located a short distance away from the tunnel right-of-way, as when a rapid transit tunnel follows the center of a street. Such buildings will settle in front, stretch, and frequently be subject to extension at the top, when they are located on the flank of the settlement trough. The rear of such buildings tends to remain immobile. These buildings are also usually subjected to shear stresses and displacements, particularly when they are tied together so that extension at the top does not occur.

Most buildings can withstand a good deal of strain without structural damage, or even without noticeable cracks. The sensitivity of different types of buildings to differential settlements and curvature of settlement profile has been the subject of several analyses, primarily based on empirical data (see MacDonald, 1956; Feld, 1965; D'Appolonia, 1971; Grant et al, 1974). The box on the following page delineates the important factors to consider, and damage criteria are indicated in Fig. 2–19.

Fig. 2-16. Typical Ground Surface Cracking and Distortion Caused by Adjacent Excavation.

Fig. 2-17. Sidewalk Settling Away From Buildings on Piers or Piles.

Fig. 2-18. **Another Example of Settlement Effects**



From Skempton and MacDonald (1956) and Bjerrum (1963)

Fig. 2-19. Damage Criteria for Settlement of Buildings Under Their Own Weight. L = building length; δ = differential settlement

Behind a retaining wall for an open excavation, the soil movements have quite similar effects. The settlement profile behind a retaining wall is generally less curved than that over a tunnel. Consequently, any buildings in the zone of influence are subjected to differential settlements, stretch and shear, rather than curvature.

Even if a structure rests on deep foundations (piles or piers), it may suffer deleterious effects due to ground movements. Settlements of the soil surrounding the deep foundations generate downdrag forces that may cause settlements of the structure. Most deep foundations are vertical and offer little resistance to horizontal displacements. Buildings on piles can, therefore, suffer damage due to horizontal extension even if they do not settle appreciably.

Based on settlement analyses and estimates, assessments of the settlement's effect on structures, utilities and other environmental effects, and risk analyses, the designer can optimize a tunnel design to include the most cost-effective combination of positive environmental protection and measures to minimize settlements and hazards. Positive protection against deleterious effects may include underpinning, protective walls or soil stabilization, utilities relocation, or even acquisition of endangered structures, all of which are relatively expensive. Protection may also be accomplished through preventive measures. Such measures might include: (1) increased efforts to determine a priori the relevant soil and groundwater conditions and their possible effects, (2) exclusion of certain types of construction techniques or details prone to generate excess movements, and (3) increased control over the contractor's procedures and workmanship. Monitoring of construction will allow evaluations of the contractor's performance to be made during construction and will provide the necessary data to predict tunneling effects further along in the construction. Monitoring will also provide data for enforcement of changes in construction details.

The approach to provide positive protection rather than preventive measures to preclude deleterious effects is conservative and usually safe but costly. It has been favored by authorities in many cities for political reasons and for reasons of distruct of preventive measures. In this Handbook, the second approach (preventive measures) is emphasized, and ways to make this approach safe and desirable are analyzed. Monitoring of tunnel construction is a key effort in this endeavor.

Factors Influencing Tolerable Movements of Existing Buildings:

Movement	Building
Magnitude	Design
Rate	Construction
Direction	Age
Distribution	Condition
Cycling	Current use

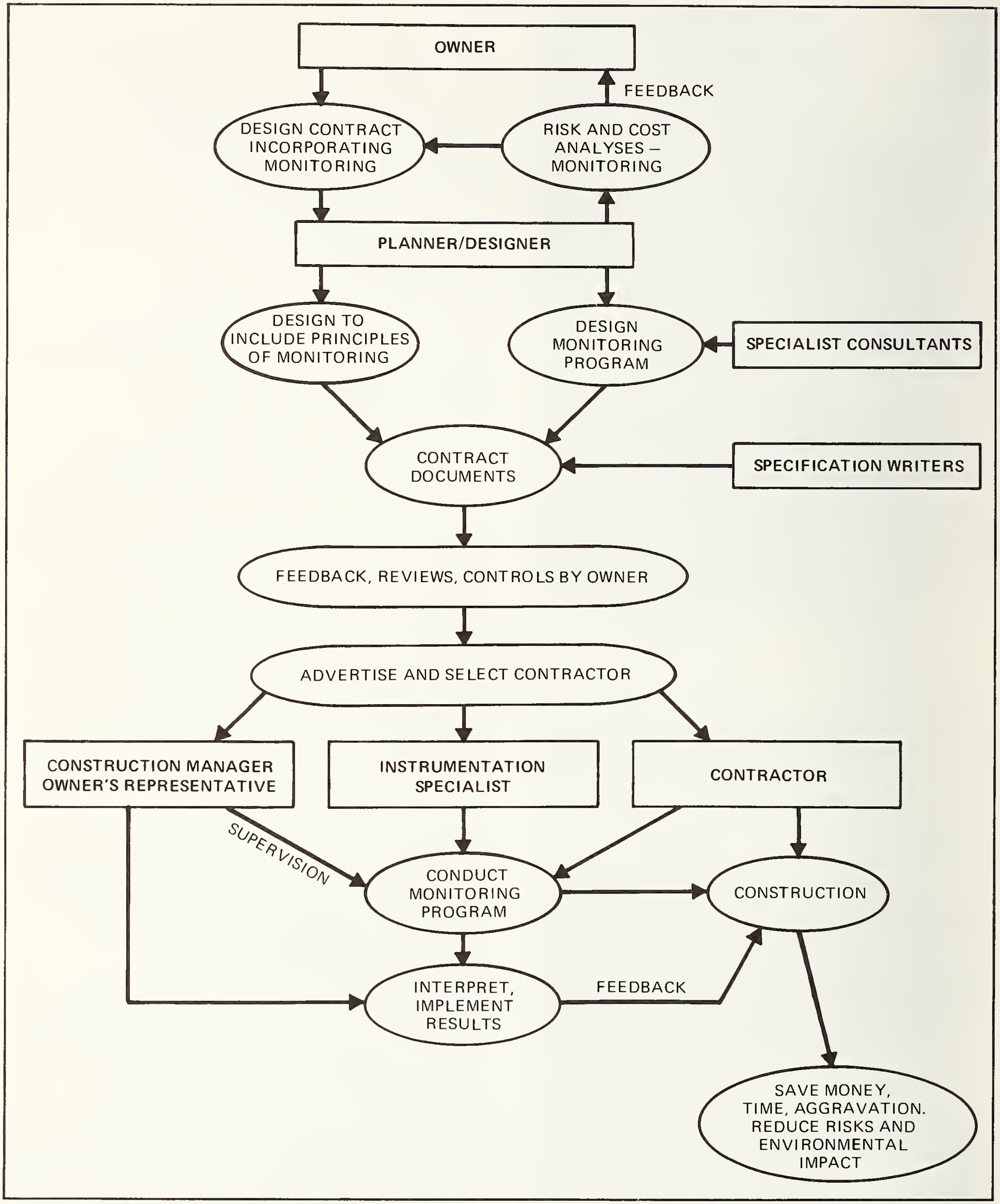


Fig. 3-1. Who Makes Monitoring Work?

3. Monitoring—Implementation, Objectives, and Functions

"Monitoring cannot by itself reduce costs or provide greater safety; rather, it provides the data base for making intelligent cost and safety-related decisions."

— *The Author*

3.1. The People and the Organizations

To execute a monitoring program for a tunnel or deep excavation project and to ensure success in deriving all desired benefits are complex matters. The process requires involvement by almost all agencies associated with the design and construction of rapid transit tunnels.

The owner must be made aware of the possibilities afforded by tunnel construction monitoring and instrumentation, both as regards the possible cost savings and other benefits to the project segments being monitored, and the long-term benefits that may accrue to future segments of the transit system. In the same vein, national funding agencies must be made aware of the long-term research and development needs of the profession which may be fulfilled by monitoring efforts. These benefits and needs are described in detail in Chapters 4 and 5. Section 5.3 describes a setup that will allow maximum benefits to be realized on a systemwide basis.

Unless the owner is apprised of these benefits, he will not be able to allocate the required resources to monitoring efforts that will include the appropriate required expertise. The owner also needs this information to properly phrase contracts with design firms to include in the scope of work a thorough examination of the benefits and cost-effectiveness of monitoring and instrumentation both on individual segments and in the entire system.

In his appraisals, the owner is assisted by planners and general designers. Planning, staging, staffing and funding requirements and decisions are made jointly by the planners and general designers, and the owner. Each general designer must give the owner his appraisal of monitoring benefits, must set up the organization necessary to derive the benefits (see Section 5.3), must include an appropriate scope of work for the final designer, and must monitor the final designer's work. The general designer may acquire the services of specialist soil consultants or specialist instrumentation consultants to assist in this work.

Each final designer must execute the detailed appraisal of monitoring benefits on his allotted segment, involving the necessary risk and cost-benefit analyses, and present recommendations for approval. Under guidance from the general designer's specialists, and possibly instrumentation specialists, the final designer must then prepare contract documents that will safely take advantage of the benefits of monitoring, and detail the monitoring program. The selection of monitoring parameters and instrumentation hardware is treated in detail in Chapter 6, while Chapter 7 describes the requirements of the contract documents and other arrangements. At a minimum, the final designer's geotechnical engineers, tunnel or structural engineers, and specification writers must become involved.

The monitoring or instrumentation specialist enters as a consultant to the general and the final designer. This specialist will develop basic monitoring requirements and advise on practical instrumentation selections and layouts. He may also be asked to perform the installation of certain types of instruments and other duties for the inspecting engineers (see Chapter 7).

The contractor's obligations must be specified in the contract documents. To be of benefit, the results of monitoring must be made to influence the contractor's work. The documents must tell as accurately as possible just how monitoring results may influence his work or limit his prerogatives. Responsibilities regarding the actual execution of monitoring tasks must also be explained.

The inspecting engineers or the construction manager, supported as required by the designer's experts and specialist consultants, must carry out their allotted part of the monitoring program, perform the necessary interpretations, and ensure that the intentions of the designers are carried out in full. Perhaps the heaviest and most important responsibilities for the successful use of a monitoring program are those of the inspecting engineers. Complex instrumentation, and especially such instrumentation and monitoring that offers little or no interference with the contractor's work, should usually be installed, maintained, and read under the guidance of the inspecting engineers.

Positive Action Schemes:

Owner:

- Insist on design evaluation of immediate benefits from monitoring
- Consider long-term benefits for system

Planner and General Designer:

- Set up organization to coordinate and promote monitoring and provide feedback
- Work out standard procedures for monitoring efforts and their implementation

Section Designer:

- Analyze all situations where monitoring is required
- Analyze all possibilities for integrating monitoring into design; cost out alternatives using risk analysis

Specification Writers:

- Make sure all tools are available for utilizing monitoring results in contract
- Make sure contractor is paid equitably for necessary efforts

Instrumentation Specialist:

- Resist the temptation to over-instrument

Contractor:

- Understand the intent of monitoring

Construction Manager:

- Follow the intent of monitoring
- Interpret and implement results expeditiously
- Do not ask the contractor to do more than contract requires, unless additional compensation is provided

3.2. Stages of a Monitoring Program

A systematic approach to monitoring includes at least four basic steps:

- Assessment of needs and benefits of monitoring and basic design to take advantage of monitoring
- Selection of monitoring parameters and how to monitor them
- Installation and maintenance and data acquisition
- Data processing and implementation

These tasks may be subdivided in many ways, as shown in Fig. 3–2. It is axiomatic that all tasks must be carried out with equal care and expertise. If just one step is deficient, the whole benefit of monitoring may be lost.

The pivot around which the whole monitoring program revolves is the definition of the specific purpose and benefit desired for the program. Without this definition it is not possible to prepare appropriate construction documents and select the proper monitoring parameters and methods. The most important functions and benefits of monitoring programs are defined in Section 3.3 and in Chapters 4 and 5.

With a clear goal, construction specifications can be written to take full advantage of monitoring (see Section 7.6). Data ranges and probabilities must be anticipated, and performance criteria based on monitoring data included in the documents where applicable. Courses of action that depend on the outcome of monitoring interpretation must be clearly defined, and provisions must be made to implement the results. Such provisions may include means for the inspecting engineers to enforce minor modifications of construction procedures, or to delay construction until conditions are improved. They may also include alternative options for the contractor that may be selected on the basis of performance data—for example, a choice between underpinning or improved methods of ground control, or between different methods of ground control (see Chapter 4).

The selection of monitoring parameters and instrumentation are treated in detail in Chapter 6. However, engineering criteria for selecting monitoring parameters include at least the following:

- The parameter must be a measurable physical state or property that will undergo change due to tunneling and that is relevant in a diagnostic or predictive sense to the specific identified problem.
- It must be amenable to theoretical or empirical analysis, and it must be possible to take action that will change the outcome of monitoring data.

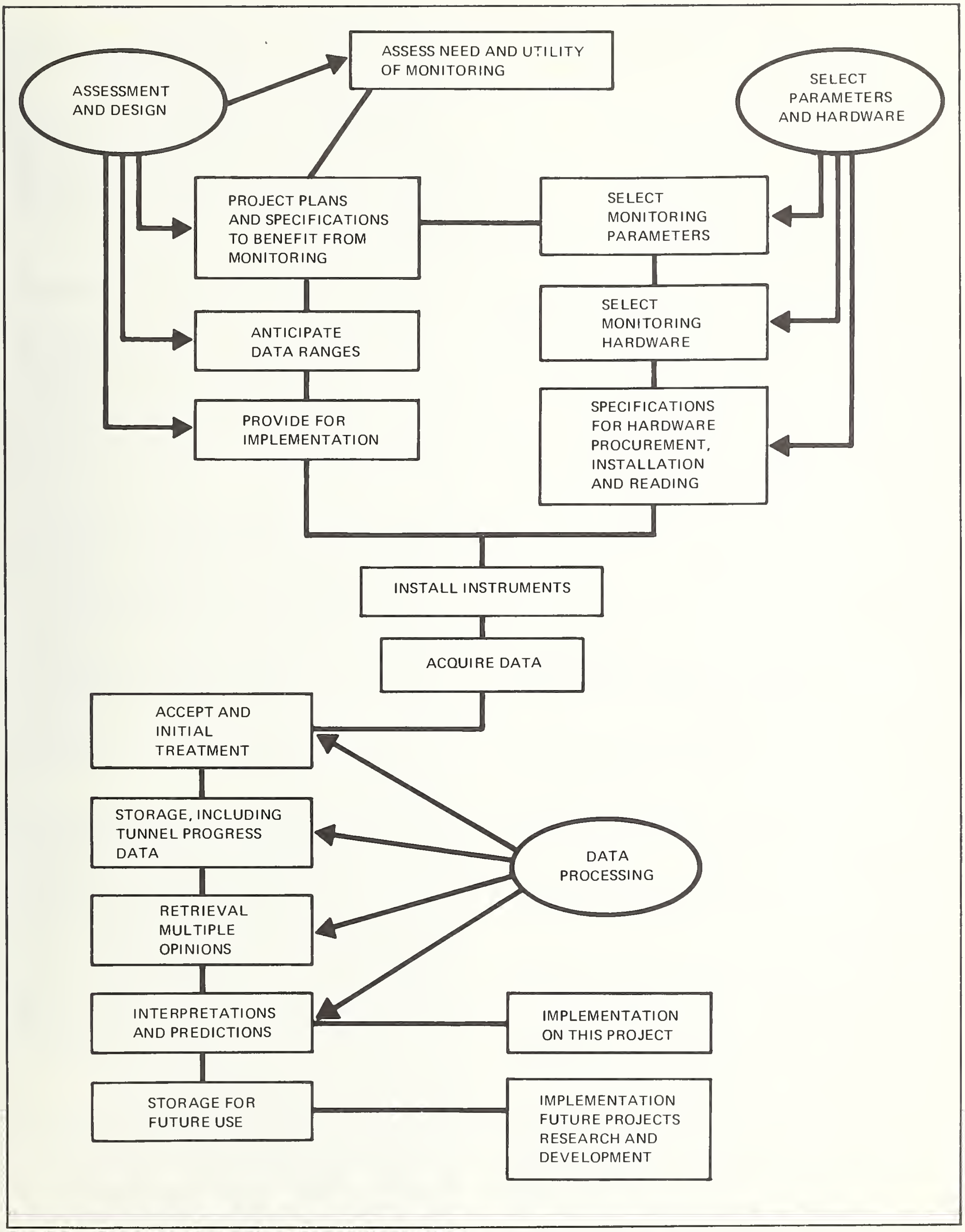


Fig. 3-2. Systematic Approach to Tunnel Construction Monitoring.

Check List for Planning a Monitoring Program:

- Define the problem
- Define the purpose of monitoring
- Select monitoring parameters
- Make predictions of behavior
- Define instrumentation needs
- Determine assignments
- Select instruments, components and systems
- Determine which factors may influence data
- Plan procedures for ensuring correct and reliable data
- Plan instrument layout
- Write procurement and Installation specifications
- Plan procedures for implementation; incorporate in specifications

Engineering criteria for selecting instrumentation hardware, and installation and data acquisition methods include at least the following:

- *Reliability.* The tunneling process is dynamic and there may not be a second chance to recover data.

- *Accuracy.* There must be no question as to the credibility and accuracy of the data. Provisions for field verification are desirable.

- *Sturdiness.* On building sites, vandalism and construction hazards are rampant. Simplicity is preferred to sophistication.

- *Practicality.* Monitoring must not impede construction and not introduce extraordinary costs.

- *Safety.* Frequently, measurements must be taken in the midst of heavy street traffic; in such instances remote reading may be suitable, though costly.

As a rule, monitoring data must be examined and analyzed quickly, and a task force must be made available to do so. The makeup of such a task force is described in Section 7.7. The credibility of the data must be assessed at once, and the impact on the specific identified problems must be determined as soon as enough data are available. Certain items such as groundwater data may be utilized at once without major analysis, but ground movement data must be gathered in quantity and analyzed in detail.

Where computerized processing or storage of the large quantities of ground movement data is contemplated, the makeup of the program should be prepared early enough to allow input forms to be available at the beginning of the contract. Dry runs should be performed to debug the program and ensure its adequacy.

3.3. Objectives and Functions of Monitoring

Some basic objectives of monitoring are briefly outlined in the box; they are treated in detail in Chapters 4 and 5. For monitoring to achieve these objectives, it must serve five basic functions: diagnostic, predictive, legal, documentation and verification, and research and development. Depending on the specific objectives, several or all of these functions come into play. It is useful to examine these functions in a little more detail, because they affect the level of the required monitoring effort, the types of monitoring required, the contractual distribution of responsibilities, and the impact of monitoring decisions on design and construction parameters and on criteria.

Through combinations of the following five functions, a number of benefits may be obtained by monitoring, as described in Chapter 4.

Diagnostic Functions. To determine the interaction of the soil and groundwater with excavation and construction processes, to determine the suitability of construction and dewatering details for a specific soil environment, to form the basis for modification of these details during construction, and to help maintain the safety of the work.

Predictive Functions. To permit a prediction of soil behavior, face stability, and ground movements under similar conditions later in the project; to predict future and delayed settlements of streets and buildings; to predict the effects of driving an adjacent tunnel; and to form the basis for modification of construction details or implementation of protective features such as grouting, underpinning, and compressed air.

Legal Functions. Documents that show actual settlements, displacements and strains of streets, buildings and other structures—before-and-after records—are valuable material during litigation, and may even encourage out-of-court settlements of claims on the part of property owners or contractors.

Documentation and Verification Functions. Obligations of the contractor, for example, to meet lines and grades within certain tolerances, or to conduct the work with contractually stipulated acceptable ground movements, require documentation of the actual results of his work. In many instances assumptions

Some Objectives of Monitoring Tunnel Construction:

- Economy — to allow construction modifications based on better than anticipated performance
- Resolve uncertainties — to furnish vital information during construction, to verify design assumptions, and to provide data for deferred decisions and construction modifications
- Warning — to detect signs of impending danger
- Compliance — to document contractor's meeting of contractual obligations
- Legal — to provide evidence against claims and suits
- Check theories — to provide data for validating design theories
- Improve construction — gain in-depth experience by monitoring of pilot tests of new designs or construction technologies
- Local experience — accumulate stock of data on local soil and construction conditions

regarding loads, stresses or movements of temporary or permanent structural members must be verified during field operations so that alternate or remedial measures (e.g. additional struts, tie rods, or anchors) may be employed if required.

Research and Development Functions. To correlate soil and groundwater parameters and construction details with observed ground behavior; to build up greater confidence in pre-construction assessments of ground movements and their effects on loads and stresses; and to provide better future design data.

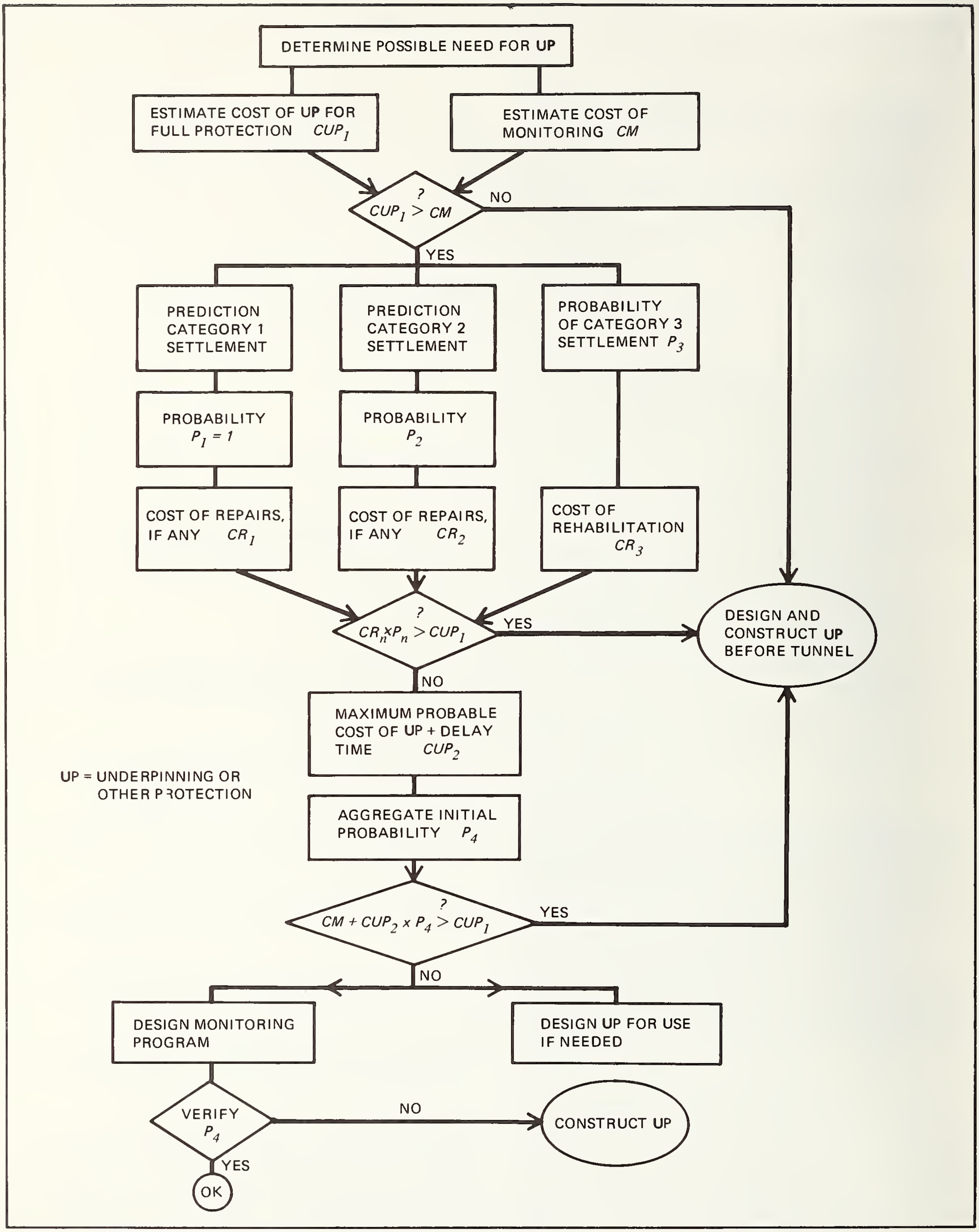


Fig. 4-1. Underpinning Design Chart.

4. Immediate Benefits of Monitoring

"Traditionally, underpinning of a structure is more often executed because of uncertainties in estimating settlements and their effects than because of the calculated effects of estimated settlements."

— The Author

When construction monitoring is part of a deliberate scheme to eliminate underpinning of structures, to save on horizontal braces in an excavation, or to avoid installation of temporary tie rods in a tunnel, the benefits can be measured with some accuracy in terms of dollars and cents. But how does one measure the economic benefit of an accident that did not take place, a delay that was not incurred, a building that did not crack? And how does one measure the value of monitoring data when they result in favorable claims settlements out of court?

Although many benefits associated with monitoring are hard and tangible, other benefits, though significant, can only be realized intuitively or in probabilistic fashion.

Direct and Immediate Monitoring Benefits:

- Avoid underpinning — save money
- Assist in restoration or safe maintenance of structures
- Reduce some environmental hazards — settlements, noise, fumes, etc.
- Safety — avoid accidents
- Improve quality control
- Reduce requirements for temporary supports while maintaining safety
- Verify design assumptions
- Keep track of important construction parameters — groundwater loads, etc.
- Legal records for contractual obligations, claims, etc.

Some of the most important possible or probable immediate benefits of a well-conceived, planned, and executed monitoring program are discussed in this chapter. Long-term benefits are discussed in Chapter 5.

4.1. Cost Reduction Through Avoidance of Underpinning

A possibly large and tangible cost saving on a bored tunnel results from avoidance of utilities relocation, underpinning or other protective measures. This saving may come about in one of two fashions.

First, instead of providing positive protective measures, the owner and designer may elect to restrict ground movements through prohibition of certain construction methods that are known to result in excessive ground losses. Alternatively, certain construction methods designed to minimize ground losses may be enforced. In these cases the contractor is required to perform in accordance with specific ground movement tolerances stipulated in the construction documents. The cost of tunneling may increase, but the added cost may be more than offset by the savings in protection. In this instance, monitoring is required to show adherence to requirements, to predict movements further down the line, and to diagnose sources of lost ground that may be eliminated through minor changes in construction details.

In addition, it may be profitable to defer decisions regarding underpinning until the contractor's performance in a given environment has been evaluated. It is realized that this approach often encounters practical opposition, and that it has rarely been followed in the past. The approach is clearly not possible for structures near the beginning of a contract, but structures a few months down the line may well be treated this way. If this course of action is selected, the design and decision process follows roughly the chart shown in Fig. 4–1. In this chart, category 1, 2 and 3 settlements are in increasing order of severity as previously discussed. Category I settlements are the estimated minimum and unavoidable settlements. Category 2 settlements are the peaks of the normal settlement profile, caused essentially by more or less random variations of the soil or the construction details. Category 3 settlements are catastrophic settlements, those that should never occur, but that may occur due to totally unanticipated soil problems or gross misjudgment of soil conditions. Obviously, those personnel responsible for such analyses and judgment must be highly qualified and experienced tunnel engineers on the designer's staff. While settlements of Category I have an occurrence probability near unity, settlements of Categories 2 and 3 have probabilities of occurrence at a given spot significantly less than one.

To determine if a deferred decision is appropriate, it is necessary to estimate costs of underpinning (CUP_1 on the chart), construction monitoring (CM), and repairs and rehabilitation if needed (CR_1, CR_2, CR_3). Recognizing that a deferred decision will, in some instances, result in a need for underpinning, the cost of that underpinning, including any delay costs, must also be estimated (CUP_2). To perform the risk analysis, probabilities of occurence must be estimated (P_1, P_2, P_3), including the probability (P_4) that monitoring will in fact indicate the need for underpinning. A monitoring program is then required at the beginning of the project to verify magnitudes of settlements and probabilities of occurrence, so that the deferred decision may be made. At the second decision point, the term CR_nP_n refers to the largest of CR_1P_1, CR_2P_2 and CR_3P_3. The final verification of P_4 is made after executing the monitoring program, at which time field values replace estimated probabilities.

While this entire risk analysis and decision sequence may appear complicated, it is not much different from the sequence of thoughts the owner and designer must intuitively go through in any case where a decision on underpinning or protection must be made. It is clear that, when used in this way, monitoring is an integral part of both design and construction and that construction documents must be carefully prepared to allow deferred decisions of this nature in an equitable fashion.

Example: Assume that a building is located on the flank of the anticipated settlement trough, and Category 1 settlement of the building extremity is estimated to be 1 inch. In theory, no underpinning would be needed, but there is a slight possibility that minor crack repairs may be needed. This building would usually be underpinned or otherwise protected at a cost of perhaps $150,000 ($CUP_1$), because: (1) the settlement estimate is regarded as very uncertain, and (2) it is not politically attractive to expose private property to this risk.

Through proper analysis one may determine the probability (P_2) of creating Category 2 settlements of about 2 inches, and the probable associated repair cost (CR_2) may be estimated. Further, slight probability of incurring major Category 3 settlements (P_3) may be estimated, and the effect of such settlement assessed in terms of hazards and rehabilitation costs.

If the risk of Category 2 settlements occurring is $P_2 = 30$ percent, and the repair cost is $CR_2 =$ $50,000, the expected monetary value is $15,000. If the risk of Category 3 settlements is $P_3 = 4.0$ percent and the rehabilitation cost is $CR_3 =$ $500,000, then the expected value is $20,000. It is evidently advantageous to eliminate underpinning.

Such risk analyses are uncertain and are based on assumptions regarding the contractor and the capabilities of his procedures, made at a time when the contractor is not even selected. However, if the effects of tunneling are monitored at an early stage of construction, predictions can be made through careful analysis and extrapolation of real and applicable data. Thus, as soon as monitoring data are available, the risks can be reassessed intelligently, and several options may be made available. If excessive ground movements can be diagnosed and shown to be caused by specific construction details and procedures, the contractor can modify these procedures, and the effect of the modifications can be ascertained through continued monitoring. If excessive ground movements must be ascribed to ground conditions more adverse than anticipated, and construction modifications cannot be counted on to reduce the predicted settlements, then a decision may be made to execute underpinning.

In this last instance, it is not usually possible to finish underpinning or other protection at the originally anticipated cost; also, a delay in tunneling must be expected. The protection may cost $200,000 instead of $150,000, and two weeks' tunneling delay may cost another $250,000, for a total of $CUP_2 =$ $450,000. This is three times the originally estimated underpinning cost. Clearly, underpinning should not be performed in this instance, before construction begins, unless there is more than about 30 percent probability (P_4) that underpinning will eventually be required.

4.2. Assistance in Restoration or Safe Maintenance of Structures

Certain protection measures for structures subject to settlements require continuous monitoring of structural movements, and continuous adjustments to compensate for settlements.

Column Pick-up. Where settlements are estimated to be moderate and where conventional underpinning would be expensive, a suitable structure may be restored through installation of a jacking system to allow raising individual columns or walls as needed to nearly maintain the original elevation of the structure. The jacks may rest on the original foundations or on specially prepared new foundations. Settlements may occur quite rapidly, and nearly continuous monitoring is required as an integral part of this protection scheme.

As a variant example of this scheme, consider the 7th Street Bridge over I-95 in Washington, D. C., where four tunnels beneath the bridge would cause some settlements. To minimize ground losses in the tunnel, the soil was stabilized by chemical grouting. Accepting, nonetheless, possible slight damage or displacement of pier and abutments, the bridge girders were individually adjusted by jacks as settlements occurred, thus avoiding excessive twist or differential settlements. Eventually, the bridge surface was restored and bearings reconstituted, allowing continuous unhindered traffic on the bridge. Here, again, settlement monitoring is an integral part of the scheme.

Compensation Grouting or Mud-jacking. These are techniques of injecting thick, viscous cement grout into the soil or beneath slabs to compact the soil and raise the overlying structure. These techniques can be used after all settlements have taken place, to restore original elevations, or they may even be used during the construction process causing settlements, gradually densifying the soil and compensating for settlements as they occur. Very careful execution of such schemes involves detailed and close monitoring of movements.

4.3. Reduction of Environmental Effects

The most significant environmental effects that may be reduced by implementation of monitoring results are those associated with ground movements. Secondary effects are associated with lowering of the groundwater level. To reduce ground movements it is necessary to know their extent and cause. Consequently, monitoring is required to establish the general magnitudes, to check acceptability, and to diagnose the causes of ground movements.

By careful interpretation of data it is possible to determine quite precisely the origin of ground movements at the leading edge of the shield, in front of the shield, or over the tail void. It is also possible to learn the horizontal extent of the origin of movement — whether localized over the crown, spread over the width of the tunnel, or wider, and the contribution of groundwater to ground movements and face instability. These data coupled with visual observations of tunnel construction procedures and events can accurately pinpoint the specific mechanisms of ground loss. Armed with this information, the contractor can change his construction details (though not his general procedure). At least the following options for modification are usually available, depending on the general procedure employed:

- Adjust the air pressure in a compressed air tunnel to provide better support of soft clay or to counterbalance hydrostatic pressures.

- Increase the efficiency of dewatering or temporarily halt construction until the groundwater level is at an acceptable elevation.

- Institute or increase the use and effectiveness of face breasting.

- Apply ground stabilization locally (grouting, freezing).

- Prevent overexcavation in front of shield.

- Increase jacking pressure on fully covered wheel excavator.

- Apply tail void filling sooner and more frequently to reduce time of exposure of soil in the tail void.

- Change backfill grout mix or replace grout seal if defective.

- Apply second stage grouting at higher pressure to fill voids possibly left open.

Depending on the contractor's procedures many other options may be available. All of these modifications may be instituted at moderate cost and would serve to minimize settlements. They are, however, frequently not required to maintain tunnel safety and construction progress. The contractor, therefore, would have incentive to institute them only under cost penalty or specification requirement.

Groundwater directly affects face and tail void stability in the tunnel, and wall and bottom stability of an excavation. Significant secondary effects of groundwater lowering include widespread settlements over compressible soils, and sometimes settlements due to removal of fine soil particles by the dewatering process. It is important to distinguish between settlements caused by dewatering and those caused directly by construction in order to prescribe remedial action, if necessary. Dewatering and construction records, together with groundwater elevation and settlement monitoring over the appropriate time intervals, are required for this purpose.

4.4. Increased Safety

Many of the effective controls for cost reduction and environmental protection also have a beneficial effect on safety. The risk of material falling out of the face, for example, is reduced by proper face breasting. Potentially, the most severe hazard is the innundation of the tunnel by a massive soil and water flow. The risk of such occurrences can be virtually eliminated by proper surveillance of the groundwater pressures in the tunnel region, and by proper dewatering when needed.

Monitoring of groundwater pressures, or groundwater levels, serves to reduce or eliminate the hazards of major and minor soil and water flows into the tunnel and to check the efficiency and adequacy of dewatering procedures. Monitoring of water pressures immediately at the crown of the tunnel before the leading edge reaches the point of monitoring is particularly important in this respect, but to preclude the possibility of encountering water-bearing seams within the height of the tunnel, observation wells extending throughout the height of the tunnel are also useful. Depending on the general continuity of strata, these observation wells do not necessarily have to be located within the horizontal extent of the tunnel.

Other safety and health related monitoring efforts should include air quality, noxious and explosive fumes, air-borne dust, and special health hazards associated with compressed air tunneling. These items are not treated in this Handbook.

4.5. Verification of Design Assumptions

As a rule, the design of the finished structure is executed in the design phase and fixed in the contract documents. There are no opportunities for changing the design of segmented tunnel liners during construction, primarily because the lead time for delivery of such items prohibits significant changes. Even when the final lining is cast-in-place concrete, the thickness of the concrete is determined a priori, and the shield diameter is selected to accommodate the necessary dimensions. A change to a thinner lining during construction would result in minimal savings. Where there are initial uncertainties with regard to the adequacy of, for example, an innovative lining system, monitoring may be performed to verify the predicted behavior of such systems. There must, of course, be recourses established for the case where the systems are found to be inadequate. In general, instrumentation of the final lining structure will benefit only future construction projects, but it is highly useful for this purpose.

On occasion, erected tunnel linings are subjected to excessive distortion due to improper application of tail void grouting, very soft soils, irregularities within the soils or voids left behind the lining. Where such distortions persist, temporary tie-rods may be required to hold the shape of the lining. Measurement of immediate distortion and monitoring of distortion with time will help in determining these needs.

Where twin tunnels are driven close together, the driving of the second tunnel often creates distortions in the first tunnel, and it may itself become distorted. Monitoring is usually required to determine these effects and the needs for tie-rods.

4.6. Benefits for Deep Excavations

Temporary remaining walls for deep excavations are designed for reasonably conservative earth pressures and groundwater level assumptions. The distribution of earth pressures and the movements associated with the excavation are quite uncertain, however, and monitoring is frequently called for to ensure the compliance with assumptions regarding water levels and to minimize ground movements.

Cost savings may on occasion accrue by the monitoring of wall movements, settlements and strut loads. If wall movements are considerably smaller than expected, or the effect of strut prestressing better than anticipated, it is sometimes possible to eliminate some or all of the lower struts. Alternatively, the vertical spacing of struts may be increased, thereby not only reducing the cost of strutting, but allowing more efficient operations due to the improved working space. At the same time, monitoring of strut loads provides a measure of safety. Since buckling of a single strut or snapping of a single anchor can have catastrophic effects, monitoring of loads in some of these members allows the detection of dangerous overloads.

4.7. Documentation and Project Control

As previously explained, there is a need for monitoring of ground movements, groundwater pressures and tunnel distortions, to diagnose causes of deleterious effects and to implement changes in construction procedures. This monitoring allows the contractor to modify procedures on his own initiative, and allows the owner's representative to enforce such modifications, provided the construction documents give him the power to do so.

For most types of structures, a verification of dimensions, and an evaluation of the general quality and appearance of the final structure constitute the most important criteria for the owner's acceptance of the final structure. In the case of tunneling, the criteria for acceptance must include many items directly associated with the manner in which the contractor performs his work. The contractor's performance has a direct effect on the final product, but the concern for safety and environment, plus specific criteria established for decisions concerning underpinning or utilities relocation, make the contractor's performance throughout construction subject to quality control. Construction monitoring of the types discussed constitutes a significant part of the project quality control. Construction documents must, in general, include criteria for acceptability based on monitoring results.

Conventional construction documents usually include such criteria only to a very minor extent.

Monitoring serves additional purposes beyond project control and acceptance. Monitored settlement data of adjacent buildings and utilities are important legal documents and are extremely useful during later litigation and resolution of insurance claims. The amount of legal fees that may be saved by expediting these matters with the availability of adequate data can be significant.

4.8. Alignment Control During Construction

Ultimately, the line and grade of the tunnel, and the tunnel clearances, are subject to control and acceptance by the owner. In the San Francisco BART System, after completion of a tunnel, permanent centerline monuments were placed in the tunnel at intervals of approximately 1,000 ft., and at tangent-spiral (TS) and spiral-circular (SC) curve points (Peterson & Frobenius, 1973). From these monuments, measurements were taken radially to critical clearance points to ensure that the clearance envelope was in accordance with design requirements. In one stretch of the BART System, measurements were made on all rings to ensure that all clearance requirements were met, and to provide data for recalculation of track alignment if needed.

During construction, monitoring of lines and grade, other geometrical properties of erected lining rings, and shield attitudes aid the contractor in steering the shield and in guiding erection procedures. Since time delays caused by survey work cannot be tolerated, it is in the contractor's interest to develop efficient methods to transfer tunnel centerline, stationing and grade from primary control monuments to the tunnel, to carry these forward through the tunnel, and to control the shield and lining erection operations within tolerances. Inefficient methods may cause delays. Inaccurate methods may cause ultimate rejection of parts of the finished tunnel.

Each tunneling setup imposes different requirements to, and restrictions on, methods of line and grade control. In modern tunneling, laser beams are most often employed both for control of shield attitude and for verification of tunnel ring geometry. It is unnecessary to describe these methods in detail in this Handbook. The methods are described elsewhere (for example, Peterson & Frobenius, 1973).

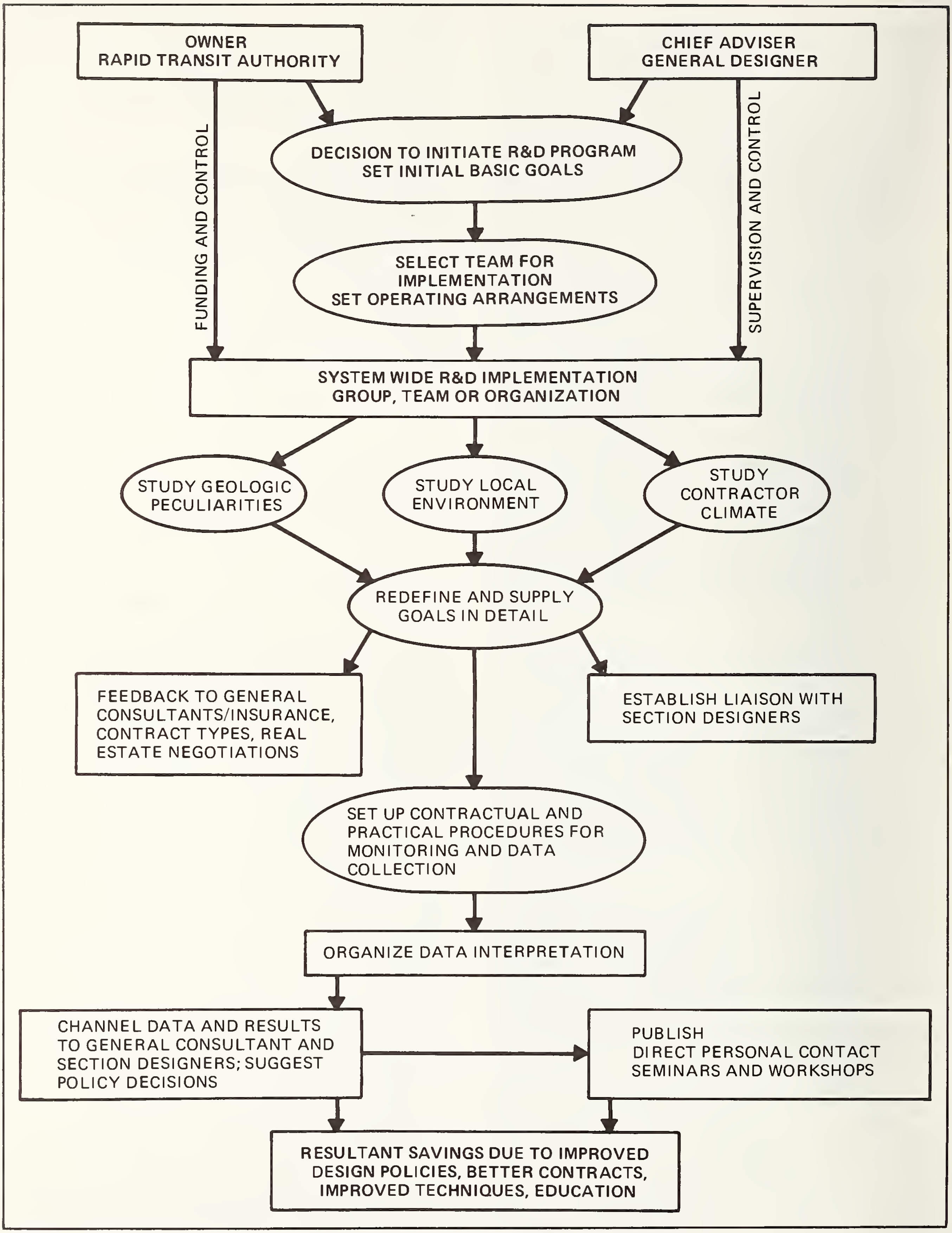


Fig. 5-1. Makeup of Systemwide Monitoring and Implementation Program.

5. Long-Term Benefits of Monitoring

"....... those who refuse to learn from the mistakes of the past are forever condemned to repeat them."

Santayana

5.1. Needs Defined:

In the past, most monitoring of tunnel construction, and a great deal of deep excavation monitoring, have been performed to gather data for advancing the state-of-the-art. In many instances, when monitoring was expected to benefit a project directly, this benefit was not fully achieved due to inadequate planning or other reasons. Yet these data, when subjected to later analyses, have increased the understanding of soil behavior, soil-structure interaction, and the effects of tunneling and deep excavations.

The concepts discussed in the previous chapters have been directed toward the optimization of monitoring benefits to the project from which the data are collected. Most of these data will also be extremely useful for improving future designs and construction contracts, particularly those executed in the same geological setting; for example, future contracts of the same transportation system.

Many concepts of soil behavior applicable to tunnel construction are reasonably well understood at this time. However, the owner's, designer's, and contractor's confidence in predictions of soil behavior based on these concepts is limited for the following reasons:

- The quality and quantity of geotechnical data (stratigraphy, soil properties) usually available for analysis are insufficient for proper correlation with empirical data and for thorough theoretical analysis.

- The concepts and methods of analysis have never been fully tested by comparing predictions based on full analyses with measured performance.

- The effects on soil behavior of a great variety of available or conceivable construction procedures have not been critically tested.

- The great variety of construction procedures has never been subjected to a full and critical review with respect to their effects on soil behavior in tunneling.

- Recorded experience of soil behavior is limited to several reasonably well-documented histories, many of which are not easily accessible, and most of which have not been subjected to analyses using modern concepts.

Because of the vagaries of tunneling and the peculiar effects of tunneling on soil behavior, theoretical work can only supply a background or framework, providing approximate functional relationships between parameters, causes, and effects. No theoretical result can be trusted until verified and modified by empirical data. Because of the importance of being able to predict tunnel behavior in advance, it is of great importance to gather monitoring data intelligently and to make these data available for research.

Types of Monitoring Projects Defined:

- Monitoring for *Demonstration Projects:* Verification and demonstration of economic and technical feasibility and applicability of novel techniques
- Monitoring of *Research Test Sections/ Stations:* Research and development in local area of project, primarily to further systemwide or national goals, secondarily to benefit project itself
- *Intensive Project Monitoring:* Often includes test stations, primarily intended for project control, secondarily for systemwide or nationwide goals.
- *Limited Project Monitoring:* Not usually including test sections; primarily serves legal and contractural obligations, and construction convenience (groundwater monitoring); secondarily useful for gathering systemwide and similar statistics

5.2. Local Systems Benefits

Several times in the recent past, major rapid transit construction was begun in cities where no significant comparable underground construction experience existed—San Francisco, Washington, D.C., and Toronto are the most prominent examples—and construction is beginning in other cities (Baltimore, Atlanta). Experiences with sewer construction and deep basements are often inadequate for extrapolation to the massive construction efforts required for underground rapid transit.

Each city has its own geological setting and inherent soil problems; each city develops its own basic requirements for a rapid transit system; and each city has its own political environment. Many experiences learned in one city cannot profitably be transferred to another city.

Sometimes the construction climate—union regulations; availability of knowledgeable local designers and contractors; prevailing types of construction contracts; general fairness of reimbursement for construction effort and settlement of claims; insurance arrangements and regulations, etc.—are just as important as the resolution of purely technical problems. For this reason, demonstration projects in the beginning of a series of major construction efforts are useful in developing a proper atmosphere of mutual trust, leading to fairness of contracts and limitation of spurious law suits. Such demonstration projects require model specifications and contractual arrangements, and full documentation of the efforts, based in part on extensive monitoring.

But this is an intangible benefit. The development of technological knowhow is of more direct relevance. Demonstration projects, or projects with test sections designed specifically for research and development purposes, are extremely useful in defining the response of typical local soil strata to tunneling and deep excavations of various types, and in establishing criteria for dewatering, compressed air, geometry, and other technical details. Unknown problems, specifically related to the pecularities of local geology, may well surface in the course of such deliberate research.

When such data are accumulated, properly interpreted, and disseminated, they can serve to set or change basic design criteria, specifications, or construction for later projects in the system. In addition, these data can serve to establish goals for ground movement control, and demonstrate what can, indeed, be accomplished under the given circumstances. They will also help in determining the proper attitudes toward underpinning or other protection decisions, right-of-way arrangements, insurance requirements and equitable types of insurance arrangements, all of which in the final analysis spell financial benefits.

Past experiences have not always fully demonstrated these benefits. There have been problems with lack of centralized planning and coordination, of adverse relations between different agencies, of delayed or incomplete dissemination, and of failure to carry through on the conclusions.

5.3. Systemwide Organization for Monitoring and Construction Improvement

It cannot be emphasized too strongly that such local research and development through test sections, experimentation and demonstration projects, must be based on specific yet flexible goals and purposes, set out in advance, with a deliberate, dedicated, and continuous program of interpretation, implementation and dissemination. This requires attention, and investments, on the part of the owner and foresight on the part of his chief advisors. It also requires the establishment of an organization within the organization: i.e., a group of knowlegeable professionals whose sole or primary purpose is to provide the continuous guidance and the implementation policy for a pre-considered improvement program. Such an improvement program may be set up, for example, as shown in Fig. 5–1.

The systemwide monitoring implementation group must initially be established by the Owner and his Planners or General Designer. This group should include geotechnical, instrumentation, and tunnel engineers. Once established, this group is responsive to the Owner's needs. In addition, it is responsible for developing the basic goals set up by the General Designer and analyzing the feasibility of new goals it may itself initiate. The scope may include items of improvement other than those directly related to monitoring, such as improvements to contract documents, improvements and standardization of design based on local conditions, and modifications of geotechnical exploration standards, all of which to greater or lesser extent depend on observation and analysis of ongoing or completed projects.

Results of the work should be channeled back to the General and Section Designers as soon as they are available. In this fashion early experiences may be put to use promptly. This feedback may take the form of case histories or reports, and may be followed up by recommendations that may become standards or directives.

To accomplish this, systematic procedures must be developed to recover the necessary construction data and statistics. If a single Construction Manager is selected to serve as the Owner's representative on all separate contracts, the Construction Manager's monitoring team (see Section 7.7) may step in to provide most of the necessary monitoring and other data; indeed the Construction Manager could take over most of the tasks described. If, on the other hand, construction supervision is done by different firms (e.g., the original Section Designers for different sections) a central group under the General Designer is required.

5.4. National Long-Term Benefits

Similar benefits, perhaps with greater technical emphasis and less emphasis on administrative and contractual matters, are derived from proper development programs based on construction monitoring, on a national scale. Current sponsored research is, and has been, emphasizing development of new theories and technologies. The taking and utilization of construction monitoring data has had but a small place in the ongoing research programs.

Tunnel construction monitoring is required in at least three general areas:

1. To verify assumptions made in the development of new design and construction methods, for example, during demonstration projects.

2. To improve the data base on which tunnel lining design, selection of construction methods, specification writing, and the setting of construction criteria are made.

3. To enhance the confidence with which designers and contractors regard the prediction of ground behavior during construction.

Some of the important concept developments for tunneling that require accumulation of data from experience are listed below. These concepts are not necessarily listed in order of direct importance. Consideration has also been given to the plausible short-range development possibilities:

1. The effect of construction details and procedures on soil behavior, especially ground movements. Very careful recording of construction details is required to correlate associated ground movements at depth and at the surface, as well as horizontal displacements.

2. The distribution of horizontal displacements due to tunneling, and their effects, as a function of type and magnitude of ground loss. The results of 1 above, are required, in addition to direct observations. The distribution of vertical displacements (settlements) as a function of ground loss is already fairly well known.

3. The effect of loosening or densification of soil on settlement profiles. Settlement data at multiple elevations are required.

4. Tolerance of structures to withstand the strains and displacements imposed upon them by underground construction. Numerous building observations are required.

5. The effects of construction details and soil properties on lining distortions. Monitoring data on distortions are required as a function of construction procedures and time, including effects of driving the second of twin tunnels.

6. Development and verification of new procedures for designing dewatering systems for tunnels. Pumping data, groundwater observations and observations of groundwater problems in tunnels are required.

7. Development of finite element computing methods for prediction of ground movements and lining stresses. Major problem is determining boundary conditions as function of construction procedures and appropriate soil properties. All data in 1 through 4 and 6 above are required.

8. Development of more appropriate and economical methods of tunnel lining design. Data on stresses and lining distortion are required.

9. Development of criteria for design of grouting to minimize ground loss and to serve as protection of adjacent structures. Requires development of grout selection criteria based on soil properties and stratification, lab and field evaluation of grouted soil strength and coherence, development of analytical procedures, and field verification through testing, monitoring, and observations.

The following are also required for deep excavations:

1. Improved analyses of beneficial effects of wall rigidity and prestressing of struts or anchors. Wall movement measurements, settlements, strut, or anchor loads are required.

2. Further development of finite element methods for design of temporary and permanent walls (see 7, above).

Many innovative design and construction techniques, both for tunnel construction and for deep excavations have appeared recently and have been widely employed. Others have yet to see extensive use. Some of these are slurry trench-tremie concrete (or precast) walls, earth and rock anchors for wall support, root piles (pali radice) for underpinning, grouting for support or ground loss prevention (not new, but not much used), articulated shields for minimizing ground loss, various means of face support, articulated segmental liners.

To further the use of any of these and other advanced techniques, confidence must be gained in their applicability and in their individual benefits. Test sections with monitoring of appropriate parameters where such innovative techniques are used, or bona-fide demonstration projects, are needed to show the applicability of the techniques, their advantages and limitations, and the basic criteria for their selection and design. Programs such as these, with intensive monitoring and appropriate dissemination efforts, have a place in a nationwide research program.

Fig. 6-1. Plan Showing Typical Layout of Instrumentation. This illustration shows the arrangement of monitoring instruments emplaced at the beginning of a tunneling project. These instruments allow data gathering for project control, for modification of tunneling procedures as required, and for evaluating the need for protection of buildings further along. Monitoring intensities and types of instrumentation vary greatly with local conditions and specific project requirements.

6. Selection of Monitoring Parameters and Hardware

Some of the most basic general criteria for selecting monitoring parameters and instrumentation are shown in the box inserts; these basic criteria are self-explanatory. But it is necessary in this Handbook to be more specific. Previous chapters dealt with various types of problems and their effects. In this chapter, the types of monitoring are discussed, together with the most suitable monitoring methods. The types of monitoring parameters can be classified as:

- Groundwater parameters
- Ground deformations
- Observations on existing structures
- Soil-structure interaction monitoring
- Progress monitoring and observations

Guidance is given for selection of monitoring parameters for bored and cut-and-cover tunnels and deep excavations. The selection of parameters which require monitoring at a given project depends on:

- Monitoring objective
- Soil and groundwater conditions
- Type and location of existing structures
- Depth of the tunnel
- Distance between adjacent tunnels
- Degree of conservatism of design
- Nature of any deferred decisions

Generally, it is easy to overdo a monitoring program by asking for too many observation points, too many instruments or too frequent readings. For one thing, this is costly, but an excessively elaborate program would supply a deluge of data which would require a large, qualified staff for proper and timely interpretation. At best, the interpretation and implementation could be delayed; at worst, the real problems could be buried in a huge volume of paperwork. The optimum monitoring program includes just sufficient data points to resolve the identified questions and problems at hand, and no more. A certain redundancy of data is desirable for statistical reasons, for safety, and to ensure that data obtained are typical, but the degree of redundancy must be carefully engineered.

It is tempting to line up observation points along existing street or building lines. This may sometimes serve a purpose, especially when monitoring is essentially "for the record." To be useful for diagnostic and predictive purposes, however, it is essential that the data gathering points be distributed so as to make

BASIC CRITERIA FOR PARAMETER SELECTION:

- Parameters must be a <u>meaningful physical quantity</u>, subject to change due to construction activity
- Parameter change must be <u>associated with a significant problem</u>, related to cost, environmental impact, safety, or an identified research objective
- Parameter change must be <u>capable of interpretation</u> by known or developing theories or concepts, so that its meaning can be assessed
- Better knowledge and understanding brought about by monitoring the parameter should lead to <u>identifiable</u> benefit.

BASIC CRITERIA FOR INSTRUMENT SELECTION

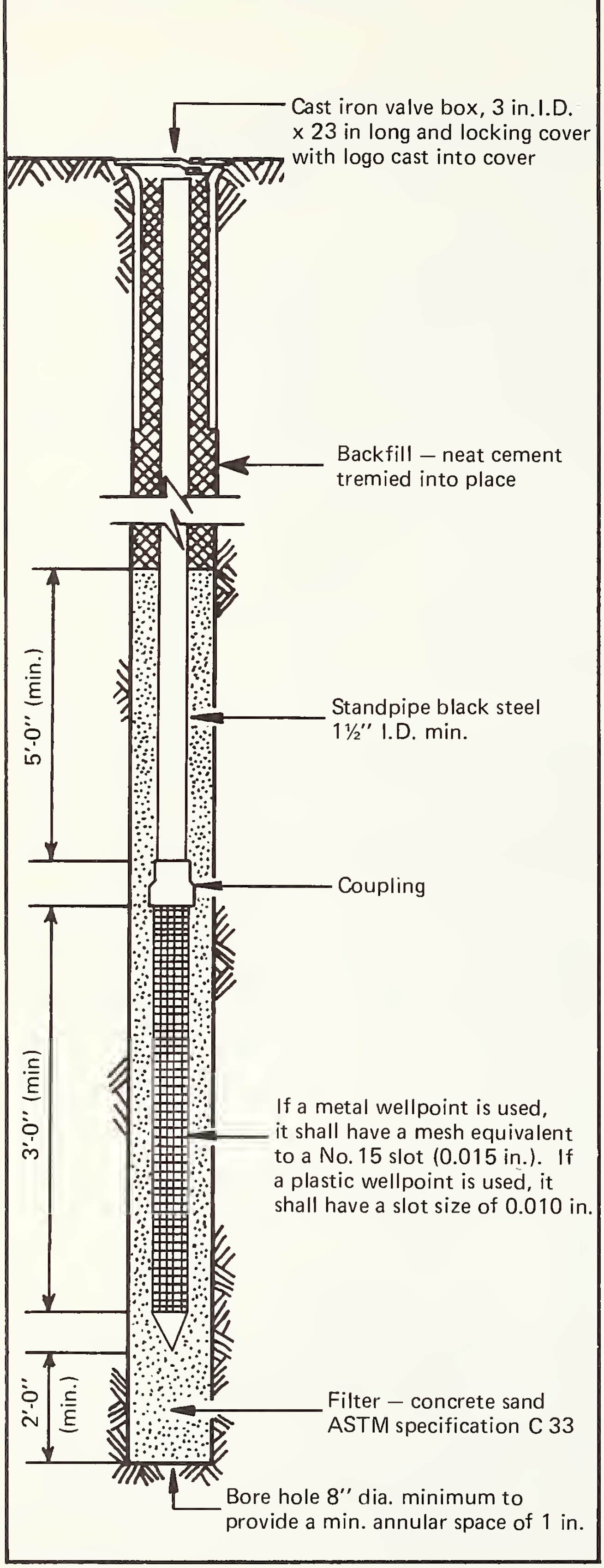
Instrument should:

- Supply reliable data for the duration of the construction
- Be durable and resistant to vandalism for the duration of construction
- Use simplest feasible design (complexity often leads to lack of reliability)
- Be designed for repeated calibration.

Installation and reading of instrument:

- Should not interfere with contractor's activities
- Should match capability of available personnel.

Fig. 6-2. Typical Wellpoint Piezometer



interpretation easy and straightforward. This would mean, for example, lining up settlement points at right angles to, or parallel to tunnel alignments and excavation walls, even if that makes data gathering inconvenient.

6.1. Groundwater Parameters

Wherever tunneling or deep excavations extend below the groundwater table, there is a need to monitor groundwater levels or flows. Monitoring provides warning of possible instability of tunnel face or excavation bottom, verification of dewatering efficiency, determination of compressed air requirements, and several other benefits.

The following parameters may be considered for monitoring:

- *Groundwater level* at tunnel centerline, or at some distance from the centerline, using an observation well open throughout the entire depth from ground surface to below tunnel invert, a well open to one or several identified aquifers, a well located at critical point near and above crown, or a well open throughout the height of tunnel.

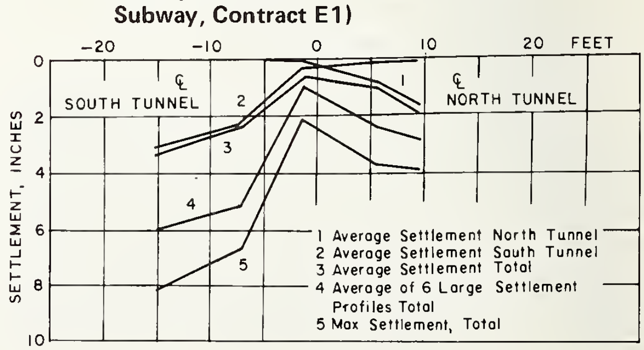
- *Dewatering progress,* i.e., time history of pumping volumes and drawdown in pump wells and observation wells; also, turbidity of water removed

- *Water infiltrating* tunnel or excavations, and any associated soil flows

- *Water pressure,* for example in a pervious stratum beneath a deep excavation, to guard against bottom instability.

The preferred instrument for monitoring groundwater level is the wellpoint or open standpipe piezometer. This type of device is simple and reliable (see typical example, Fig. 6–2). A "heavy liquid" version is avail-

Fig. 6-3. Typical Transverse Settlement Profiles Showing Development of Settlements During Construction Process (Toronto Subway, Contract E1)



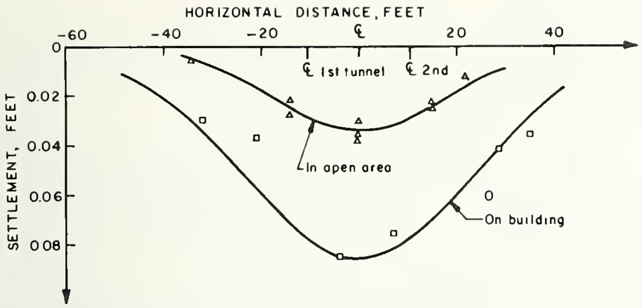


Fig. 6-4. Another Set of Typical Transverse Settlement Profiles (Toronto Subway, Contract B4)

able, whereby the water in the standpipe is replaced by a liquid of greater density, so arranged that the liquid cannot mingle with the groundwater. This expedient overcomes freezing and vandal problems by reducing the upper level of standpipe liquid, and reduces response time. Wellpoints and standpipe piezometers are unsuitable if rapid response is required or if the vertical standpipe creates construction or reading problems. These limintations are overcome by use of a pneumatic or vibrating wire strain gage piezometer, or a piezometer made by appropriate packaging of a standard electrical pressure transducer. Highly reliable commercial pressure transducers are available and are likely to be used increasingly for piezometric measurement, particularly where rapid or remote reading is required.

6.2. Ground Deformations

Settlements and other ground movements may be monitored for legal, diagnostic or research purposes or to provide data for predictions of ground deformations at other locations.

Fig. 6-5. Three Centerline Surface Settlement Records Shown as a Function of Shield Advance (Toronto Subway, Contract B4)

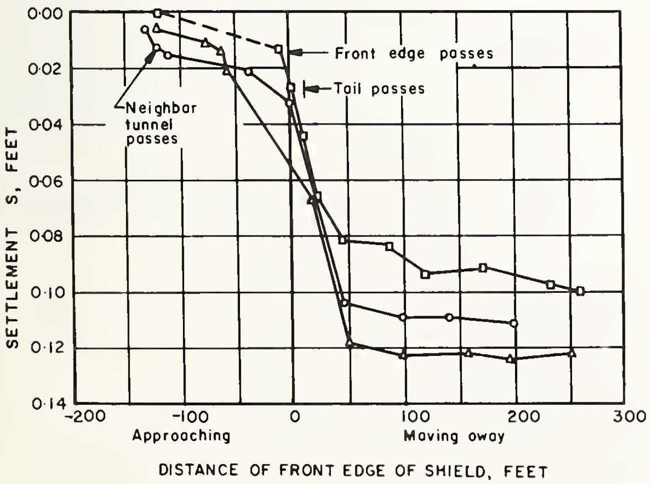
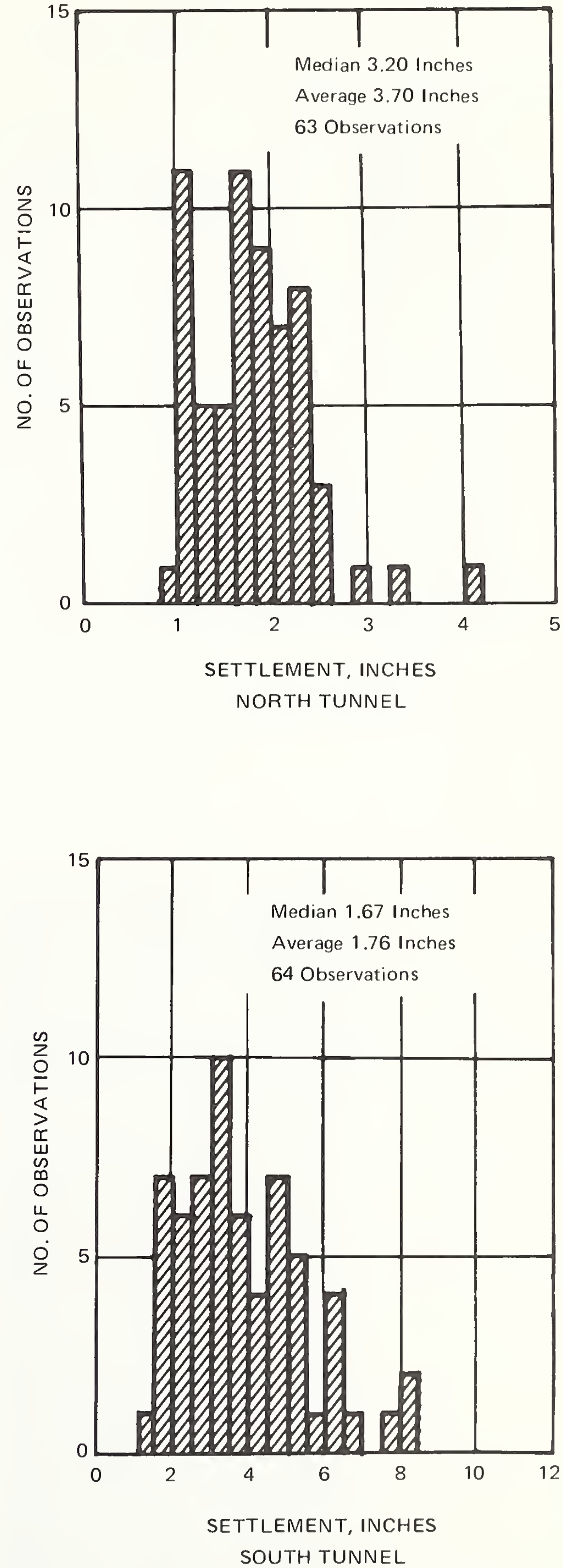


Fig. 6-6. Statistics of Centerline Settlements (Toronto Subway, Contract E1)



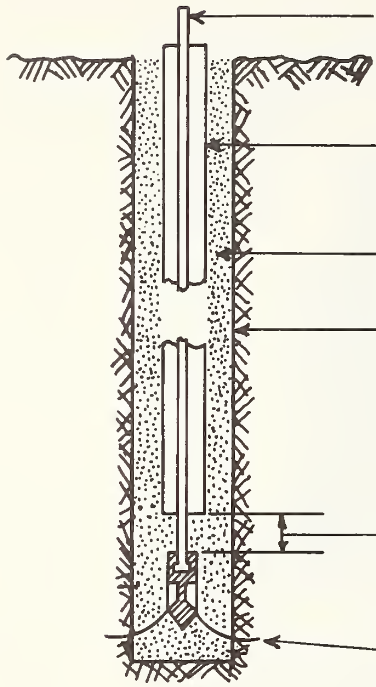


Fig. 6-7. Typical Subsurface Settlement Anchor

Surface Settlements. These measurements are taken along the tunnel centerline, primarily near the shield location, and along lines at right angles to the centerline. Measurements are usually made using conventional optical surveying techniques; they frequently interfere with traffic and may entail time-consuming data reduction. Modern laser-based surveying techniques may in the future cut labor requirements and make part of the reading and recording effort semi-automatic. Figures 6–3 and 6–4 show typical transverse surface settlement profiles over two tunnels. Figure 6–5 shows the development of settlements over the center of a tunnel as construction proceeds. A statistical analysis of maximum settlements for a project is shown in Fig. 6–6.

Subsurface Settlement. These measurements are made directly above the tunnel crown to determine the source of lost ground, and at multiple points in a vertical line above the tunnel crown. For research purposes settlements are also monitored at deep points away from the centerline. Single-point measurements are made using rod extensometers or "subsurface settlement anchors," (see example, Fig. 6–7) usually with mechanical readout. If direct mechanical reading causes traffic interruption and danger to reading personnel, an electrical sensor may be used. Multipoint measurements are made using a magnet/reed switch settlement gage or multipoint rod extensometer with mechanical or electrical readout.

Surface Horizontal Displacements and Strains. These measurements are used particularly for correlation with building damage, normally at right angles to the tunnel centerline and, less frequently, along the centerline. Measurements are made by conventional surveying techniques.

Subsurface Horizontal Displacement. These measurements are useful as a diagnostic tool around cut-and-cover excavations, and less frequently for bored tunnel construction. Measurements are made using an inclinometer within a special, vertically installed casing. For cut-and-cover excavations the casing is located either on the supporting wall or in soil directly behind the wall. For bored tunnels displacement measurements are most often made alongside the tunnel. Figure 6–8 is a schematic diagram showing the inclinometer's operating principle. A type of commonly used inclinometer casing is shown in Fig. 6–9, and Fig. 6–10 shows an inclinometer with readout device.

Tail Void Encroachment. Defined as the rate at which soil fills the tail void, this measurement is useful for diagnostic purposes. Measurements are made through grout ports, either visually or by using a portable mechanical gage.

Ground Heave. These measurements may occasionally be made at the bottom of an open-cut excava-

Fig. 6-8. Inclinometer for Measurement of Horizontal Movement

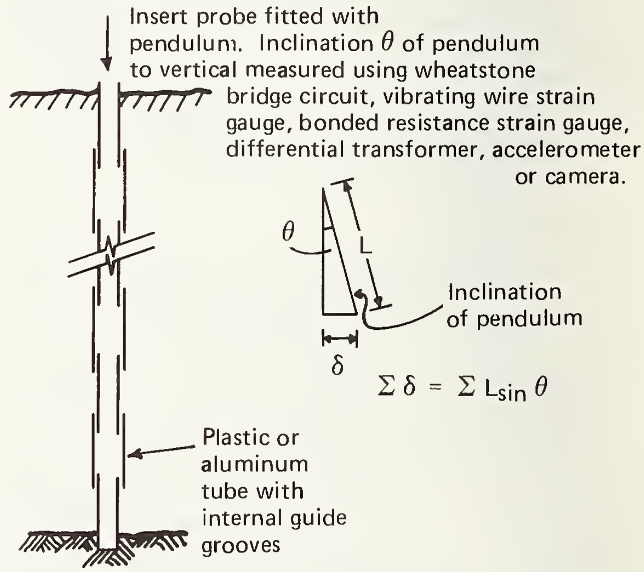


Fig. 6-9. Aluminum Slope Indicator Casing. Self-aligning grooves in the casing orient the slope indicator instrument while readings are taken.

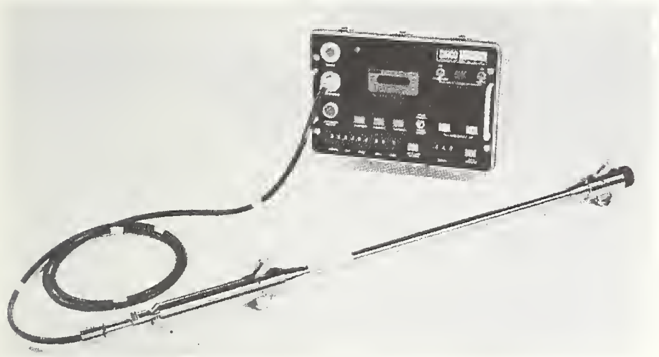


Fig. 6-10. Inclinometer

tion in soft clays or silts using simple mechanical procedures. An anchor is embedded at the bottom of a borehole below the eventual excavation bottom, and the hole is filled with a colored, heavy slurry. As excavation progresses a probing rod is inserted to mate with a receptacle on the anchor, and anchor elevation is determined.

6.3. Observations on Existing Structures

Existing structures are monitored for diagnostic, legal, and research purposes. Measurements are normally correlated with ground deformations. Observations may be categorized as:

- *Before-and-After Observations,* including elevations and displacement by conventional survey, crack surveys, photographs.

- *Settlements* monitored during construction, both of peripheral walls and of interior columns, using precise optical leveling or hose leveling techniques.

- *Horizontal Displacements and Strains* by chaining, optical survey, or portable tape or rod extensometers.

- *Tilt Measurements* of building walls and floors. These have rarely been made in the past, but by using currently available precise tilt-meters they can provide valuable data.

- *Strain in Utilities* (of limited use except when utilities are truly continuous).

6.4. Soil-Structure Interaction Monitoring

This type of monitoring is directly useful during construction of cut-and-cover excavations, and for research during construction of bored tunnels.

Structural Loads in Cross-Lot Bracing. These are measured for safety, predictive and research purposes. Either a fully temperature-compensated, vibrating-wire strain gage (Fig. 6–11) may be used, or a bonded or weldable resistance strain gage. Use of resistance gages requires that a full bridge be incorporated at each measuring point, cables from the bridge be shielded and run along the same path, that no cabling changes be made after first installation, and that electrical connections be made by experts. A backup mechanical strain gage system (Fig. 6–12) should always be used. Gage points should be carefully machined and attached to bracing using drilled-in studs, and temperature corrections should be made.

Structural Loads in Tie-Backs. These are best measured using mechanical (Fig. 6–13) or photoelastic load cells. A simple, inexpensive mechanical load cell, may be made up from a calibrated-in-place telltale rod installed alongside the sleeved length of a tie-back (Schmidt and Dunnicliff, 1975). If access to the tie cannot be maintained during construction, an electric cell using resistance or vibrating-wire strain gages is appropriate.

Fig. 6-11. Vibrating Wire Strain Gage

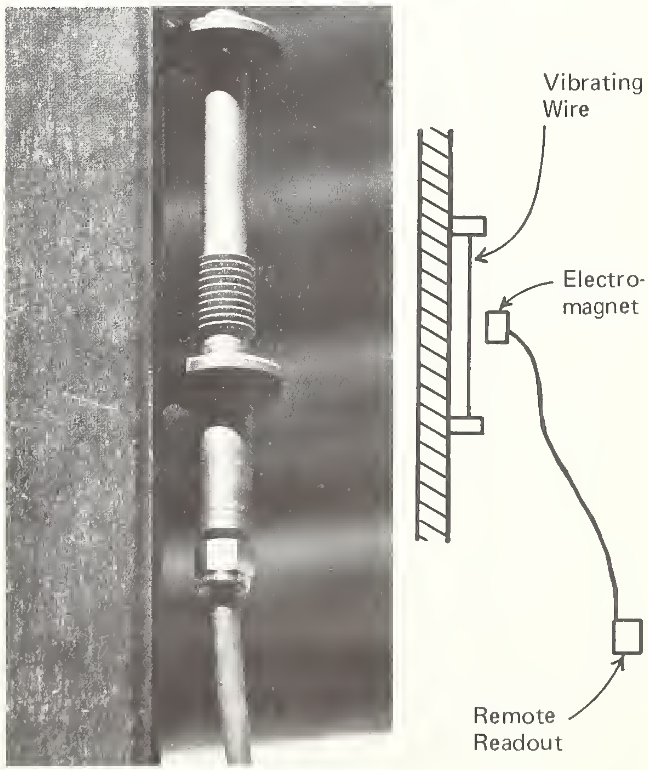


Fig. 6-12. Typical Mechanical Strain Gage

Structural Loads and Moments in Walers, Soldier Piles or Walls. These are measured using vibrating wire, resistance, or mechanical strain gages.

Horizontal Displacements of Temporary Retaining Walls. Measurements of horizontal displacements of temporary retaining walls (steel sheet piles, soldier piles, slurry-trench tremie concrete, or other) are very useful in determining the efficiency of the support system and the effects of excavation. Such measurements are often desirable when an excavation is adjacent to existing structures, and settlements must be minimized. Ordinarily, a series of inclinometer casings just behind the wall would be monitored for this purpose. Figure 6–14 shows a typical application of such measurements.

Distortions of Tunnel Linings. These are observed to verify that distortions will remain within tolerances and to determine need for temporary tie-rods. Observations are normally made to define increase in horizontal diameter and lowering of crown, using conventional surveying procedures. Typical results of such measurements are shown in Fig. 6–15. Measurements of the entire distorted shape are made for research purposes, using a variable length tape or rod extensometer and a trilateration procedure.

Earth and Water Pressure on Walls and Linings. These measurements in bored tunnels are made for research purposes. Water pressures are measured using piezometers and earth pressures by either using earth pressure cells, or backfiguring from circumferential strain gage measurements at frequent intervals around the liner. For cut-and-cover excavations earth pressures may be measured using earth pressure cells, but in practice these cells have frequently malfunctioned. Alternatively, pressures may be backfigured from load measurements in bracing, but it must be remembered that horizontal earth pressures are radically altered if bracing is prestressed.

Thrusts and Moments in Tunnel Linings. Measurements of these forces are required if a test station is completely monitored for research purposes. Circumferential stresses and longitudinal stresses due to shield jacking are measured using electrical strain gages with automatic recording facilities. Loads in shield jacks are most readily measured by adding a tee in each hydraulic line and monitoring hydraulic pressure using electrical pressure transducers.

6.5. Gases in Tunnels

In many parts of the country, notably the Detroit and Los Angeles areas, natural gases in the soils pose potential dangers of explosions in tunnels. Elsewhere,

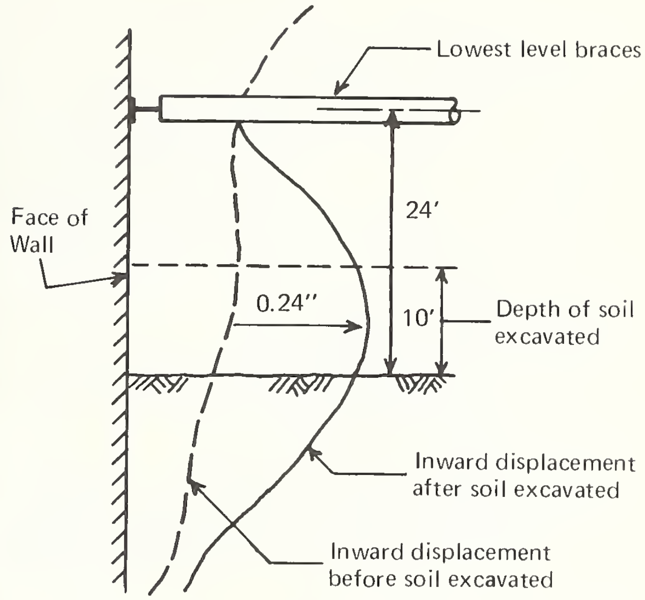


Fig. 6-14. Inclinometer Data Show Effects of Excavation Below Last-Placed Strut

gas main breaks can pose similar dangers. It is often appropriate to employ automatic gas monitoring devices of the several types used in mines to warn against impending explosion danger. Other air quality monitoring devices may also be requried.

6.6. Progress Monitoring

To permit an analysis of cause and effect, it is necessary to maintain a complete record of relevant construction data together with other monitoring data. This construction record will also contain information needed for geometrical control during construction, and for steering. For bored tunnels, data required for correlation include at least the following:

- *Stationing* and time at beginning of each shove (ring) for reference

- *Attitude and position of shield* relative to theoretical position — vertical and horizontal

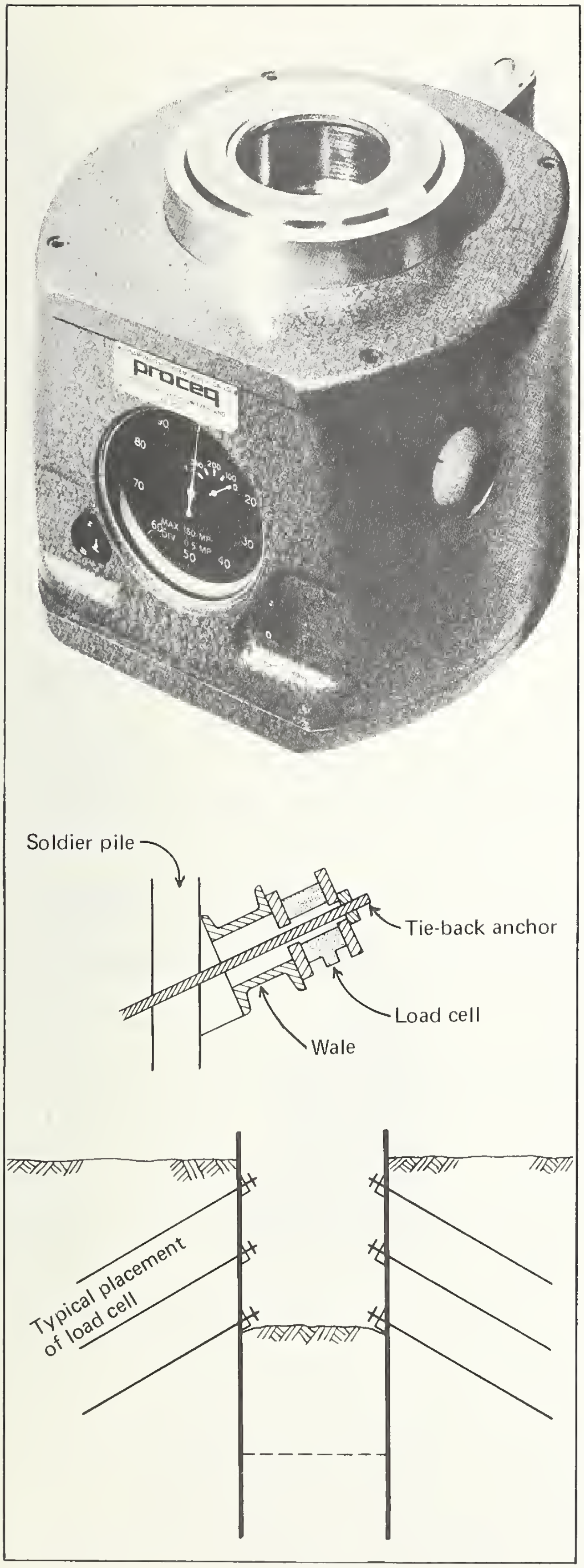


Fig. 6-13. Load Cell for Tie-Back Anchor Load

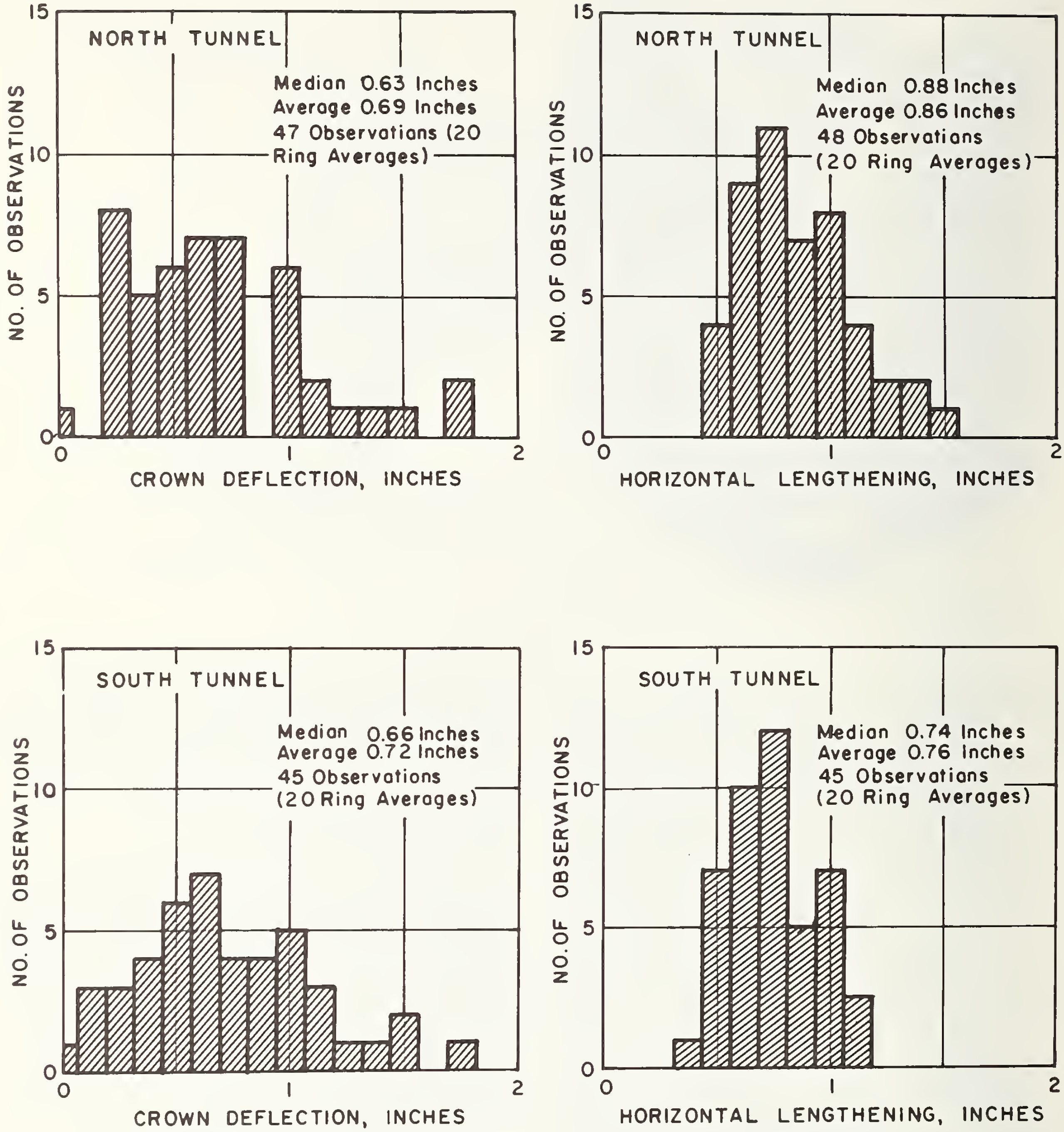


Fig. 6-15. Typical Lining Distortion Measurements (Toronto Subway, Contract E1)

Table 6-1. Selection of Monitoring Parameters for Bored Tunnels

Water Conditions \ Soil Conditions		Ideal soil, Cohesive granular, Stiff clay, No boulders	Soft clays, or silts	Cohesionless sands	Many boulders and obstructions
Above groundwater	A	1	—	1	1
	B	1	—	1	1
	C	1 or 3	—	5	4
Below groundwater; no water control contemplated	A	1	2	—	2
	B	1	3	—	2
	C	2 or 3	3 or 4	—	4
Below groundwater; compressed air	A	—	2	2	2
	B	—	3 or 4	3 or 4	4
	C	—	5	5	4
Below groundwater; dewatering or other control	A	2	2	2	2
	B	2	3 or 4	2 or 3	2
	C	3	5	5	4

Legend for Status of Nearby Structures

A = Structures outside zone of influence.

B = Structures inside zone of influence, underpinned.

C = Structures inside zone of influence, not underpinned or underpinning decision deferred.

Legend for Parameter Selection

1 = No monitoring required; or spot settlements only.

2 = Groundwater monitoring; spot settlements.

3 = Groundwater if appropriate; surface settlements; structures monitoring.

4 = Groundwater if appropriate; surface and subsurface settlements; possibly surface horizontal displacements, structures monitoring.

5 = As 4 plus subsurface horizontal displacements; tail void encroachment; lining distortion; possibly also temporary and permanent stresses in lining and earth and water loads in lining employed for limited lengths only or for research.

— = Not applicable.

Note: The above guide is a gross simplification, and selection must always recognize specific needs and constraints of each project. Progress monitoring is required in all cases, and should include observations of ground movement from within tunnel and other factors listed in text "Progress Monitoring".

- *Push data,* start and stop of each shove — pressure and jacks used
- *Curvature of tunnel* (from design drawings) to estimate theoretical ground loss due to plowing
- *Soil encountered,* especially if different from expected and if associated with a problem
- *Water quantity* entering the tunnel through face or elsewhere
- *Grout quantities* injected as lining backfill
- *Environmental factors* which may, in themselves, affect monitored data, for example temperature, nearby construction activities
- *Incidence of extraordinary ground losses,* groundwater behavior, observed distress, deviations from normal construction procedures, or any other unusual event

Table 6-2. Selection of Monitoring Parameters for Cut-and-Cover Tunnels

Soil Conditions / Water Conditions		Ideal soil, cohesive granular, stiff clay	Soft clays or silts	Cohesionless sands
Above groundwater	A	1	–	1
	B	1	–	1
	C	1 or 3	–	4
Below groundwater; no water control contemplated	A	1	2	–
	B	1	3	–
	C	2 or 3	5	–
Below groundwater; dewatering or other control	A	2	2	2
	B	2	3	2
	C	2 or 3	5	4

Legend for Status of Nearby Structures

A = Structures outside zone of influence.

B = Structures inside zone of influence, underpinned.

C = Structures inside zone of influence, not underpinned or underpinning decision deferred.

Legend for Parameter Selection

1 = No monitoring required; or spot settlements only.

2 = Groundwater monitoring; spot settlements.

3 = Groundwater if appropriate; strut or anchor loads; structures monitoring.

4 = Groundwater if appropriate; strut or anchor loads; surface and subsurface settlements and horizontal displacements of structures, soil and supporting walls; possibly stresses in walls and earth and water pressures on walls.

5 = As 4 plus bottom heave.

— = Not applicable.

Note: The above guide is a gross simplification, and selection must always recognize specific needs and constraints of each project, and the conservatism of temporary support design. Progress monitoring is required in all cases, and should include all factors listed in text "Progress Monitoring".

For cut-and-cover tunnels, progress monitoring should include at least the following:

- *A record of depth* of excavation versus time, at close stations, including berm details, if any

- *Time of installation* of all walers and struts, with preload records, if any, and depth of excavation below strut at time of installation

- *Incidences of extraordinary ground losses,* groundwater behavior, observed distress, deviations from normal construction procedures, or any other unusual event

- *Complete as-built construction plans* and records, including pile driving and soil log

- *Environmental factors* which may, in themselves, affect monitored data, e.g. temperature, nearby construction activities.

6.7. Systematic Guide to Selection of Parameters

A systematic guide for the selection of basic monitoring parameters for various construction conditions is given in Tables 6–1 and 6–2. It must be realized,

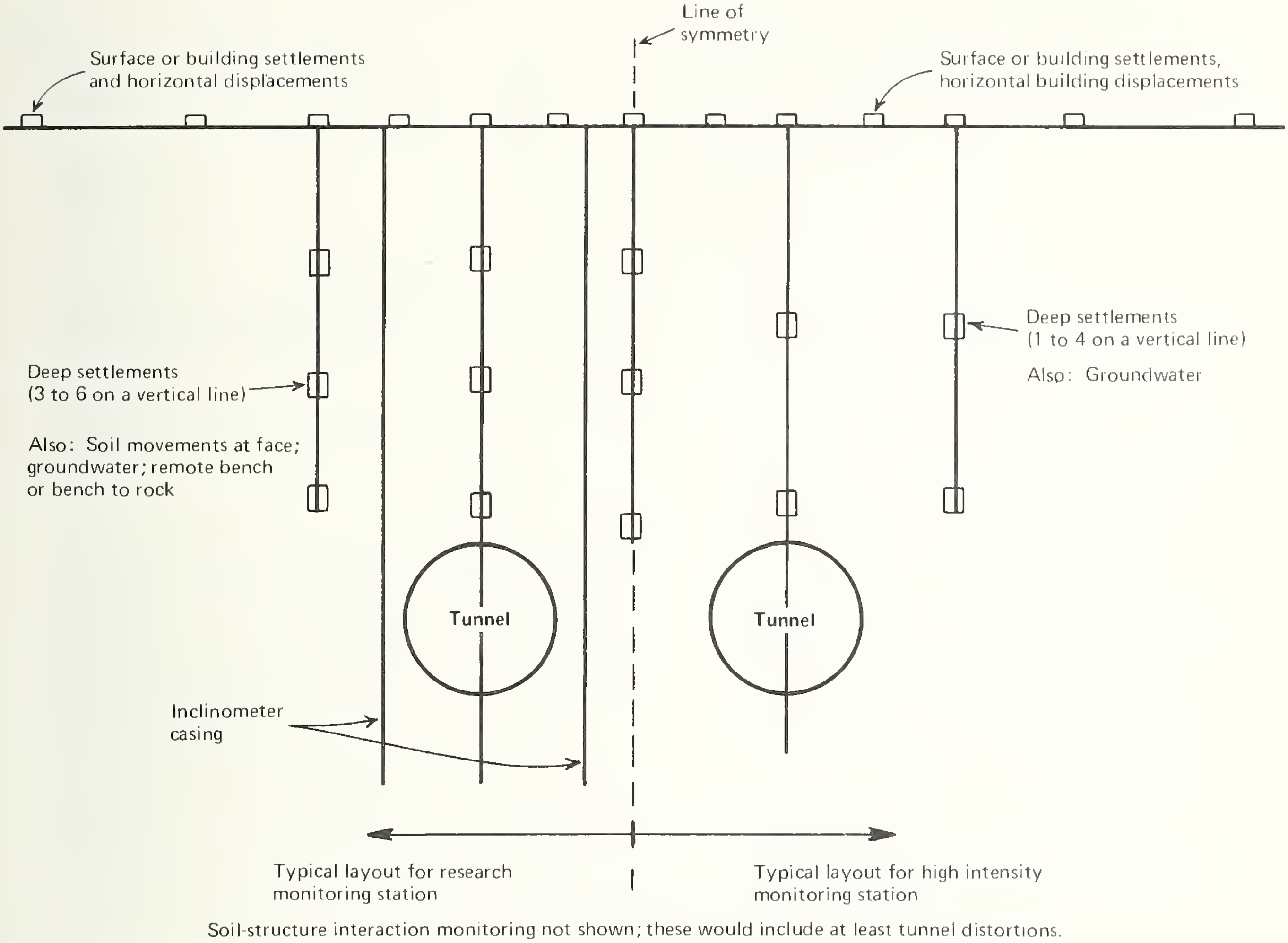


Fig. 6-16. Typical Research and High-Intensity Monitoring Stations for Ground Movements

however, that this guide is highly simplified. It is difficult to include all possible conditions in a simple table, and local practices, regulations, and labor conditions influence the selection of monitoring parameters.

Some typical monitoring layouts are shown on the accompanying figures following the tables. Figure 6–1 shows a monitoring plan at the beginning of a tunnel project. Figures 6–16 and 6–17 show typical monitoring arrangements of various intensities. For a pair of bored tunnels some 2,000 to 3,000 feet long in soil, where construction monitoring is deemed vital, a suitable selection of monitoring stations or cross sections might include:

- Two research-type stations
- Four to six high-intensity monitoring stations
- Six to twelve medium-intensity monitoring stations
- Low-intensity stations roughly every 50 feet

The research-type stations should be located near the beginning and near the middle of the tunnel drive. Since the initial distance of a tunnel drive is not usually typical of the contractor's capability, a research-type station should perhaps be placed one or several hundred feet from the beginning.

However, it is important that any problems be diagnosed early. Therefore, several high-intensity monitoring stations should be placed within the first several hundred feet. Other high-intensity stations should be placed where ground conditions have changed significantly, or where the data would have specific interest relating to existing structures down

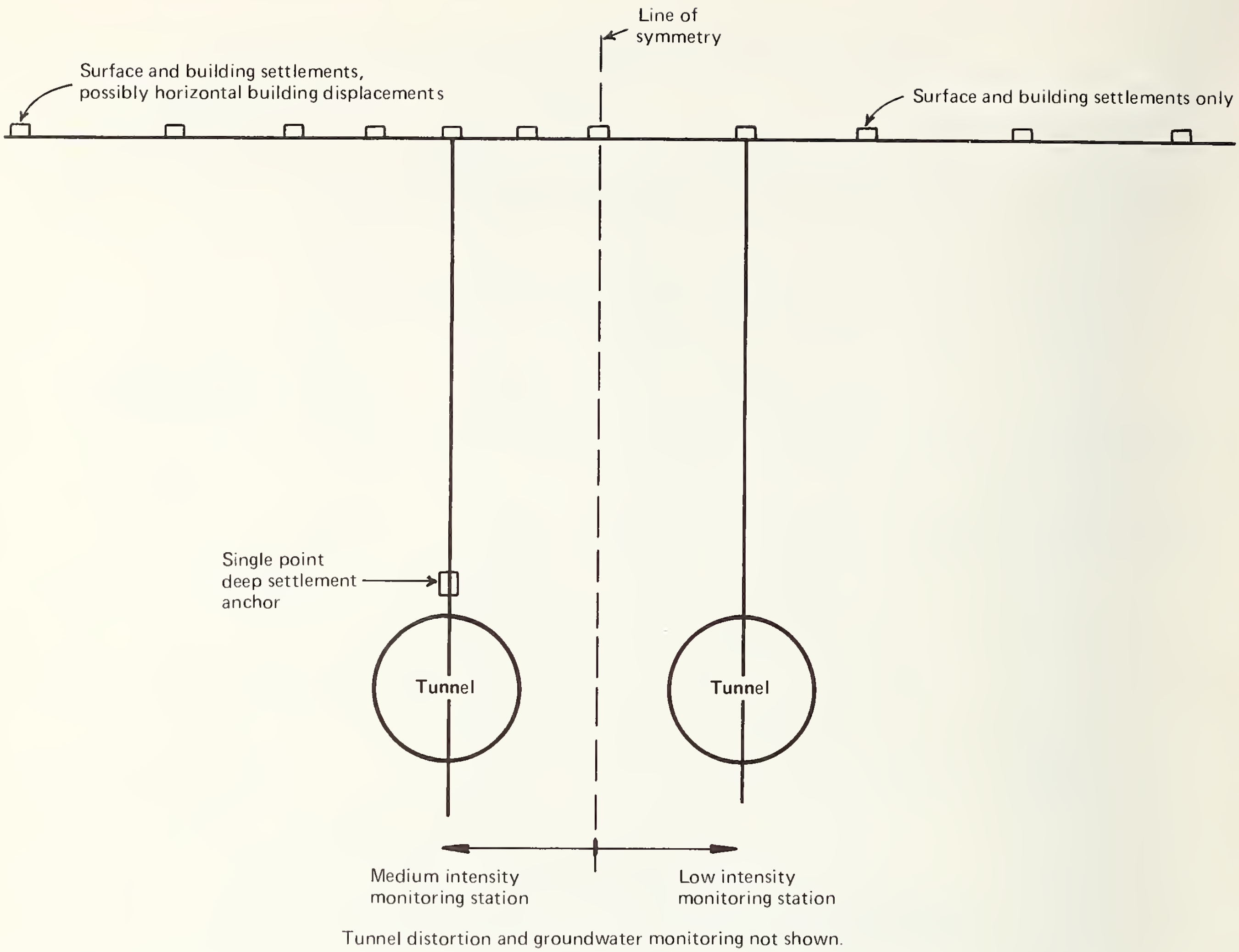


Fig. 6-17. Typical Medium- and Low-Intensity Monitoring Stations

the line. Medium- and low-intensity stations would be placed so as to gather sufficient coverage and sufficient statistical material and to cover specific existing structures.

The layouts shown are idealized. With street and building patterns prevailing in downtown areas where monitoring is of interest, it is not usually possible to provide complete monitoring stations. The station locations should be carefully chosen to take advantage of available space and to minimize traffic interference. Some of the measuring points may be on the exterior walls of buildings. It is often of interest whether the adjacent ground surface settles more or less than the building; therefore, it is often useful to place observation points on the ground and on the building, close together.

It is sometimes also necessary to monitor ground movements inside buildings; for example, interior columns, basement floors, or walls might be monitored. These points, however, are often poorly accessible, and their number should be minimized.

The necessary number and the location of observation wells depend greatly on the geologic conditions and on the locations of dewatering wells.

For deep excavations, monitoring points may include surface settlements and horizontal displacements every 50 feet along the wall, and inclinometer casings every 200 feet. The need for strut or anchor load measurements will depend greatly on the type of structure.

6.8. Monitoring Cost

The cost of monitoring includes not only the procurement and installation of instruments and reading points, but also the design work, maintenance and reading, and interpretation work. Often, the instrumentation itself is but a small portion of the total cost.

For most buried instruments, the cost of installation exceeds the cost of the instrument itself. Assuming that drilling a hole 4 inches in diameter costs $10 per foot (or a drill rig costs $450 per day), some typical estimate prices for procurement and installation of instruments are:

Inclinometer casing, 100 feet deep	\$2,000-\$3,000
Magnet/reed switch installation, 6 points, 100 feet deep	\$2,000-\$3,000
Two-point settlement anchor, 60 feet deep	\$800-\$1,400
Observation well, 100 feet deep	\$1,250-\$1,750
For remote readout depending on type and length of cable installation (not applicable to inclinometer) add for each	\$1,000-\$1,500
Marking and installing surface points, per point	\$10+

These estimates include the cost of engineering supervision, but not of special readout equipment, survey instruments, inclinometer torpedoes, and other equipment.

With prices such as these, the procurement and installation costs of the complete stations, shown previously on the figures, are about as follows:

Typical research monitoring station:	\$22,000
High-intensity monitoring station:	\$5,500
Medium-intensity monitoring station:	\$2,500
Low-intensity monitoring station:	\$100

For a typical tunnel project with intensive monitoring, the total instrumentation and installation cost could, then, amount to between \$80,000 and \$120,000. The directly associated planning and design work would be about 25 to 30 percent of this figure, for a total of \$100,000 to \$150,000. Assuming that part-time personnel would be mostly used for data acquisition and interpretation, with at least one full-time engineer, the personnel cost for six months of operation could be of the same order of magnitude, including all overhead and profits.

Finally, the use of a computer for data storage and retrieval and assistance in interpretation, is estimated at between \$15,000 and \$20,000.

The total cost of a complete, intensive monitoring program is, of course, highly variable, depending on its purpose and magnitude and the general conditions. To obtain the full benefits of a program of the scope just outlined, a cost of at least \$200,000 to \$300,000 must be expected. These costs are not often easily determined on an actual project, since they are spread through several contract items and amongst the owner, designer, contractor, and inspecting engineers.

Costs may be reduced by cutting the number of observation points, frequency of reading, or interpretive effort, or by eliminating one or several types of monitoring. Cutting inclinometer observations, in most cases, would eliminate a source of diagnostic data, but would ordinarily not severely restrict the benefits of tunnel construction monitoring (but would remove significant benefit from excavation monitoring). Since inclinometers are expensive, it would appear, then, that they are among the least cost-effective for tunnel monitoring. However, deep settlement monitoring is essential for diagnosing sources of ground loss and is probably the most important type of ground movement monitoring. Deep settlement anchors should not be eliminated as a cost-savings measure.

Dollar for dollar, the most cost-effective and essential effort is in the interpretive and implementation work, provided sufficient data are available for use.

Following is an example of monitoring essentially for research purposes; items of soil-structure interaction monitoring are included.

Example: A sewer tunnel in Staten Island was instrumented essentially for research purposes as follows:

- Strain gages to measure tunnel lining stresses caused by jack shoving loads
- Strain gages to measure also circumferential stresses
- Changes in tunnel diameter
- Surface settlement
- Subsurface settlements using magnet/reed switch device
- Piezometers

Six stations were thus instrumented, at a total cost of the order of \$40,000 per station, including design, layout, installation, monitoring, and report.

It is difficult to determine precisely what is the optimum monitoring effort for a particular project. It is a problem akin to the determination of precisely how many exploratory borings and tests are necessary to properly carry out design and construction. It is intuitively known that the more data obtained, the better that conditions can be predicted. Yet, there is a point of diminshing returns, and a point at which ordinary data handling and engineering just cannot cope with the mass of data to derive meaningful results. With future computer usage, perhaps the utility of such large data quantities can be extended.

7. Tools for Implementation

7.1. Overview

For a monitoring program to succeed and to benefit the project on which it is implemented, careful attention must be paid to specifications, contractual arrangements, and the setup of the inspection and implementation team to achieve the following goals:

- An awareness of the purpose and scope and the capabilities of the program instilled in both the contractor and the inspecting team

- An appropriate distribution of responsibilities, designed to maximize the motivation of all parties and minimize job interference

- The proper setup of contractual arrangements and payment items to achieve this goal

- The proper specifications for carrying out all monitoring and instrumentation duties

- The necessary tools in the specifications and contract arrangements to implement results of monitoring

- The appropriate team for data gathering, interpretation, and implementation

- Means to secure the contractor's indulgence and cooperation.

To avoid unnecessary concern on the part of the contractor that his work may be encumbered by excessive interference, only the items that are vital to the success of the construction should be subject to provisions empowering interference with the contractor's work. For example, items that are clearly related to construction safety only, for which the contractor himself is liable, should not ordinarily be subject to control by the inspecting engineers.

Furthermore, when the designer determines that control of the contractor's performance is vital, he must be specific in stating precisely under which circumstances such control may or may not be exercised, and to what degree it may be exercised. In some cases, it may be necessary to spell out the details of construction that may be subject to control, and precisely how. It is also important to allow the contractor equitable payment for certain items of work specifically requested by the inspecting engineers on the basis of such provisions.

These procedures should allow the contractor to present a bid without fear of undue interference, and thus without undue contingencies embodied in the bid. It is vital, however, in the interest of contractor cooperation that he understand the purposes and scope of all monitoring items.

Geotechnical Design Report. "Better Contracting for Underground Construction" (1974) recommends that *"All factual subsurface data, professional interpretations thereof, and design considerations thereby raised should be made available to bidders, but with a careful distinction drawn between factual data and interpretation or opinion."* It has been proposed that such information be included in a so-called Geotechnical Design Report, to be submitted to prospective bidders. This type of report is a perfect vehicle for supplying the contractor with expectations of his performance and for describing the purpose of the monitoring program. Perhaps nowhere are the design concepts more needed for bid evaluation and construction than when performance monitoring is made an integral part of design and construction.

When monitoring is determined to be vital for a project, the designer, as a matter of course, has spent considerable efforts in deciding what, under the prevailing circumstances, is possible and feasible and a reasonable requirement to the contractor. The reasoning behind these decisions is of vital interest to the contractor, and their presentation will tend to spur his pride and ingenuity, and raise his interest in developing the proper methodology for the project at hand. The contractor may, of course, not fully agree with all the interpretations made, but at least all bidders will understand what, in principle, is expected of them and thought possible.

In addition to factual exploration and test data, and other relevant observations and concepts, the report may contain the following types of information relating directly to monitoring efforts:

- Concerns for adjacent existing property and safety:

  1. *Concepts defined.* Background and reasoning behind selected protection schemes; role of monitoring in decisionmaking

2. *Acceptable movements of structures.* Criteria for acceptability; sensitivity of the various identified structures to settlement and distortion

- Basic purposes of monitoring:

1. *Types of monitoring employed.* Settlements and displacements, groundwater, and in-tunnel measurements; relation to identified potential problems

2. *Methods of interpretation.* Data handling procedures; methods of data reduction, analysis, and prediction

3. *Possible action based on monitoring data.* Means of altering contractor's work methods based on performance, means of control and reimbursement; refer to specifications

4. *Possible savings to the contractor.* Working procedures and short-cuts allowed only on the basis of favorable data.

7.2. Distribution of Responsibilities

The delegation of duties and responsibilities for execution of a monitoring program is a critical item. To ensure that instruments are properly installed, that readings are made with sufficient care and frequency, and that interpretations are done properly and in time, responsibilities should ideally be lodged with those who have the greatest incentive for quality monitoring, i.e. those who stand to gain by proper execution.

Practicality, site, and construction considerations, however, may require a deviation from this general principle. It may not be practical, for example, to distribute essentially similar types of surveying work to two or three different agencies. Also, the potential for interfering with the contractor's work and progress may make it desirable to let the contractor monitor parameters that are not strictly essential for his work but may be required for other purposes.

The responsibilities of the designers are relatively clear. They must define the scope and purpose of monitoring; prepare contract drawings, specifications and other materials such as to take full advantage of monitoring benefits; select monitoring parameters; design a monitoring program, including instrumentation; and prepare the necessary specifications for monitoring and instrumentation. They must also advise the owner of the most appropriate contracting arrangements, insurance arrangements, and inspection procedures. It is clear that inspection, insurance, contracting procedures, and specifications must mesh, but several combinations of arrangements may work satisifactorily.

Designer's Responsibilities:

- Define scope and purpose of monitoring
- Prepare drawings and specifications to implement benefits
- Select monitoring parameters
- Design monitoring and instrumentation program
- Draw up specifications for monitoring program
- Select contract arrangements
- Distribute responsibilities

Contractor's Responsibilities:

- Understand purpose and intent of monitoring
- Procure, install, monitor designated monitoring devices
- Report any other data required for interpretation
- Cooperate with inspecting engineers to minimize interference
- Improve construction methodology based on diagnoses from monitoring program

Inspecting Engineer's Responsibilities:

- Understand purpose and intent of monitoring
- Procure, install, monitor designated monitoring devices (often through specialist subcontractor)
- Supervise and check contractor data recovery
- Interpret
- Implement

The responsibilities of the contractor, which should be carefully defined in the specifications, would include the procurement and installation of all instruments within his direct work area, and certain other types of instruments. They would also include certain reading and maintenance tasks, replacement and removal of instruments, restoration, etc. The contractor may or may not be required to install instruments

Type of Instrumentation Monitoring		Simple	Sophisticated	Sophisticated
Location of Instruments or Monitoring		Anywhere	Outside contractor work area	Inside contractor work area
Examples		Observation well; optical survey; tunnel distribution and location	Deep settlement marker; inclinometer	Load cells or strain gages on structural supports; instruments within tunnel
Contract to Furnish and Install	Regular Item in Prime Contract	Suitable	Not suitable	Not usually suitable
	Separate Specialist Contract	Not required	Suitable	Not usually suitable
	Cost-Plus Items in Prime Contract	Not required	Suitable	Suitable, usually preferable
Prime Monitoring Agent		Contractor	Construction manager or his specialist	Contractor's specialist subcontractor

outside his direct work area. As a rule, the contractor must employ a specialist instrumentation subcontractor to supply, install, and maintain—and possibly read—sophisticated or complex instrumentation. Contractual arrangements must ensure that the specialist instrumentation subcontractor is employed on the basis of experience *and* cost, rather than on cost alone.

The contractor must also be responsive to suggestions and/or directives based on the results of monitoring. Clearly, monitoring is a way of measuring a contractor's performance, and certain boundaries would have been established to define acceptable performance. If the contractor does not meet performance requirements, modifications to his construction methods or remedial actions may be required. Specification items must be included to cope with this situation.

The responsibilities of the inspecting engineers are somewhat broadened by the effective use of monitoring. They include supervision of instrument procurement and installation in accordance with specifications and standards, certain reading and maintenance tasks, and data storage, retrieval, interpretation, and implementation, i.e., corrective action if required. It is very important that the inspecting engineers are fully aware of the designer's intent as regards the purposes and necessary follow-up of the monitoring program. It is probably necessary, as a general rule, to employ the consulting services of the original designer if he is not himself conducting construction inspection. The various possible arrangements and organizations for implementing a monitoring program are examined in the following section.

7.3. Contract Arrangements

The most feasible contract arrangements are apparent from the preceding discussion, but some special concerns and favorable arrangements should be noted. The box indicates three basic contract types that may be used for various monitoring programs.

Items Within Contractor's Expertise. Monitoring and instrumentation items that do not fall outside the ordinary contractor's expertise may be included in the specifications as contractor-supplied items (unless supplied and handled by the inspecting engineers). These may include:

- *Observation Wells.* Standard, standpipe-type wells or piezometers installed according to standard specifications at locations and elevations to be indicated by the design engineer. Elevations may be subject to field changes depending on soil stratification; it is desirable to place well screens immediately at a boundary between a lower impervious and upper pervious stratum, particularly if the tunnel is in part to be located in the pervious stratum.

- *Dimensional Measurements Within Tunnel.* The contractor will, for his own purposes, need a surveying system for steering and control of alignment and dimensions. Due to the severely restricted space available within the working tunnel, the introduction of unnecessary people, agents, measuring gadgetry and activities must be discouraged to minimize interference with work progress. To avoid conflicts, in-tunnel measurements (alignment checks, crown elevation, horizontal diameter, and variations of these) should usually be made by the contractor or an agent under his control. The log books of activities (chronological record) of grout quantities and water discharge quantities may also be kept by the contractor.

It is emphasized that the inspecting engineer must have full and immediate access to these data, must be allowed to monitor the taking of data, and must make occasional verification as needed. As for the observation wells, the inspecting engineers must have access to their reading as well.

Conventionally these items can be included in the bid. Observation wells can be included with a bid price per unit or per foot of installed well. These prices should include maintenance, reading, replacement, and removal. In-tunnel measurements and logging can be included either as a separate lump sum or as part of excavation costs.

Minimum requirements for log keeping as to detail and frequency must be presented in the specifications. It is often a good idea to present a form or format to be used for data presentation.

Items Outside Contractor's Expertise. Items that fall outside most contractors' expertise, but are significantly within their areas of work, or are of significant pecuniary interest to the contractor, should be included in his contract as cost-plus items, but should be carried out by a specialist subcontractor. It is recommended that the required specialist instrumentation subcontractor be selected in advance by the owner on a professional basis, or by the contractor in accordance with strict qualification requirements, and be subject to approval. The contractor will be allowed to bid a markup on the specialist's estimated cost to retain a degree of competition, but will not be responsible for the final selection of the specialist nor will he control his price. The approximate cost must be estimated by the designer (and/or the specialist) and entered in the bid schedule as fixed. The scope of the instrumentation work must be presented in such detail that the contractor may assess the possible interference with his work.

With this arrangement, the owner is assured quality instrumentation and monitoring work because the specialist will be hired on the basis of qualifications, not solely on least cost; yet the specialist works for the contractor, who will be able to properly schedule all required work with least interference. It is also possible to make even radical changes to the monitoring program during the course of the work—which is often necessary or desirable—without having to stop for lengthy renegotiations with the contractor.

Monitoring items that may fall into this category include, for open cuts, loads and stresses in anchors or tiebacks, and displacements within the excavation; for tunnels, monitoring of tail void space encroachment, stresses and loads in linings or tierods, and extensometers, if required.

Where the owner or the construction manager employs a team devoted to the implementation and utilization of monitoring efforts (more or less as described in Section 5.3), it would sometimes be appropriate to execute these types of monitoring directly by this team or under its jurisdiction. Supervision approval, checking, interpretation, and implementation certainly fall within this team's responsibility.

Items Outside Contractor's Work Area. A third category of monitoring items can be performed by noncontractor personnel with little or no interference with contractor progress. This category includes surface settlements and horizontal displacements of surface points and points on buildings adjacent to open cuts and over tunnels; deep settlements measured by extensometer rods or similar; and deep horizontal displacements measured by inclinometers. Though at least the surface settlements could be read by the contractor, all of these items could be made the responsibility of the inspecting engineers (but allowing the contractor access to the data). This will allow consistency in the taking and interpretation of the data. Groundwater level observations may be included in this package of monitoring, as well, provided the contractor has the opportunity to request readings to serve his needs.

Since the measurement of ground movements and their effects is part of the owner's control of the contractor's performance and not usually or traditionally of the contractor's interest, it stands to reason that, while the contractor may well install parts of the monitoring system, most such monitoring and all interpretation should be the responsibility of the inspecting engineers in collaboration with the original designers. Often, however, because of the relative simplicity of the work, surface settlements are measured by the contractor. Groundwater level observations are also most often carried out by the contractor—or more properly by his dewatering subcontractor—as an integral part of his dewatering program.

Example: For a section of the Baltimore Rapid Transit System, the proposed distribution of duties and responsibilities are as follows:

Final Designers:
- Conduct all feasibility studies, suggest monitoring program and distribution of responsibilities, write specifications including all items for contractor

General Designer and Geotechnical Consultant:
- Review and approve; organize contracts, insurance, and other items

Contractor:
- Install and monitor surface settlement points, including buildings
- Install and monitor groundwater observation wells (integral part of dewatering program)
- Monitor all elevations, locations, and distortions within tunnel and excavation

Construction Manager (through specialist consultant):
- Monitor horizontal displacements at surface, including buildings
- Monitor deep settlement points
- Monitor horizontal displacements at depth (inclinometer)
- Monitor strut (anchor) loads in station excavation
- Maintain all data files, interpret, implement.

Specifications are written, indicating as precisely as possible the potential impact of data interpretation on construction activities, including fair and equitable pay items where appliable and possible. A building protected by column pickup will be completely monitored by the contractor (or his subcontractor), including settlement, horizontal displacement as well as tilt.

The following example shows how a specification can be written for the selection of a specialist consultant or subcontractor for sophisticated monitoring, and how payment may be arranged. Such an arrangement can be organized in greater or lesser detail, depending on the degree of difficulty of the work.

Example: Monitoring Systems Specification (excerpted and adapted (excerpted and adapted from a specification by Erdman, Anthony Associates, Rochester, New York; comments in parentheses):

1. General
   (Contains definition of work, items of procurement, and distribution of duties and responsibilities.)

2. Geotechnical Consultant
   A. General. Engage the services of an approved Geotechnical Consultant (Specialist Instrumentation Subcontractor) to provide the technical services as specified herein.
   B. Selection Procedure.
   (1) Within 30 days submit the names and professional resumes of three Consultants to perform all the technical work associated with this item.
   (2) Within 30 days of submission, Engineer will inform the Contractor of the acceptability of any of the proposed Consultants. If any of the proposed Consultants are acceptable to the Engineer, Contractor will be directed to negotiate with the Consultant designated by the Engineer. If none are deemed acceptable, additional names and resumes will be submitted within 10 days of notice of rejection. Engineer is the sole judge of Consultant's acceptability. (A partial list of possibly acceptable professionals or firms may be supplied by the Engineer at time of Notice of Award or sooner.)
   (3) Terms, conditions, and scope of services of negotiated subcontract are subject to the Engineer's approval.
   (4) Submit the roster of personnel designated for the project to the Engineer for approval; include technical qualifications and experience records.
   (5) Engineer reserves the right to request removal of any person for just cause.
   C. Professional and Staff Requirements.
   (1) Consultant firm shall have special competence in geotechnical instrumentation and instrument installation and maintenance. (If subcontractor is to interpret data and perform other tasks, define here the necessary qualifications.)
   (2) Consultant firm shall employ personnel directly assigned to this project, with the following (or equivalent) qualifications:
      (a) Senior Geotechnical or Instrumentation Engineer: M.S. in Geotechnical Engineering, minimum three years experience in design, installation, and operation of geotechnical monitoring systems, registered in xxxxxxxxxx State.
      (b) Geotechnical Engineer: B.S. in Geotechnical Engineering and special competence in installation and operation of geotechnical monitoring systems.
   (3) Assign additional technical and

support personnel as necessary to fulfill work requirements specified herein.

(4) The Senior Geotechnical Engineer shall personally perform or supervise all instrument installations or replacements, and shall personally supervise and be responsible for all monitoring.

(5) He shall not be replaced without the Engineer's consent, unless he ceases to be in the Consultant's employ.

D. Responsibilities and Duties.

(1) Know all available relevant geotechnical data

(2) Know the purpose and intent of monitoring

(3) Perform pre-installation tests and calibrations as necessary to ensure acceptability and proper function of all instruments

(4) Install or supervise installation of all required equipment and service same

(5) Perform all required measurements, readings, and observations

(6) Report all certified data to Engineer in accordance with designated schedules

(7) All monitoring items, instrument, and equipment selection and schedules to be approved by the Engineer

(8) Evaluate and interpret all data (if selected to be within Consultant's duties). Notify Engineer of any deviation from design assumptions or criteria or established trends. Recommend course of action if required

(9) Submit interim and final reports as scheduled herein

(10) Attend all meetings that are deemed necessary for the progress of the project, at the request of the Engineer

(11) Perform such other duties as may be requested by the Engineer, consistent with the requirements of this section

E. Program Planning.

(Contains schedule of required conferences and submittals, and methods of submitting modification proposals.)

3. Instrumentation and Monitoring

(Contains all procurement, storage, installation, servicing, protection, and monitoring specifications and schedules, restoration requirements, and equipment salvage procedures; for more detail see Section 7.4.)

4. Claims

No time extension or extra payment will be recognized if based wholly or in part on unwarranted delays on the part of the Contractor in procuring the Consultant's services or in procuring the necessary equipment and appurtenances.

5. Just Cause for Dismissal

If the Consultant does not abide by the conditions and responsibilities as set forth herein or as amended by mutual consent, the Engineer may deem this non-compliance to be just cause for dismissal. The Engineer may then order the termination of the Consultant's services and his immediate replacement, and may order cessation of all related or affected work, until such time as the instrumentation program is again operative in the opinion of the Engineer, all at no extra cost to the Owner.

6. Inspection and Data Availability

The Owner, Engineer, or any designated representative may inspect equipment to be used, may inspect installation and monitoring operations, and may perform his own observations using any installed equipment. All data and observations shall be available to all parties of the contract. However, no data shall be divulged to any outside party or published in any form at any time without the Owner's written approval.

7. Measurement and Payment

A. Hardware. Payment for equipment and instrumentation hardware based on actual cost, supported by approved purchase invoices, to include all procurement, delivery, and storage expenses.

B. Labor. Payment for direct labor other than that performed by persons in Consultant's employ, performed under the Consultant's supervision and at his request, plus associated materials, at cost plus overhead, plus a 10 percent profit, based on documented expenditures. (Other force account procedures may be used.)

C. Consultant Services. Payment for Consultant's services on a professional fee basis based on approved, negotiated subcontract between Contractor and Consultants, plus a Contractor's markup of maximum 10 percent (bid item).

D. Allowances. Include the following allowances in Base Bid to cover all work specified in this section. Actual payment shall be in accordance with the terms set forth for each item:

(1) Equipment and Instrumentation Hardware (no markup): $ allowance

(2) Direct Labor, Materials and Expendables (including 10% markup) $ allowance

(3) Consultant's Services $ allowance

(4) Markup on Consultant's Services, (bid) % of item C $ bid

7.4. Specifications for Monitoring

Portions of the monitoring program to be carried out by the contractor can be detailed in relevant sections of the technical specifications. For example:

- Observation well installation and monitoring, when carried out by the contractor, belong in the section on dewatering. In this way, the observation of groundwater more clearly becomes an integral part of the dewatering program.

- Tunnel liner distortions and associated measurements, when taken by the contractor, belong in the section on earth tunneling and lining erection. This is where construction tolerances and items such as the possible need for tie rods would be written, together with other criteria based on the results of monitoring.

- Settlement and other dimensional monitoring directly related to an underpinning or other protection effort belong in the respective section describing that effort.

- Other types of monitoring, such as the monitoring of grout backfill behind linings and injection grouting, and the necessary record-keeping of miscellaneous progress data and observations, may be placed in sections describing the respective activities. This works well when the monitoring program is not too elaborate, and it can be paid for either as a part of the respective activity (when clearly defined), or on a unit basis where possible, e.g., number of measuring points, wells. The latter method of payment is best because it allows the engineer to request additional installations at a given rate of payment.

More elaborate monitoring efforts carried out by the contractor, and efforts not directly identifiable with a single construction activity, are best placed in a separate section on monitoring and instrumentation. A typical example would be the monitoring of surface settlements and displacements, and settlements of buildings, both over tunnels and adjacent to excavations.

When monitoring requires sophisticated instrumentation outside the contractor's ordinary expertise, but still to be conducted as a subcontract, a rather detailed specification is required for the proper execution of the work. This specification would be included in a section that would also describe the required subcontractor qualifications, method of payment, distribution of responsibilities, and conduct of the work within the subcontract.

Conditions are not much different, if the monitoring is to be carried out by a subcontractor under the auspices of the construction manager or a similar agent of the owner, except that the complete specification here forms a contract between the owner's agent and the subcontractor. A format similar to that shown in Section 7.3 can also be used for this purpose.

Either way, the specification or contract must, in addition to the elaboration of the general contractual arrangements and requirements, contain the necessary details of instrument selection (if not already selected), procurement, installation, reading, and reporting. The scope of this Handbook does not allow a complete description of detailed instrumentation specifications. For this, the reader is referred to Cording et al (1976), Schmidt and Dunnicliff (1975) and a Manual of Instrumentation to be prepared in 1976 under UMTA sponsorship. The main points that must be covered by the specification are briefly summarized below, in checklist format.

- *Procurement and Quality Control:* Minimum requirements for hardware; reference to standards where applicable; reference to drawings or details, including brand names where applicable; accuracy or tolerance required; durability standards. An interim instrument procurement specification, covering items applicable to many types of instruments, is shown in Schmidt and Dunnicliff (1975), Volume II.

- *Installation:* Reference to drawings for locations and details; detailed specification of, for example, observation well or inclinometer casing installation, or strain gage placement, including also readout boxes for remote reading where required.

- *Protection:* Covers or locks against vandalism; drainage facilities to prevent water accumulation; signals to make instruments visible to prevent accidental damage by workers or construction equipment.

- *Replacement:* Damaged or inoperative instruments to be replaced at no cost to the owner if caused by contractor negligence.

- *Accessibility:* Provide all necessary access to instrument locations, including ladders if required.

- *Removal:* Instrument removal and restoration of street surface; salvage of instruments if possible.

- *Checks and Calibrations:* Calibrations where possible at regular intervals and/or immediately before critical measurements.

- *Measurement Schedule:* Timing and frequency of readings related to construction progress and actual data.

- *Other Data:* Those that are necessary for interpretation, such as temperature, progress data, and miscellaneous observations.

- *Record Keeping and Reporting:* Format of records, schedule and timing of reports.

These items of specifications for monitoring and instrumentation deal with the data gathering process. The manner of implementing the results of the monitoring program is, perhaps, of even greater importance. If there is no mechanism for requesting a modification of work methods based on monitoring data, the data become nearly useless except as a legal and contractual record. The next section examines some of the ways to provide equitably for such modifications.

7.5. Specifications for Implementation

General Contractual Provisions. Specifications are often separated into three parts: the general provisions, the special provisions, and the technical specifications. The complete document also includes plans and drawings. The general provisions are included in all contracts of the type considered.

Since monitoring programs are tailor-made for individual contracts, little material relevant to monitoring enters the general provisions. These do, however, spell out in general terms the contractual and insurance arrangements that may have relevance to the writing of other pertinent paragraphs in other parts of the specifications.

Special Provisions. These will contain some or all of the following items:

- Amendments and additions to the general provisions regarding contractual arrangements, such as the requirement that the instrumentation specialist to be in charge of specific items (mandatory), be (a) the one selected by the owner, (b) one of several specialists prequalified by the owner, (c) meet specific qualification requirements and approved by the engineer.

- Method of payment for monitoring and instrumentation tasks designated for the contractor to implement. Preset estimated cost with markup as the sole bid item is preferred for most of these tasks except those directly related to steering and the achievement of devised tunnel geometry. This item may also be placed in the instrument specification.

- Explanation of all monitoring efforts not included in the contractor's efforts, but which may affect his work.

- Incentive awards (or penalties) based on monitored performance. Cash awards may be made for the driving of tunnels in designated sections with resulting settlements less than a specified amount. The first, say 100 feet, may be excluded from such award, and the award may be reduced by a progressive formula for each segment unsuccessfully tunneled.

> *Example:* Assume 3,000 feet of twin tunnels in an urban area. A maximum $300,000 award may be given for driving these tunnels from a point 100 feet from the edge of the construction shaft to the end, with monitored settlements everywhere less than, say, two inches. For each 100-foot section (with designated boundaries) completed with maximum single-point settlement between two and three inches, but average centerline settlement less than two inches, $10,000 would be subtracted from the award. For each 100-foot section with maximum single-point settlement greater than three inches, or average greater than two inches, $20,000 would be subtracted. The settlement measurements applicable to this provision would be those taken after the second of the twin tunnels has passed 100 feet beyond the section in question.

Depending on the type of insurance and arrangements with adjacent property owners, incentives could also be tied to recognized damage or claims from property owners.

Technical Specifications. The items to be covered under technical specifications are discussed in the following subsections.

- *Instrumentation and Monitoring.* The specifications covering the instrumentation and monitoring efforts themselves are described in Section 7.4.

- *Excavation.* Excavation covers a multitude of construction efforts. Some or all of the following items may be affected by monitoring results.

    1. If compressed air is used, the air pressure may be determined in part on the basis of ground movement monitoring and observations at the face.

    2. Face support may be requested or modified based on monitoring data and observations. Note that anticipated face support requirements may affect the contractor's choice of equipment (wheel or hoe excavator).

3. Excavation beyond the cutting edge of the shield may or may not be allowed, depending on monitoring data. This item may work out to the advantage of the contractor, allowing him to work ahead of the face if data are favorable.

- *Dewatering.* As an example, work may be halted (at no extra cost for delay time) if soil is not adequately dewatered by the system of wells. The term "adequately dewatered" must be clearly defined, e.g. by the allowed height of groundwater above an impervious strata boundary. The requirement may be relaxed if monitoring data and observations demonstrate that no significant ground movement or ground loss will result. While the layout of observation wells may be developed in principle by the designer, it is considered advisable to have the contractor or his subcontractor design the dewatering system and the detailed layout of observation wells. To achieve the most efficient dewatering system, it is usually necessary to log the soils encounted during placement of pumping and observation wells, and to monitor both pumped quantities and water levels in observation wells. Specifications should require a groundwater monitoring effort that is commensurate with the anticipated approach to dewatering, and the complexity of the groundwater regime, to be carried out by the contractor. Observations at the tunnel face and in the excavation are necessary to ensure that the dewatering goals are achieved.

- *Lining and Backfilling.* The success of ground control in the region of the tail void is highly dependent on proper timing and execution of grout backfilling. In areas of caving soil (as diagnosed by observations and/or by measured ground movements, preferably extensometers just above the centerline), grout shall be applied under adequate pressure to achieve complete filling as soon as possible after each shove. This requirement may be relaxed in areas shown to be stable. The grout seal shall be maintained in an adequate state of repair. Work may be halted (at no extra cost to the owner) if the seal will not allow proper filling in diagnosed caving areas. Temporary tie rods may be required until grout backfilling is complete if measurements show difficulty in achieving the desired circular shape (the acceptable deviations must be defined elsewhere under tolerances). Likewise, temporary tie rods may be required in soft soils in the first of two twin tunnels when the second tunnel passes nearby, if measurements show excessive distortions of the first tunnel due to the driving of the second tunnel. A unit price pay item is needed for each tie rod installed and removed with the engineer's approval or at his request.

- *Ground Improvement.* Where injection grouting is foreseen as a possible remedy against excessive ground movement, ground losses at the face or in the tail void, or ground losses caused by groundwater flow, the specifications should require (1) the availability of standby grouting equipment (with a mobilization bid item), (2) availability of qualified grouting personnel at, say, 24-hour notice, and (3) unit bid items (or upset items) for grout application by measured materials and for delay time measured from the time the engineer requests or approves the grout application and tunnel driving stops until the last grout application is finished. Such grouting may be conducted from the ground surface or from the tunnel itself. In the former case, delay time may not be invoked. Grouting in lieu of dewatering shall not be paid for unless the ground water has been drawn down to the required elevation or unless the engineer determines that it is impractical or impossible to do so.

- *Excavation (Shafts and Stations).* The maximum allowed excavation depth below the last installed strut or anchor level should be stipulated. If unanticipated excessive ground movements can be ascribed to this feature by diagnostic analysis of monitoring data, the maximum allowed excavation depth may be adjusted. Assuming, however, that the engineers have not disapproved excavation and shoring plans submitted by the contractor, a reimbursement for the extra effort is called for, and provisions should be made for negotiating this as a change. In rare instances, appropriate bid items based on several different support spacings may cover this contingency. If, on the other hand, excavation at one point has reached bottom with ground movements better than anticipated, the contractor may be allowed to propose a greater support spacing or other changes, subject to approval and negotiation of a reduced price.

- *Bracing.* Should strut load measurements or other observations indicate impending danger, the contractor shall be obliged to stop any work that might increase the danger and install appropriate additional support at no extra cost to the owner unless conditions qualify for the changed condition clause.

- *Underpinning and Other Protection.* It is unlikely that unanticipated underpinning would be required during the course of construction. This may happen when an underpinning decision has been deliberately deferred and performance monitoring discloses significantly adverse ground movements, or it may be due to truly changed and adverse conditions. In such instances, provisions should be available for giving the contractor standby payments, perhaps deliberately preset lower than cost to discourage misuse of such an item, and a negotiated or force account payment for underpinning items. It is easier to accommodate within the contract additional protective work in the form of injection grouted walls or foundation support. Such work may be included in a format similar to that indicated previously under Ground Improvements.

- *Final Note on Specifications.* It must be recognized that no specification items and no monitoring can be made effective unless the basic performance requirements are well thought out and properly stated, and that restrictions considered essential are carefully entered into the contract documents. The design of the contractor's shield and his methods of operation must be compatible with the performance requirements. For example, it may be necessary to prohibit the use of forepoling plates, overcutting in front of the cutting edge, excessive relieving bar or bead on the cutting edge, or a shield design allowing excessive tail void space. It is also necessary to state the required and acceptable tolerances of work, the required dewatering and results. Great care should be taken in the writing of the specifications to make all requirements and restrictions compatible with the expected performance and the possible effects of monitoring results.

7.6. Project Inspection and Control

The Inspection Team. The duties of the inspecting engineers, contract arrangements, and responsibilities were touched upon in Section 7.2. Section 5.3 shows the type of organization required to make the most out of tunnel construction monitoring for a complete local system encompassing a number of individual contracts. Here it suffices to expand on the technical requirements of the inspection team on a single contract basis.

Obviously, the size, the level of expertise, and the level of decision-making power depend on the size and complexity of the individual contract. For small contracts, or contracts where monitoring is to be done only for the record, the general staff of the owner or his designated agent may accomplish the necessary work, with access to expert advice for troubleshooting.

More commonly, on a standard-size contract, a more elaborate team is required, dedicated specifically to this contract, but with expert guidance from the management to ensure uniformity of decisions to be made and to ensure that the data will be available to other contracts and to other designers in need. The team would include:

- An experienced senior geotechnical/tunnel engineer, with organizational and analytical abilities

- One or several engineers (graduate students may fill several of these positions)

- A survey crew (several crews at critical times) for surface surveys, if not performed by the contractor

- One or several technicians for instrument readings (may use junior engineers or graduate students)

- One key punch operator.

The engineers should be capable of providing rapid logging and interpretation of data, with computer assistance as needed. Crews and personnel should be available for night shift work when necessary. On many projects, one member of the team should be present at the tunnel face at practically all times during work for logging, for critical face observations, and for any in-tunnel measurements. In cuts, the continued presence of a team member may not be required.

Certain decisions may be made in the field by a qualified team member, or in the field office by the team field manager, with concurrence by the resident engineer. Field decisions involving work interference or significant additional expenditures will need concurrence by the construction management.

Methods of Interpretation and Prediction. One of the functions of the system manager will be to educate the inspection and monitoring personnel. This is a relatively new and highly specialized field, and the methods of analyzing this type of monitoring data and making appropriate predictions and assessments are not well-known.

Insofar as possible, methods of data treatment, interpretation, and the resulting predictions should be standardized throughout a project, indeed throughout an entire system; provided, however, that improvements be incorporated as they develop.

As an example, surface settlements over tunnels should be analyzed using the error function as a standard. Settlements and other ground movements adjacent to cuts should be treated in dimensionless formats to give credence to extrapolation. Data sheets and presentation formats should be standardized where possible.

Computerized Data Handling. The large quantity of data ordinarily accumulated during tunnel construction monitoring, together with the appropriate standardization of data processing, lends itself to computerized data handling. A computer program to handle most ground movement and groundwater data for tunneling in soil has been described in Schmidt and Dunnicliff (1974). While this program is not yet available, it may be written in a matter of weeks at a nominal cost. Such a program would be of considerable value in providing rapid conclusions to be developed by the responsible parties.

Though a similar program description for open-cut monitoring is not yet available, it can be produced with little effort. For example, inclinometer data are already now generally subject to computerized data treatment. Strut load data on the San Francisco BART system were routinely handled by computer. Wherever automatic data acquisition (from remote or inaccessible data points) is required, consideration should be given to incorporation of equipment that will produce computer-ready copy.

Final Notes. It must be acknowledged that a rigorous and standardized data treatment may tend to oversimplify certain types of problems. On the other hand, where large quantities of data have to be treated by a number of individuals, uniformity of data handling and control must be maintained to prevent arbitrary and inconsistent decisions.

Nonetheless, there is no substitute for intelligent and educated assessment of the data, and for the involvement of high-caliber professionals in this type of work.

Continued education of engineers and planners on all levels, accumulated experience of professionals, and the evolutionary changes in contract types and specifications continually occurring promise to make monitoring increasingly more successful and cost-effective in the future.

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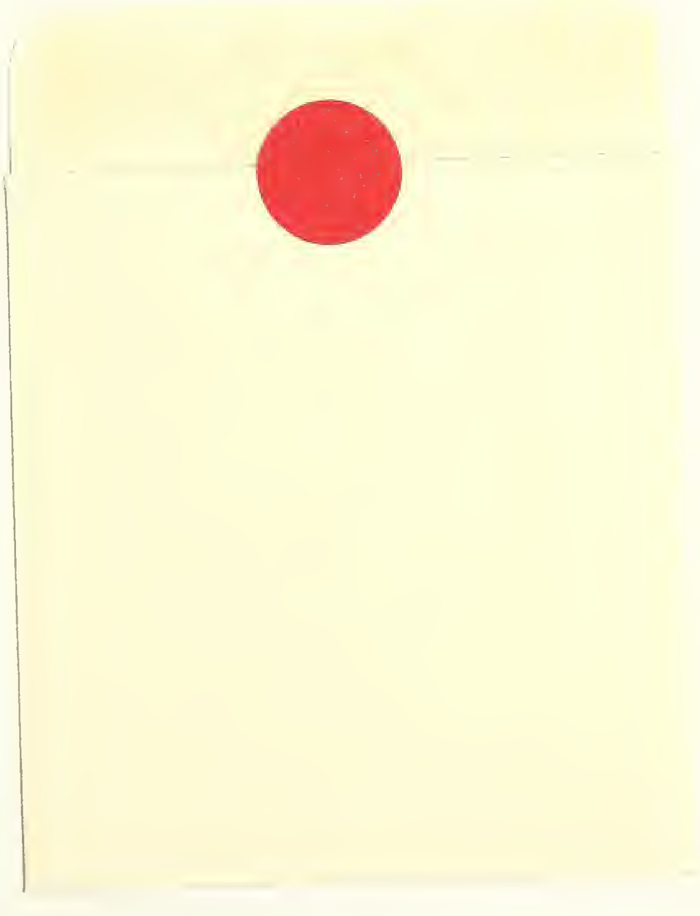

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