Design of Tunnel Support Systems

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This paper deals with the results of a recent evaluation of procedures for the design of tunnel liner systems; the relationships among the geologic materials to be tunneled, construction methods, and support systems; practical guidelines for the design of tunnel supports in both soil and rock; and problems associated with improving existing support systems for high-speed tunneling.

•SELECTION AND DESIGN of the support system are only two of many interrelated factors in the overall design of a serviceable and economical tunnel. The type of support, the method of excavation, and the character of the ground are inseparable considerations. If the route is laid out to encounter the worst rather than the best geological features, or if the construction method is ill-suited to the geology, no amount of refinement of the lining can appreciably influence the economy of the job. Nevertheless, for each tunnel layout and each construction method, some types of lining are preferable to others. Initial support during construction and final support during the functional life of the tunnel pose separate requirements; sometimes both are best satisfied by a single support system.

Rational design presupposes a knowledge of the demands on support systems, criteria for successful performance, familiarity with the capabilities of available systems, and methods of analysis verified by experience. Improved practice in the future is likely to have its roots in a clear understanding of the shortcomings and requirements of today's practices. This paper summarizes several current studies on the various aspects of design of the support systems for transportation tunnels.

TYPES AND FUNCTIONS OF TUNNEL SUPPORT SYSTEMS

The basic functions of a tunnel support system are to keep the tunnel stable and to make the opening usable. The specific purposes of support systems, however, depend greatly on the purposes of the tunnel.

Traditionally, tunnel supports have been classified into two groups, temporary and permanent. In modern transportation tunnels, however, no such clear distinction can be drawn. Modern supports do not rot away and thus are not as temporary as the timber sets used years ago.

The first supports installed will probably carry all the loads ever expected on the tunnel as long as the supports do not deteriorate. These supports, which carry either the full load or the greatest share of the load, are called the primary support system. The primary support system must provide the initial support for the opening, control the deformations within the tunnel, and minimize disturbance to adjacent and overlying structures.

Any lining that covers the primary support system is called the secondary liner. In a transportation tunnel, a secondary liner may be required to provide corrosion protection for the primary support system, to provide watertightness, or for environmental

Paper sponsored by Committee on Soil and Rock Properties and presented at the 49th Annual Meeting.

reasons such as aesthetics. It may be uneconomical and unnecessary to make transportation tunnels watertight because infiltrating water can often be easily controlled and drained from the tunnel. Thus, except for the case of a watertight tunnel, the secondary liner need not be designed as a structural member. In a watertight tunnel, the secondary liner can be designed to share the load with the primary support system.

A savings of up to one-third of the total cost of a tunnel can sometimes be achieved by eliminating the secondary liner altogether (6). On some projects merely making the primary support system corrosion-resistant has permitted elimination of the secondary liner.

TYPES OF PRIMARY SUPPORT SYSTEMS

Rock Tunnels

Three main types of primary support systems are presently used in rock tunnels in the United States. They are rock bolts, steel sets, and shotcrete. Shotcrete is a pneumatically applied large-aggregate concrete. The need for a secondary lining in a tunnel supported by shotcrete depends on the purpose of the tunnel. Table 1 gives present use of the three types of primary support systems for rock tunnels in various rock conditions. Each of the three support systems can be used under a wide range of tunneling conditions, with some limitations in the poorer quality rock.

Recently, the Bernold System has been used with considerable success in poor quality rock in Europe (9). The system consists of the use of pumpcrete to fill the annulus between curved expanded metal sheets that are placed close to the face. Movable steel sets provide temporary support until the concrete cures.

Soil Tunnels

Table 2 summarizes the applicability of several types of support systems in various soil conditions. In contrast to tunnels in rock, only one or two support systems are likely to be both technically and economically feasible in any given soil condition. Soil tunnels often have secondary liners, but shield-driven tunnels have traditionally been constructed without a secondary liner because the primary support system was of cast iron and corrosion-resistant. More modern shield tunnels, lined with concrete or coated steel segments, are also corrosion-resistant and require no secondary liner.

PLANNING AND DESIGN OF TUNNEL SUPPORT SYSTEMS

Planning and design decisions are of two classes, conceptual and detailed. Decisions of the first class are based on considerations of such factors as the purpose of the project; the depth, alignment, and geometry of the opening; the external environment; and

TABLE 1

USE OF PRIMARY SUPPORT SYSTEMS FOR ROCK TUNNELS

Support System	Quality of Rock				Remarks
	Good	Fair	Poor	Very Poor	
Rock bolts	Yes	Yes	?	No	Difficult or impossible to obtain anchorage in poor and very poor rock.
Shotcrete	Yes	Yes	Yes	?	May not require secondary liner for corrosion protection. Future developments are promising. Supplementary support is required in poorer quality rock.
Steel sets	Yes	Yes	Yes	Yes	Usually more expensive but sometimes is the only system that can be used.

Note: Table reflects 1969 technology.

TABLE 2

PRIMARY SUPPORT SYSTEMS FOR SOIL TUNNELS

Type of System	Remarks
Bolted steel segments	Generally used in poor soil conditions. Too expensive in other soil conditions. Have been coated with corrosion-resistant film and used without a secondary liner (10).
Bolted cast iron segments	Often used for shield-driver tunnels in soft soil. Too expensive in other soil conditions. Does not require secondary liner for corrosion protection.
Bolted concrete segments	Not yet used in the United States. Applicable to poor soil conditions. Does not require secondary liner for corrosion protection.
Unbolted concrete segments	Used only in soil having long stand-up time, such as very stiff clay. Does not require secondary liner for corrosion protection.
Steel ribs and wood lagging or with liner plates	Versatile under most soil conditions except running or flowing sand and squeezing clay.
Liner plates without steel ribs	Used only for small-diameter tunnels.
Shotcrete	Useful in soils having sufficient stand-up time. Cannot withstand thrust from shield. Does not require secondary liner.
Cast-in-place concrete	Used only for small-diameter tunnels in good soil conditions.

Note: Table reflects 1969 technology.

the required watertightness. The results of these decisions constitute the conceptual design of the underground opening. It may include several alternatives.

The detailed design is then performed to provide several alternate construction methods and support systems that meet the requirements of the conceptual design. The tunneling scheme that results in the lowest total cost for the project is selected.

Few decisions in the design process can be made completely independently of each other. The geology associated with alternate axes at different depths and alignments should be a fundamental consideration in the conceptual design. The selection of the depth and alignment determines the geologic materials that must be tunneled. The materials encountered, in turn, dictate which types of construction methods are feasible. Other construction methods, even though intrinsically cheaper, no longer can be considered. The support system must be compatible with the geology and the construction method. Hence, with the geology and construction method fixed, only a few support systems can be considered.

The selection of the route alignment and grade is one of the most important decisions to be made. If unfavorable conditions will be encountered, the resulting high construction costs cannot be offset by refinements in the design of the support system.

The design of a support system is usually a matter of selection. The selection is more complex than indicated by Tables 1 and 2. Throughout planning and design, the engineer needs to be aware that the geology of the material to be tunneled is the most important variable in establishing the design, construction, and, ultimately, the cost of the tunnel.

MODERN CONCEPTS OF THE DESIGN OF TUNNEL SUPPORT SYSTEMS

During excavation, most of the existing stresses in the ground are redistributed around the opening by mobilization of the strength of the soil or rock. The redistribution is often described as arching. Usually only enough support must be added within a short time after excavation to help the soil or rock hold itself up.

Current soil and rock mechanics practice is to recognize and treat the behavior of any system as a complex function of the interaction of the behavior of the individual components of the system. In contrast, previous concepts and theories for the design of tunnel supports have been based solely on assumed loading diagrams; hence, they are unsatisfactory. Furthermore, because the soil or rock being tunneled does not meet the appropriate assumptions, elastic and elastic-plastic theories are rarely satisfactory for predicting the loads in tunnel supports. The designer must somehow account for the deformation in both the soil or rock and the support. The best way to visualize this interaction phenomenon is by the simplified ground reaction curve shown in Figure 1.

A schematic load-deformation diagram is shown in Figure 1. The ordinate represents the load in a support when deformation of the tunnel walls has ceased. As the soil or rock deforms toward the tunnel, more strength of the medium is mobilized and more stress is redistributed around the opening. The ground reaction curve qualitatively reflects this redistribution. For any given radial deformation, the ordinate of the ground reaction curve represents the load that must be applied to the walls of the opening to prevent any further deformation.

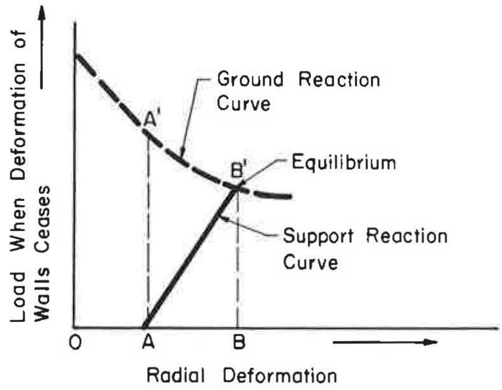

Figure 1. Simplified ground reaction curve.

The inevitable deformation that occurs before the supports can be installed is denoted by line OA. If at this stage a perfectly incompressible support is installed, the load in the support is represented by the ordinate of the ground reaction curve, line AA′, at that deformation. But supports are, in fact, not incompressible. The stress-strain curve of the support is represented by the support reaction curve. While the supports deform radially, the walls of the tunnel also deform until equilibrium is reached at a deformation of the walls of the tunnel equal to OB, a deformation of the supports equal to AB, and a load in the supports equal to BB′.

Unfortunately, at the present time the ground reaction curve cannot be theoretically defined in most materials. Furthermore, even if theory could be used to predict the curve, the large local variations in construction procedures would inhibit the usefulness of the curve for practical design of supports. Research and field instrumentation are continuing to develop these concepts, but for the present the semi-empirical methods described in the following sections appear to be best for practical design of tunnel supports.

GUIDELINES FOR THE SELECTION OF PRIMARY SUPPORT SYSTEMS FOR ROCK TUNNELS

This section presents practical guidelines for the selection and sizing of primary support systems for tunnels in rock. The recommendations are keyed to rock conditions that are described and quantified by a weighted or modified core recovery, RQD (rock quality designation). The RQD differs from the percent core recovery in that the RQD considers only the aggregate length of the pieces of NX core that are 4 in. in length or longer. Shorter lengths of core are not considered. The system is described by Deere et al. (1) and is correlated with the behavior of tunnels by Deere, Merritt, and Coon (2). The rock quality classification is given in Table 3.

TABLE 3

ROCK QUALITY CLASSIFICATION

Rock Quality	RQD (percent)	Approximate Tunnelman's Classification
Excellent	90-100	Intact
Good	75-90	Massive, moderately jointed
Fair	50-75	Blocky and seamy
Poor	25-50	Shattered, very blocky and seamy
Very poor	0-25	Crushed

Guidelines for selection of support systems for 20-ft to 40-ft diameter tunnels in rock are given in Table 4. The table is based on experience and the results of field measurements. The recommended rock load for steel sets is smaller than the upper bound of the original recommendations by Terzaghi (7). Support requirements are reduced in machine tunnels because the rock is not disturbed by blasting. A discussion of the use and

TABLE 4

GUIDELINES FOR SELECTION OF PRIMARY SUPPORT FOR 20-FT TO 40-FT TUNNELS IN ROCK

Rock Quality	Construction Method	Alternative Support Systems: Steel Sets			Rock Bolts[a] (Conditional use in poor and very poor rock)		Shotcrete[b] (Conditional use in poor and very poor rock)		
		Rock Load (B = Tunnel Width)	Weight of Sets	Spacing[c]	Spacing of Pattern Bolts	Additional Requirements and Anchorage Limitations[a]	Total Thickness: Crown	Total Thickness: Sides	Additional Support[b]
Excellent[d] RQD > 90	Boring machine	(0.0 to 0.2)B	Light	None to occasional	None to occasional	Rare	None to occasional local application	None	None
	Drilling and blasting	(0.0 to 0.3)B	Light	None to occasional	None to occasional	Rare	None to occasional local application 2 to 3 in.	None	None
Good[d] RQD = 75 to 90	Boring machine	(0.0 to 0.4)B	Light	Occasional to 5 to 6 ft	Occasional to 5 to 6 ft	Occasional mesh and straps	Local application 2 to 3 in.	None	None
	Drilling and blasting	(0.3 to 0.6)B	Light	5 to 6 ft	5 to 6 ft	Occasional mesh or straps	Local application 2 to 3 in.	None	None
Fair RQD = 50 to 75	Boring machine	(0.4 to 1.0)B	Light to medium	5 to 6 ft	4 to 6 ft	Mesh and straps as required	2 to 4 in.	None	Provide for rock bolts
	Drilling and blasting	(0.6 to 1.3)B	Light to medium	4 to 5 ft	3 to 5 ft	Mesh and straps as required	4 in. or more	4 in. or more	Provide for rock bolts
Poor RQD = 25 to 50	Boring machine	(1.0 to 1.6)B	Medium circular	3 to 4 ft	3 to 5 ft	Anchorage may be hard to obtain. Considerable mesh and straps required.	4 to 6 in.	4 to 6 in.	Rock bolts as required (~4-6 ft cc.)
	Drilling and blasting	(1.3 to 2.0)B	Medium to heavy circular	2 to 4 ft	2 to 4 ft	Anchorage may be hard to obtain. Considerable mesh and straps required.	6 in. or more	6 in. or more	Rock bolts as required (~4-6 ft cc.)
Very poor RQD < 25 (Excluding squeezing and swelling ground)	Boring machine	(1.6 to 2.2)B	Medium to heavy circular	2 ft	2 to 4 ft	Anchorage may be impossible. 100 percent mesh and straps required.	6 in. or more on whole section		Medium sets as required
	Drilling and blasting	(2.0 to 2.8)B	Heavy circular	2 ft	3 ft	Anchorage may be impossible. 100 percent mesh and straps required.	6 in. or more on whole section		Medium to heavy sets as required
Very poor, squeezing or swelling ground	Both methods	up to 250 ft	Very heavy circular	2 ft	2 to 3 ft	Anchorage may be impossible. 100 percent mesh and straps required.	6 in. or more on whole section		Heavy sets as required

Note: Table reflects 1969 technology in the United States. Groundwater conditions and the details of jointing and weathering should be considered in conjunction with these guidelines particularly in the poorer quality rock. See Deere et al. (3) for discussion of use and limitations of the guidelines for specific situations.

[a]Bolt diameter = 1 in., length = 1/3 to 1/4 tunnel width. It may be difficult or impossible to obtain anchorage with mechanically anchored rock bolts in poor and very poor rock. Grouted anchors may also be unsatisfactory in very wet tunnels.

[b]Because shotcrete experience is limited, only general guidelines are given for support in the poorer quality rock.

[c]Lagging requirements for steel sets will usually be minimal in excellent rock and will range from up to 25 percent in good rock to 100 percent in very poor rock.

[d]In good and excellent quality rock, the support requirement will in general be minimal but will be dependent on joint geometry, tunnel diameter, and relative orientations of joints and tunnel.

limitations of these guidelines for specific situations has been published (3). These guidelines, coupled with the designer's personal experience, form a basis for design, although small changes will doubtless be required during construction to account for the inevitable uncertainties.

GUIDELINES FOR SELECTION OF PRIMARY SUPPORT SYSTEMS FOR SOIL TUNNELS

Theoretical studies and full-scale field observations lead to the conclusion that a semi-empirical design procedure is warranted for soil tunnels (3, 5). The procedure consists of four separate steps:

1. Provide adequately for the ring load to be expected;
2. Provide for the anticipated distortions due to bending;
3. Give adequate consideration to the possibility of buckling; and
4. Make allowance for any significant external conditions not included in 1 to 3 above.

For each of the steps, recommendations are given to the extent justified by the present state of the art. Lack of enough information to permit a recommendation indicates a need for further observational data.

Ring Load

The ring load in the lining of a single tunnel, except possibly in swelling clays, is likely always to be considerably smaller than that corresponding to the overburden pressure. Nevertheless, it is suggested that the ring load for design be taken as that due to an all-around pressure γz where γ is the total unit weight of the soil and z is the depth to the axis of the tunnel. Present knowledge is inadequate to permit a more refined estimate. Furthermore, for linings of such commonly used materials as steel, cast iron, or structural concrete, design for a ring thrust to withstand an all-around pressure γz would not usually increase the minimum cross sections that would be used for practical constructional reasons. The design pressure γz also provides a satisfactory allowance for the influence of adjacent tunnels.

Bending

For a single tunnel, an estimate should be made of the magnitude of the change in diameter most likely to occur if a perfectly flexible lining of the same shape as the tunnel were installed in soil comparable to that at the site. A procedure for estimating this distortion is suggested by Peck (5). Field data show that almost irrespective of the rigidity of the lining, and even in soft clays and silts, the change in diameter of a lining rarely exceeds 0.5 percent. If the change in diameter is acceptable with respect to the non-structural requirements, two courses of action are open: (a) to provide an essentially flexible lining such as one consisting of articulated blocks, or (b) to provide a continuous lining that can change shape from circular to elliptical, by an amount corresponding to the change in diameter, without overstress. The limiting stress, whether in the elastic or inelastic range, should be ascertained by the designer according to the stress-strain properties of the material. The second alternative is slightly conservative, because the distortion will be reduced by whatever stiffness the lining possesses.

If multiple tunnels are to be constructed, the same procedure should be followed except that the lining must accommodate the additional distortion associated with the subsequent tunnels. If primary and secondary linings are used, the possibility should be investigated of delaying placement of the secondary lining until all tunnels have been driven.

Buckling

Buckling has been noted in tunnels where supports twisted or were irregularly blocked. However, there is no report of a failure by buckling of a tunnel lining due to earth pressures acting in planes at right angles to the axis of the tunnel if soil or grout was everywhere in contact with the lining. Provisions should be specified and enforced for uniform closely spaced blocking, uniform filling of the annular space behind shields, or systematic expansion of the lining against the soil. Structural features explicitly designed to prevent buckling can safely be omitted with the exceptions previously mentioned.

External Conditions

The lining should be designed with ample reserve strength for shield-jacking loads and for unsymmetrical or three-dimensional distortions likely at the heading itself. These requirements often govern the thickness of the lining. Reasonable circumferential and longitudinal strength and continuity of semi-rigid linings should be provided to allow for normal adjacent operations such as pile driving or excavating on a small scale.

IMPROVING SUPPORTS SYSTEMS FOR HIGH-SPEED TUNNELING

The future of high-speed tunneling promises many exciting changes in support systems. Innovations are likely to fall into two broad categories: (a) improvements in materials or installation techniques for existing support systems and (b) radically different methods of support. Additional requirements will be imposed on support systems if methods such as the flame-jet or laser beam are used for excavation. If any of these novel methods of rock breakage are successful in attaining production status, support systems will have to be developed that are compatible with the radically different construction method.

If high rates of advance are achieved by using conventional boring machines, the corresponding support systems will have to be both inexpensive and capable of rapid installation. Satisfying both of these requirements concurrently may prove to be difficult. Willis and Stone (8) conclude that from 1970 to 1985, liner installation is likely to represent the constraining factor on the rate of advance of soil tunnels. Mathews (4) discusses several other future problems in the development of support systems. The potential for progress in developing support systems lies in field observations to determine the behavior of actual tunnels during construction as well as in research on innovations in the installation of support systems. Support systems can thus be developed concurrently with the improvements in excavation techniques.

ACKNOWLEDGMENTS

This paper describes the results of a series of studies conducted by the Civil Engineering Department of the University of Illinois for the Office of High Speed Ground Transportation, U.S. Department of Transportation.

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