Chapter 2
General Considerations

2-1. Approach to Tunnel and Shaft Design and Construction

Design and construction of tunnels and shafts in rock require thought processes and procedures that are in many ways different from other design and construction projects, because the principal construction material is the rock mass itself rather than an engineered material. Uncertainties persist in the properties of the rock materials and in the way the rock mass and the groundwater will behave. These uncertainties must be overcome by sound, flexible design and redundancies and safeguards during construction. More than for any other type of structure, the design of tunnels must involve selection or anticipation of methods of construction.

2-2. Rock as a Construction Material

a. When a tunnel or shaft is excavated, the rock stresses are perturbed around the opening and displacements will occur. The rock mass is often able to accommodate these stresses with acceptable displacements. The stable rock mass around the opening in the ground, often reinforced with dowels, shotcrete, or other components, is an underground structure, but a definition of the degree of stability or safety factor of the structure is elusive.

b. If the rock is unstable, rock falls, raveling, slabbing, or excessive short- or long-term displacements may occur and it must be reinforced. This can be accomplished either by preventing failure initiators such as rock falls or by improving the ground's inherent rock mass strength (modulus). Either way, the rock mass, with or without reinforcement, is still the main building material of the tunnel or shaft structure.

c. Unfortunately, geologic materials are inherently variable, and it is difficult to define their properties with any certainty along a length of tunnel or shaft. In fact, most tunnels must traverse a variety of geologic materials, the character of which may be disclosed only upon exposure during construction. Thus, ground reinforcement and lining must be selected with adaptability and redundant characteristics, and details of construction must remain adaptable or insensitive to variations in the ground.

d. Geologic anomalies and unexpected geologic features abound and often result in construction difficulties or risks to personnel. For example, inrush of water or occurrence of gases can cause great distress, unless the contractor is prepared for them. Thus, an essential part of explorations and design revolves around defining possible and probable occurrences ahead of time, in effect, turning the unexpected into the expected. This will permit the contractor to be prepared, thus improving safety, economy, and the duration of construction. In addition, differing site condition claims will be minimized.

2-3. Methods and Standards of Design

a. Considering the variability and complexity of geologic materials and the variety of demands posed on finished underground structures, it is not surprising that standards or codes of design for tunnels are hard to find. Adding to the complexity is the fact that many aspects of rock mass behavior are not well understood and that the design of man-made components to stabilize the rock requires consideration of strain compatibility with the rock mass.

b. This manual emphasizes methods to anticipate ground behavior based on geologic knowledge, the definition of modes of failure that can, in many cases, be analyzed, and principles of tunnel design that will lead to safe and economical structures, in spite of the variability of geologic materials.

2-4. Teamwork in Design

a. Because of the risks and uncertainties in tunnel and shaft construction, design of underground structures cannot be carried out by one or a few engineers. Design must be a careful and deliberate process that incorporates knowledge from many disciplines. Very few engineers know enough about design, construction, operations, environmental concerns, and commercial contracting practices to make all important decisions alone.

b. Engineering geologists plan and carry out geologic explorations, interpret all available data to ascertain tunneling conditions, and define geologic features and anomalies that may affect tunnel construction. Engineering geologists also participate in the design and assessment of ground support requirements, initial ground support, the selection of remedial measures dealing with anomalous conditions, selection of lining type, and the selection of basic tunnel alignment. The engineering geologist may require the help of geohydrologists or other specialists. Note: details of initial ground support design are usually left to the contractor to complete.

c. Hydraulics engineers must set the criteria for alignment and profile, pressures in the tunnel, and tunnel finish (roughness) requirements and must be consulted for analysis and opinion when criteria may become compromised or when alternative solutions are proposed.

d. Structural engineers analyze steel-lined pressure tunnels and penstocks and help analyze reinforced concrete linings. Structural engineers also assist in the basic choices of tunnel lining type and participate in the selection and design of initial ground support components such as steel sets.

e. Geotechnical engineers participate in the design and assessment of ground support requirements, initial ground support, the selection of remedial measures dealing with anomalous conditions, selection of lining type, and basic tunnel alignment.

f. Civil engineers deal with issues such as construction site location and layout, drainage and muck disposal, site access, road detours, and relocation of utilities and other facilities.

g. Civil engineers or surveyors prepare base maps for planning, select the appropriate coordinate system, and establish the geometric framework on which all design is based as well as benchmarks, criteria, and controls for construction.

h. Environmental staff provides necessary research and documentation to deal with environmental issues and permit requirements. They may also lead or participate in public involvement efforts.

i. Construction engineers experienced in underground works must be retained for consultation and review of required or anticipated methods of construction and the design of remedial measures. They also participate in the formulation of the contract documents and required safety and quality control plans.

j. Other professionals involved include at least the specification specialist, the cost estimator (often a construction engineer), the drafters/designers/computer-aided drafting and design (CADD) operators, and the staff preparing the commercial part of the contract documents.

2-5. The Process of Design and Implementation

Aspects of tunnel engineering and design, geology, and geotechnical engineering must be considered in all stages of design. The following is an overview of the design and implementation; details are discussed in later sections of this manual.

a. *Reconnaissance and conception*. Project conception in the reconnaissance stage involves the identification and definition of a need or an opportunity and formulation of a concept for a facility to meet this need or take advantage of the opportunity. For most USACE projects with underground components, the type of project will involve conveyance of water for one purpose or another—hydropower, flood control, diversion, water supply for irrigation or other purposes.

b. *Feasibility studies and concept development*.

(1) Activities during this phase concentrate mostly on issues of economy. Economic feasibility requires that the benefits derived from the project exceed the cost and environmental impact of the project. Design concepts must be developed to a degree sufficient to assess the cost and impact of the facility, and "show-stoppers" must be found, if present. Show-stoppers are insurmountable constraints, such as environmental problems (infringement on National Park treasures or endangered species, required relocation of villages, etc.) or geologic problems (tunneling through deep, extensively fractured rock, hot formation waters, noxious or explosive gases, etc.).

(2) Alternative solutions are analyzed to define the obstacles, constraints, and impacts and to determine the most feasible general scheme including preliminary project location and geometry, line and grade, as well as access locations. In the selection of line and grade, the following should be considered:

- Alternative hydraulic concepts must be analyzed, hydraulic grade lines defined, as well as the need for appurtenant structures, surge chambers, use of air cushion, etc.

- Alternatives such as shafts versus inclines and surface penstocks versus tunnels or shafts.

- Difficult geologic conditions, which may require consideration of alternate, longer alignments.

- Tunneling hazards, such as hot formation water, gaseous ground, etc.

- Tunnel depth selection to minimize the need for steel lining and to maximize tunneling in rock where final lining is not required.

- Access points and construction areas near available roads and at environmentally acceptable locations.

- Spoil sites locations.

- Schedule demands requiring tunnels to be driven from more than one adit.

- The number of private properties for which easements are required. In urban areas, alignments under public streets are desirable. Example: A long stretch of the San Diego outfall tunnel was planned to be (not actually built at this time) placed under the ocean, several hundred feet offshore, to avoid passing under a large number of private properties.

- Environmental impacts, such as traffic, noise and dust, and the effect on existing groundwater conditions.

(3) During the feasibility and early planning stages, engineering surveys must establish topographical and cultural conditions and constraints, largely based on existing mapping and air photos. Available geologic information must also be consulted, as discussed in Chapter 4, at an early time to determine if sufficient information is available to make a reliable determination of feasibility or if supplementary information must be obtained.

(4) This phase of the work should culminate in a complete implementation plan, including plans and schedules for data acquisition, design, permitting, land and easement acquisition, and construction. Strategies for public participation are also usually required.

c. Preconstruction planning and engineering.

(1) During this stage, the line and grade of the tunnel(s) and the location of all appurtenant structures should be set, and most information required for final design and construction should be obtained.

(2) Survey networks and benchmarks must be established, and detailed mapping must be carried out. Surveying required for construction control may be performed during final design. In urban areas, mapping will include all affected cultural features, including existing utilities and other facilities. Property ownerships must be researched.

(3) Geologic field mapping, geotechnical exploration and testing, and hydrologic data acquisition must also be completed in this phase and geotechnical data reports prepared. Environmental and permitting work, as well as public participation efforts, continue through preliminary design.

(4) The preliminary design will also include an assessment of methods and logistics of construction, compatible with schedule requirements. Trade-off studies may be required to determine the relative value of alternative designs (e.g., is the greater roughness of an unlined tunnel acceptable for hydraulic performance? Will the added cost of multiple headings be worth the resulting time savings?).

(5) Preconstruction planning and engineering culminates with the preparation of a General Design Memorandum, often accompanied by feature design memoranda covering separate aspects of the proposed facility.

d. The construction stage: Final design and preparation of contract documents.

(1) Contract drawings will generally include the following information:

- Survey benchmarks and controls.

- Tunnel line and grade and all geometrics.

- Site: existing conditions, existing utilities, available work areas, access, disposal areas, traffic maintenance and control, signing.

- Geotechnical data.

- Protection of existing structures.

- Erosion and siltation control; stormwater protection.

- Portal and shaft layouts.

- Initial ground support for all underground spaces, portals, shafts; usually varies with ground conditions.

- Criteria for contractor-designed temporary facilities; e.g., temporary support of excavations.

- Sequence of construction, if appropriate.

- Final lining where required (concrete, reinforced concrete, steel).

- Appurtenant structures and details.

- Cathodic protection.
- Instrumentation and monitoring layouts and details.
- Site restoration.

(2) All segments of the work that are part of the completed structure or serve a function in the completed structure must be designed fully by the design team. Components that are used by the contractor in the execution of the work but are not part of the finished work are the responsibility of the contractor to design and furnish. These include temporary structures such as shaft collars and temporary retaining walls for excavations, initial ground support in tunnels that are strictly for temporary purposes and are not counted on to assist in maintaining long-term stability, temporary ventilation facilities, and other construction equipment. When the designer deems it necessary for the safety, quality, or schedule of the work, minimum requirements or criteria for portions of this work may be specified. For example, it is common to provide minimum earth pressures for design of temporary earth retaining walls.

(3) The specifications set down in considerable detail the responsibilities of the contractor and the contractual relationship between contractor and the Government and the terms of payments to the contractor.

(4) While Standard Specifications and specifications used on past projects are useful and may serve as check lists, they are not however substitutes for careful crafting of project-specific specifications. Modern contracting practice requires full disclosure of geologic and geotechnical information, usually in the form of data reports available to the contractor. For work conducted by other authorities, a Geotechnical Design Summary Report (GDSR) or Geotechnical Baseline Report (GBR) usually is also prepared and made a part of the contract documents. This report presents the designers' interpretation of rock conditions and their effects and forms the basis for any differing site conditions claims. Preparation of such reports is not practiced by USACE at this time, with few exceptions.

e. *Construction*.

(1) A construction management (CM) team consisting of a resident engineer, inspectors, and supporting staff is usually established for construction oversight. This team is charged with ascertaining that the work is being built in accordance with the contract documents and measures progress for payment. Safety on the job site is the responsibility of the contractor, but the CM team must ascertain that a safety plan is prepared and enforced.

(2) During construction, the designer participates in the review of contractor submittals. Where instrumentation and monitoring programs are implemented, the designer will be responsible for interpretation of monitoring data and for recommending action on the basis of monitoring data. The design team should also be represented at the job site.

f. *Commissioning and operations*.

(1) Before an underground facility is declared to be completed, certain tests, such as hydrostatic testing, may be required. Manuals of operations and maintenance are prepared, and as-built drawings are furnished for future use by the operator.

(2) Permanent monitoring devices may be incorporated in the facility for operational reasons. Others may be installed to verify continued safe performance of the facility. Typical examples of permanent monitoring facilities include observation wells or piezometers to verify long-term groundwater effects.