

# Design Guidelines for Sequential Excavations Method (SEM) Practices for Road Tunnels in the United States

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**ABSTRACT:** In the last 20 years the Sequential Excavation Method (SEM) or the New Austrian Tunneling Method (NATM) has been gaining popularity and use in the United States. Its use is versatile, in various ground conditions and at various depths. Although many of the projects were successfully completed, the lack of design guidelines for underground construction and in particular for the SEM construction, in which it relies on observational method and assessment of the ground behavior at the face, has negatively impacted the tunneling industry. Recognizing the need to develop design guidelines for underground construction, in 2007 FHWA awarded a contract to Parsons Brinckerhoff to develop and publish a design manual for road tunnels. As a result of this contract, “Technical Manual for Design and Construction of Road Tunnels—Civil Elements” was published in November 2008. The Manual provided specific guidelines for SEM construction. This paper provides a summary of the guidelines for the design and construction of tunnels using Sequential Excavation Method with emphasis on its technical aspects, contractual issues, and practices in the US based on the recommendations and guidelines made in the above stated publication.

## INTRODUCTION

The increased use of underground space for transportation systems and the increasing complexity and constraints of constructing and maintaining above ground transportation infrastructure has prompted the United States Federal Highway Administration (FHWA) to recognize the need to develop a technical manual for the design and construction of road tunnels in the US. In 2007 it awarded a contract to Parsons Brinckerhoff to develop and publish design guidelines for road tunnels. As a result of this contract the “Technical Manual for Design and Construction of Road Tunnels—Civil Elements” was published in November 2008 and placed on FHWA website [www.fhwa.dot.gov](http://www.fhwa.dot.gov). The manual included a dedicated chapter on the design and construction of tunnels using the Sequential Excavation Method (SEM) or the New Austrian Tunneling Method (NATM) or Conventional Tunneling using the nomenclature of Working Group 19 of the International Tunneling Association (ITA).

It is important to recognize that the manual consists of guidelines and not code provisions and its use by the highway and road authorities of each state is not mandatory. However, the lack of any other authorities’ guidelines or codes renders this

manual to be an invaluable source of information for the design and construction of tunnels in the United States.

The authors of this paper (being the main author of the SEM chapter and the principal investigator of the manual) provide their insight on the practices of SEM tunneling in the US relying on their experiences, knowledge, and recommendations made in the above stated manual.

## SEQUENTIAL EXCAVATION METHOD GUIDELINES

Sequential Excavation Method (SEM) design practices in the US rely on the development of ground classification and support classes based on extensive geotechnical investigations, the establishment of excavation support classes and initial support, and the use of supplemental measures (tool box) for tunnel excavation, pre-support and ground improvement measures coupled with a comprehensive monitoring and instrumentation program.

### Ground Classification and Support Classes

A series of qualitative and quantitative rock mass classification systems have been developed over the years and are implemented on tunneling projects

worldwide including the Q system and the Rock Mass Rating (RMR) system and are used on rock tunneling projects to establish a geotechnical baseline and basis for the derivation of excavation and support classification.

Rock mass classification systems aid in the assessment of the ground behavior and ultimately lead to the definition of the support required to stabilize the tunnel opening. While the above quantitative classification systems lead to a numerical rating system that results in suggestions for tunnel support requirements these systems cannot replace a thorough design of the excavation and support system by experienced tunnel engineers.

All classification systems have in common that they should be based on thorough ground investigation and observation. The process from the ground investigation to the final definition of the ground support system can be summarized in three models:

- Geological Model
- Geotechnical Model
- Tunnel Support Model

### ***Geological Model***

A desk study of the geological information available for a project area forms the starting point of the ground investigation program. Literature, previous projects, maps and published reports (e.g., from the US Geological Survey) form the basis for a desk study. Subsequently and in coordination with initial field observation and mapping results, a geotechnical investigation program is developed and carried out. The geological information from the geotechnical investigation, field mapping, and the desk study are compiled in the geological model.

### ***Geotechnical Model***

With the data from the geological model in combination with the test results from the ground investigation program and laboratory testing, the ground response to tunneling is assessed. This assessment takes into account the method of excavation, tunnel size and shape as well as other parameters such as overburden height, environmental issues, proximity of adjacent structures and facilities, and groundwater conditions. The geotechnical model assists in deriving zones of similar ground response to tunneling along the alignment and Ground Response Classes (GRC) are defined. These GRCs form the baseline for the anticipated ground conditions during tunneling. Typically, the ground response to an unsupported tunnel excavation is analyzed in order to assess the support requirements for the stabilization of the opening.

### ***Tunnel Support Model***

After assessing the ground support needs, excavation and support sequences, subdivision into multiple drifts, as well as the support measures are defined. These are combined in Excavation and Support Classes (ESCs) that form the basis for the Contractor to develop a bid as well as to execute the tunnel work.

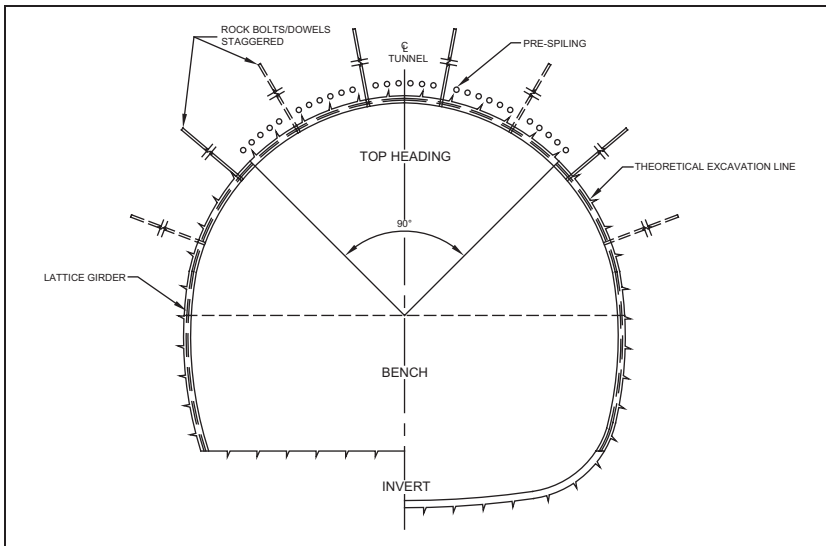
### **Excavation and Support Classes (ESC) and Initial Support**

Excavation and Support Classes (ESCs) contain clear specifications for excavation round length, subdivision into multiple drifts, initial support and pre-support measures to be installed and the sequence of excavation and support installation. They also define means of additional initial support or local support or pre-support measures that augment the ESC to deal with local ground conditions that may require such additional support. They also define supplemental support if needed.

Initial support is provided early on. In soft ground and weak rock it directly follows the excavation of a round length and is installed prior to proceeding to the excavation of the next round in sequence. In hard rock tunneling initial support is installed close to the face. The intent is to provide structural support to the newly created opening and ensure safe tunneling conditions. Initial support layout is dictated by engineering principles, and risk management needs.

The amount and design of the initial support was historically motivated mainly by the desire to mobilize a high degree of ground self support and therefore economy. This was possible at the outset of SEM tunneling applications in “green field” conditions where deformation control was of a secondary importance and tolerable as long as equilibrium was reached. Nowadays, however, safety considerations, risk management, robustness and conservatism, design life, and the need for minimizing settlements in urban settings add construction realities that ultimately decide on the layout of the initial support.

Initial support is provided by application of a layer of shotcrete to achieve an interlocking support with the ground. Shotcrete is typically reinforced by steel fibers or welded wire fabric. Plastic fibers are used for reinforcement only occasionally although its application appears to become more frequent. With higher support demands of the ground and with shotcrete thicknesses of generally 150 mm (6 inches) or greater lattice girders are embedded within the shotcrete to provide for the structural requirements. Occasionally and if needed by special support needs rolled steel sets are used in lieu of, or in combination with lattice girders.



**Figure 1. Prototypical excavation support class (ESC) cross section**

Figure 1 and Figure 2 show a prototypical ESC cross section and longitudinal section respectively. Figure 1 displays a cross section without a closed invert on the left side and ring closure on its right side. Invert closure is typically required in soft ground and weak rock conditions and in squeezing ground. Figure 2 includes elements of typical initial support including rock bolts/dowels, initial shotcrete lining and tunnel pre-support. The arrangement of rock bolts/dowels is typical and varies depending on the excavation and support. The table in Figure 2 provides details of initial support measures for a prototypical ESC Class IV. In that sense, conventional tunneling is a prescriptive method which defines clearly and in detail tunnel excavation and initial support means.

**Tunnel Profile and Distribution of Excavation and Support Classes**

Contract documents contain all Excavation and Support Classes (ESCs) assigned along the tunnel alignment in accordance with the Ground Response Classes (GRCs) and serve as a basis to estimate excavation and initial support quantities. A summary longitudinal section along the tunnel alignment shows the anticipated geological conditions, the GRCs with the relevant description of the anticipated ground response, hydrological conditions and the distribution of the ESCs. Figure 3 displays a prototypical longitudinal profile with an overlay of GRCs and corresponding ESCs, which form a baseline for the contract documents.

Geological data, Ground Response Classes, Excavation and Support Classes, the Longitudinal Tunnel Profile as well as design assumptions and methods are described and displayed in reports that become part of the contract documents. When defining the reaches and respective lengths of GRCs and corresponding ESCs it is understood that these are a prognosis and may be different in the field. Therefore contract documents establish the reaches as a basis and call for observation of the ground response in the field and the need for their adjustment as required by actual conditions encountered. Actual conditions must be accurately mapped in the field to allow for a comparison with the baseline assumptions portrayed in the GRCs.

**Tunnel Excavation, Support, and Pre-Support Measures**

The use of most common initial support measures, along with excavation and support installation sequencing frequently associated with conventional tunnels depending on the basic types of ground encountered, i.e., rock and soft ground were summarized and presented in the FHWA Technical Manual for Design and Construction of Road Tunnels. These tables indicate basic concepts to derive Excavation and Support Classes (ESCs) for typical ground conditions portrayed.

Table 1 in the manual addresses rock tunnels and builds on the use of Terzaghi’s Rock Mass Classification. It distinguished between the following rock mass qualities:

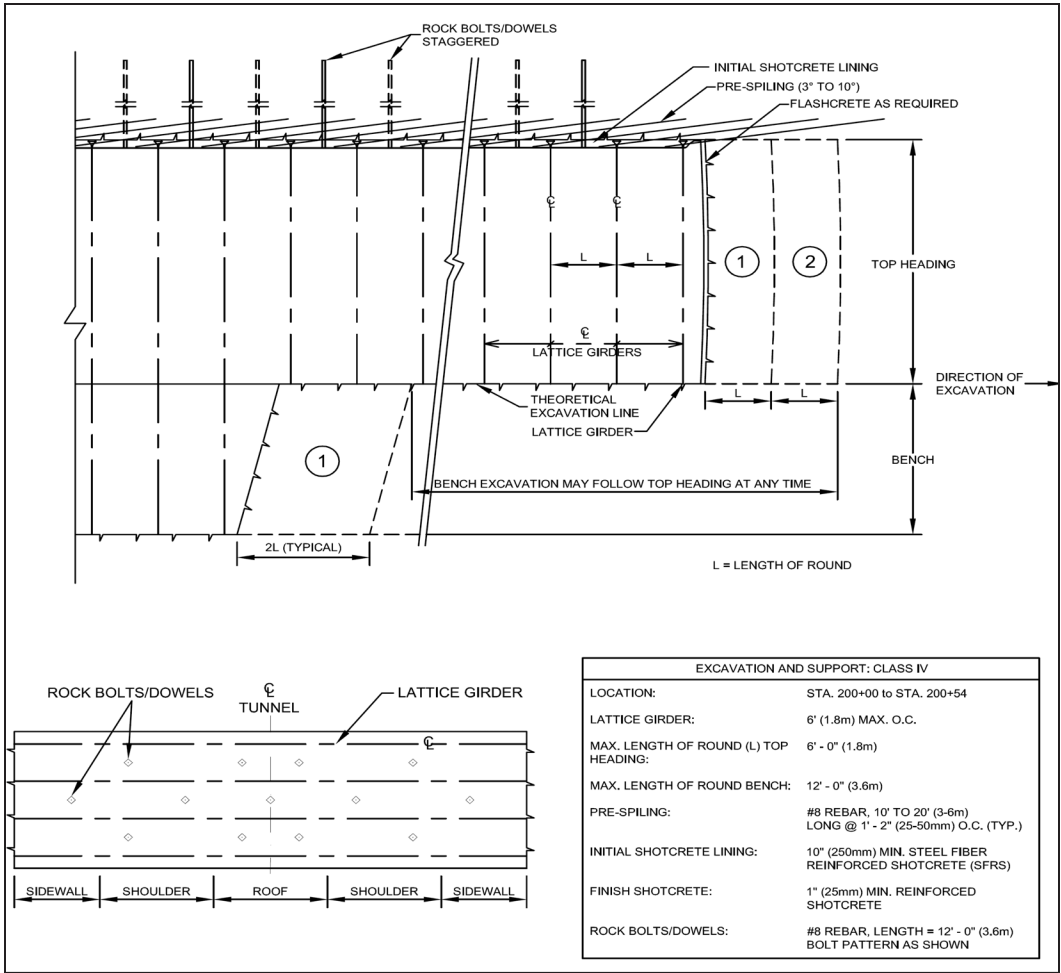


Figure 2. Prototypical Longitudinal Excavation and Support Class (ESC)

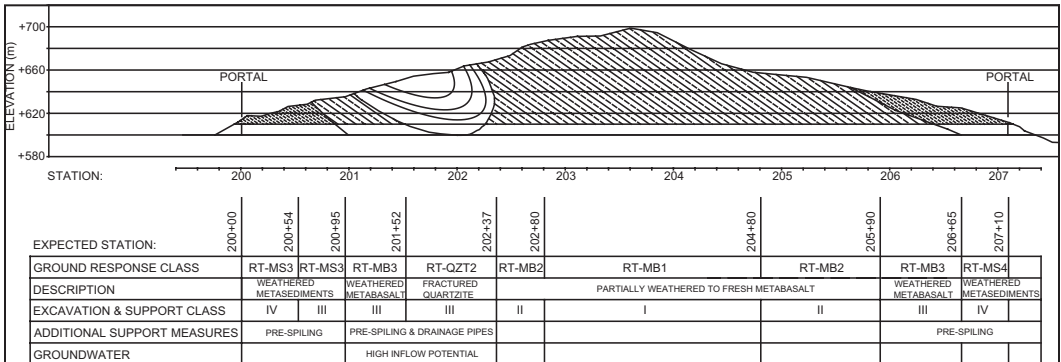


Figure 3. Prototypical longitudinal profile

- Intact Rock
- Stratified Rock
- Moderately Jointed Rock
- Blocky and Seamy Rock
- Crushed, but Chemically Intact Rock
- Squeezing Rock
- Swelling Rock

Table 2 in the Manual shows elements commonly used in excavation and support classes for soft ground. It distinguishes among the various ground types and the ground water conditions as follows:

- Stiff cohesive soil—above groundwater table
- Stiff cohesive soil—below groundwater table
- Well consolidated non-cohesive soil—above groundwater table
- Well consolidated non-cohesive soil—below groundwater table
- Loose non-cohesive soil—above groundwater table
- Loose non-cohesive soil—below groundwater table

The tables are not meant to be a “cook-book” but rather guides to the engineers to determine the potential excavation and support classes to be used.

### **Pre-support Measures and Ground Improvement: Tool Box Measures**

With the significantly increased use of conventional tunneling in particular in soft ground and urban areas over the past decades, traditional measures to increase stand-up time were adopted and further developed to cope with poor ground conditions and to allow an efficient initial support installation and safe excavation.

These measures are installed ahead of the tunnel face. They include ground modification measures to improve the strength characteristics of the ground matrix including various forms of grouting, soil mixing and ground freezing, the latter for more adverse conditions. Most commonly methods include mechanical pre-support measures such as spiling installed ahead of the tunnel face often with distances of up to 18 to 30 m (60 to 100 feet) referred to as pipe arch canopies or at shorter distances, as short as 3.6 m (12 ft) utilizing traditional spiling measures such as grouted solid bars or grouted, perforated steel pipes. Ground improvement and pre-support measures can be used in a systematic manner over long tunnel stretches or only locally as required by ground conditions.

Local non-systematic use of not only pre-support measures, but additional measures including temporary Shotcreting the face, subdivision into smaller excavation faces (multiple faces), face

support earth wedges, etc. form what is often referred to as the “tool box” measures applied as required by ground conditions.

### **Instrumentation and Monitoring**

An integral part of the SEM tunneling is the verification by means of in-situ monitoring of design assumptions made regarding the interaction between the ground and initial support as a response to the excavation process.

For this purpose, a specific instrumentation and monitoring program is laid out. The SEM instrumentation aims at a detailed and systematic measurement of deflection of the initial lining. While monitoring of deformation is the main focus of instrumentation, stresses in the initial shotcrete lining and stresses between the shotcrete lining and the ground are monitored to capture the stress regime within the lining and between the lining and the ground. Reliability of stress cells, installation complexity and difficulty in obtaining accurate readings have nowadays led to the reliance on deformation monitoring only in standard tunneling applications. Use of stress cells is typically reserved for applications where knowledge of the stress conditions is important, for example where high and unusual in-situ ground stresses exist or high surface loads are present in urban settings.

Monitoring data are collected, processed and interpreted to provide early evaluations of:

- Adequate selection of the type of initial support and the timing of support installation in conjunction with the prescribed excavation sequence
- Stabilization of the surrounding ground by means of the self-supporting ground arch phenomenon
- Performance of the work in excavation technique and support installation
- Safety measures for the workforce and the public
- Long-term stress/settlement behavior for final safety assessment
- Assumed design parameters, such as strength properties of the ground and in-situ stresses used in the structural design computations

Based on this information, immediate decisions can be made in the field concerning proper excavation sequences and initial support in the range of the given ground response classes (GRC) and with respect to the designed excavation and support classes (ESC).

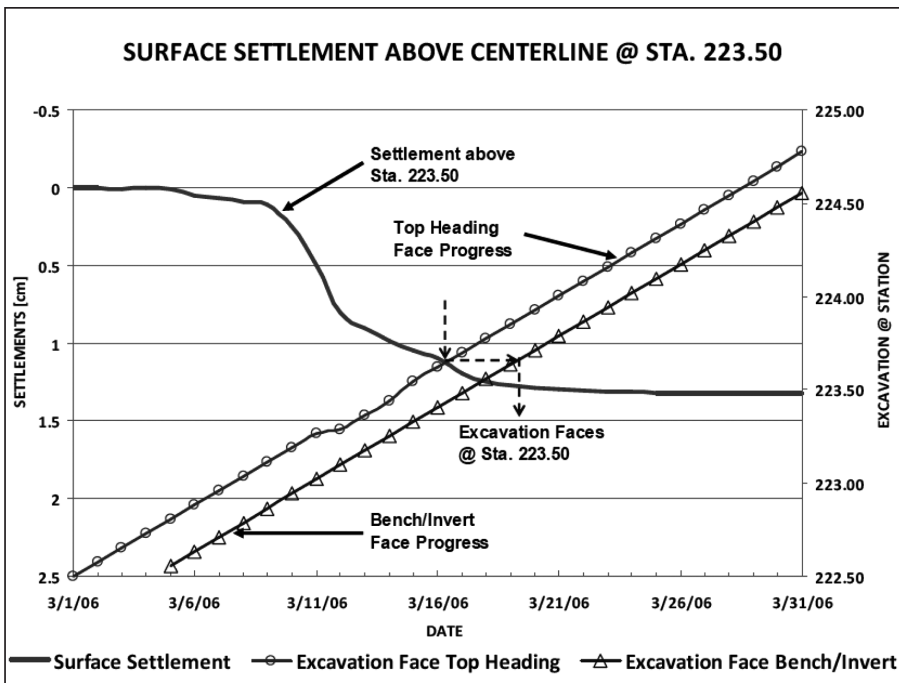


Figure 4. Prototypical monitoring of a surface settlement point above the tunnel centerline in a deformation vs. time and tunnel advance vs. time combined graph

### Interpretation of Monitoring Results

All readings must be thoroughly and systematically collected and recorded. An experienced tunnel engineer, often the tunnel designer, should evaluate the data and occasionally complement it by visual observations of the initial shotcrete lining for any distress such as cracking. To establish a direct relationship between tunnel excavation and ground behavior, it is recommended to portray the development of monitoring values as a function of the tunneling progress. This involves a combined graph showing the monitoring value (i.e., deformation, stress or other) vs. time and the tunnel progress vs. time. An example is shown in Figure 4. As can be seen from this graph, the surface settlement increases as the top heading and later bench/invert faces move towards and then directly under the monitored point and gradually decrease as both faces again move away from the location of the surface settlement monitoring point. The settlement curve shows an asymptotic behavior and becomes near horizontal as the faces are sufficiently far away from the monitoring point indicating that no further deformations associated with tunnel excavation and support occur in the ground indicating equilibrium and therefore ground stability.

The evaluation of monitoring results along with the knowledge of local ground conditions portrayed on systematic face mapping forms the basis for the verification of the selected excavation and support class (ESC) and the need to make any adjustments to it.

### CONTRACTUAL ISSUES

SEM tunnel construction requires solid past tunnel construction experience and personnel skills. These skills should relate to the use of construction equipment and handling of materials for excavation, installation of the initial support including shotcrete, lattice girders, pre-support measures, and rock reinforcing elements and even more importantly observation and evaluation of the ground as it responds to tunneling. It is therefore important to invoke a bidding process that addresses this need formally by addressing contractor's qualifications, personnel skills, and making payment provisions on unit prices basis.

#### Contractor Pre-qualifications

It is recommended that the bidding contractors be pre-qualified to assure a skilled tunnel execution.

This pre-qualification can occur very early on during the design development, but at a minimum it should be performed as a separate step prior to soliciting tunnel bids. On critical projects the owner may solicit qualifications from contractors as early as the preliminary design stage. This early involvement also ensures that contractors are aware of the upcoming work and can plan ahead in assembling a qualified work force. Pre-qualification documents identify the scope of work and call for a similar experience gained on past projects by a tunneling company and for key staff including project manager, tunnel engineers, and tunnel superintendents.

### Unit Prices

To suit the method's observational character and support its flexibility, it is recommended that SEM tunneling be procured within a unit price based contract. Unit prices also suit the need to install initial support in accordance with a classification system and amount of any additional initial or local support as required by field conditions actually encountered. The following is bid on a unit price basis:

- Excavation and Support on a linear meter (foot) basis for all excavation and installation of initial support per Excavation and Support Class (ESC). This includes any auxiliary measures needed for dewatering and ground water control at the face.
- Local support measures including:
  - Shotcrete per cubic meter (cubic yard) installed.
  - Pre-support measures such as spiling, canopy pipes and any other support means such as rock bolts and dowels, lattice girders, and face dowels are paid for each (EA) installed.
  - Instrumentation and monitoring is paid for either typical instrument section (including all instruments) or per each instrument installed. Payment is inclusive of submitted monitoring results and their interpretation.
  - Ground improvement measures per unit implemented, for example amount of grout injected including all labor and equipment utilized.
- Waterproofing and final lining installed to complete the typical dual lining structure may be procured on either lump sum basis or on a per tunnel meter (foot) basis.

The anticipated quantity of local support (additional or supplemental initial support) measures should be part of the contract to establish a basis for bid.

### Experienced Personnel

Because SEM tunneling strongly relies on experience and personnel skills, it is imperative that experienced personnel be assigned from the start of the project, i.e., in its planning and design phase. The SEM tunneling design must be executed by an experienced designer.

The SEM tunneling contract documents must identify minimum contractor qualifications regardless whether the project is executed in a design-bid-build, design-build or any other contractual framework. For example, if the project uses the design-build framework then it is imperative that the builder take on an experienced SEM tunnel designer.

The construction contract documents must spell out minimum qualifications for the contractor's personnel that will initially prepare and then execute the tunnel work. This is the case for field engineering, field supervisory roles and the labor force that must be skilled. Contract documents call for a minimum experience of key tunneling staff by number of years spent in the field on SEM tunneling projects of similar type. Experienced personnel include Senior Tunnel Engineers, Tunnel Superintendents and Tunnel Foremen. All of such personnel should have a minimum of ten (10) years SEM tunneling experience. These personnel are charged with guiding excavation and support installation meeting the key requirements of conventional tunneling:

- Observation of the ground
- Evaluation of ground behavior as it responds to the excavation process
- Implementation of the "right" initial support

Face mapping including all ground exposed should occur for every excavation round and be formally documented and signed off by both the contractor and the owner's representative. Knowledgeable face mapping, execution of the instrumentation and monitoring program and interpretation of the monitoring results aid in the correct application of excavation sequencing and support installation.

The senior tunnel engineer is generally the contractor's highest authority for the tunneling and supervises the excavation and installation of the initial support, installation of any local or additional initial support measures and pre-support measures in line with the contract requirements and as adjusted to the ground conditions encountered in the field. As a result the ground encountered is categorized in accordance with the contract documents into ground response classes (GRCs) and the appropriate excavation and support classes (ESC) per contract baseline. Any need for additional initial support and/or pre-support measures is assessed and implemented. This task is carried out on a daily basis directly at the

active tunnel face and is discussed with the owner's representative for each round. The outcome of this process is subsequently documented on form sheets that are then signed by the contractor's and owner's representatives for concurrence.

This frequent assessment of ground conditions provides for a continuous awareness of tunneling conditions, for an early evaluation of adequacy of support measures and as needed for implementation of contingency measures that may involve more than additional initial support means. Such contingency measures may include heavy pre-support and face stabilization measures or even systematic ground improvement measures.

To be able to support this on-going evaluation process on the owner's behalf the construction management (CM) and inspection team must also include relevant experience in conventional tunneling. It is recommended that the field representation includes a designer's representative who is familiar with the basis of the design. Represented in the field, the designer is able to verify design assumptions, will aid in the implementation of the design intent, and will make design changes on the spot if needed.

### **Risk Management**

It is recommended that owners should initiate at the beginning of every SEM tunneling project a risk management plan. The plan should continue throughout the design and construction phases. The risks should be documented and managed with the best available tools at each phase. A risk register should be established and maintained throughout the life of the project. It is a living document that should be updated regularly and the effectiveness of the mitigation measures should be reassessed as more information becomes available. Risks should be allocated or shared among the parties on the basis of who has better control of the risk. The allocation

of risks should be clearly documented and proper cost of accepting the risk should be included in the contract value.

### **CONCLUSION**

This paper highlights the recommendations made by the FHWA "Technical Manual for Design and Construction of Road Tunnels: Civil Elements" for SEM tunneling construction and it includes the authors experience and insights on this subject. The American Association of State Highway and Transportation Officials (AASHTO), under its Technical Committee T-20 on tunnels, adopted the manual and is in the process to publish it under its domain. It is important to recognize that the manual consists of guidelines and not code provisions and its use by the highway and road authorities of each state is not mandatory. However, the lack of any other authorities' guidelines or codes renders this manual to be an invaluable source of information for the design and construction of tunnels in the United States.

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