St. Jacques-Pullman MSE Walls – Lessons Learned

Paul Wilson, P.Eng.
Principal
Thurber Engineering

Derek Essery, P.Eng,
Technical Director, Engineered Products
Atlantic Industries Limited

Thomas P. Taylor, Ph.D., P.E., P.Eng., D.GE.
Vice President – Director of Research and Development
Big-R Bridge

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Introduction

Mechanically Stabilized Earth (MSE) structures are retaining walls with compacted soil that is reinforced with inclusions consisting of horizontally placed elements. MSE walls reinforced with steel elements are classified as inextensible. In some applications, the steel reinforcing elements connect to a facing component. The type of soil reinforcing and the corresponding facing will depend on the structure application.

This paper will discuss the challenges associated with the design of tiered MSE wall application. The paper will explain what a tiered MSE wall is and how global and compound stability are performed. Also, it will describe the roles and responsibilities of the Geotechnical Engineer and the MSE Engineer and how the roles can overlap becoming shared responsibilities and to manage them. To demonstrate, a recent successful example project will be used to demonstrate these issues. The selected project is the St. Jacques-Pullman Interchange project located in Montreal, Quebec. The owner is the ministère des Transports du Québec (MTQ).

Definition of MSE Zones

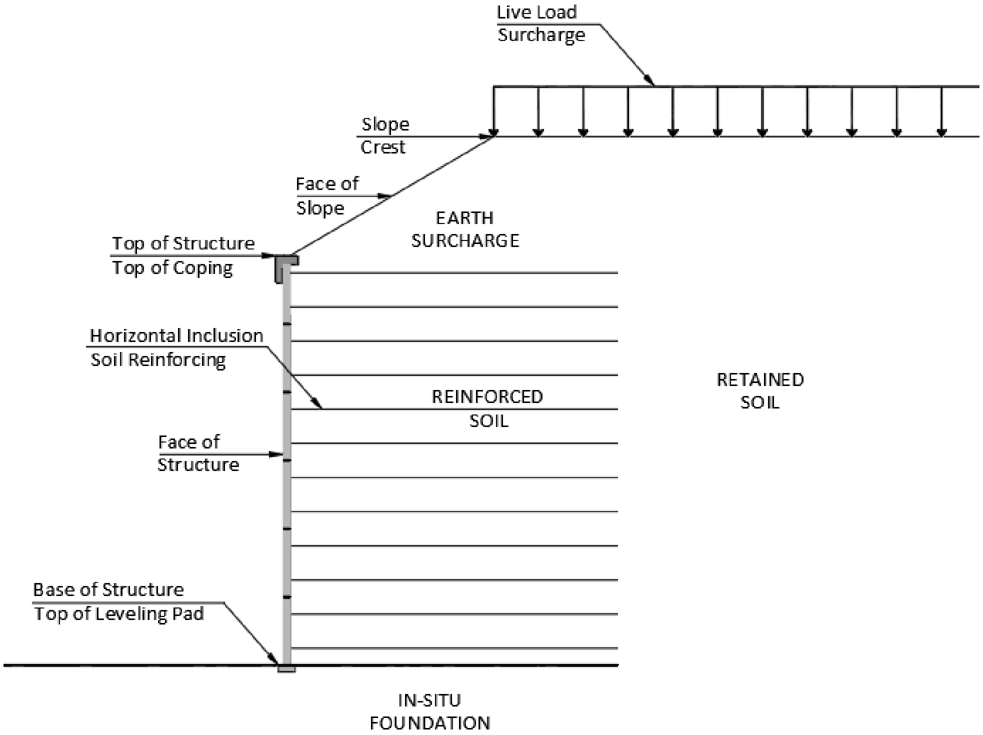

Fig- 1. Typical MSE Wall

MSE structures are retaining walls with compacted granular soil that is reinforced with inclusions consisting of horizontally placed elements. Fig- 1 shows a typical MSE structure. The main components include the compacted soil, soil reinforcing and facing element. Three distinct zones define the MSE wall and include the reinforced soil zone, retained soil zone, and in-situ foundation zone. The reinforced soil zone is the area bound by the horizontal inclusion form the facing element to the terminal end and extending from the foundation soil to the top of the top panel or coping. The combination of the compacted backfill, soil reinforcing and facing function as a composite mass. The retained soil zone is directly behind the reinforced soil zone and may be in-situ soil or it may be soil that is placed and compacted. The in-situ foundation zone is the area below the reinforced soil and the retained soil. The MSE wall may or may not include an earth surcharge, consisting of a slope. In addition, the MSE wall may or may not include a live load surcharge at the top of the structure.

A tiered MSE wall consists of multiple MSE walls that are positioned one above the other and offset by some distance. The tiered MSE wall is shown in Fig- 2 . Tiered MSE walls are used in conditions that require the support of large grade changes. They are more economical than a single MSE wall of equal height and offer aesthetic benefits. The components and zones are the same as previously described. How these walls interact with one another is a function of the offset distance. The design is more complicated than the design of a single MSE wall.

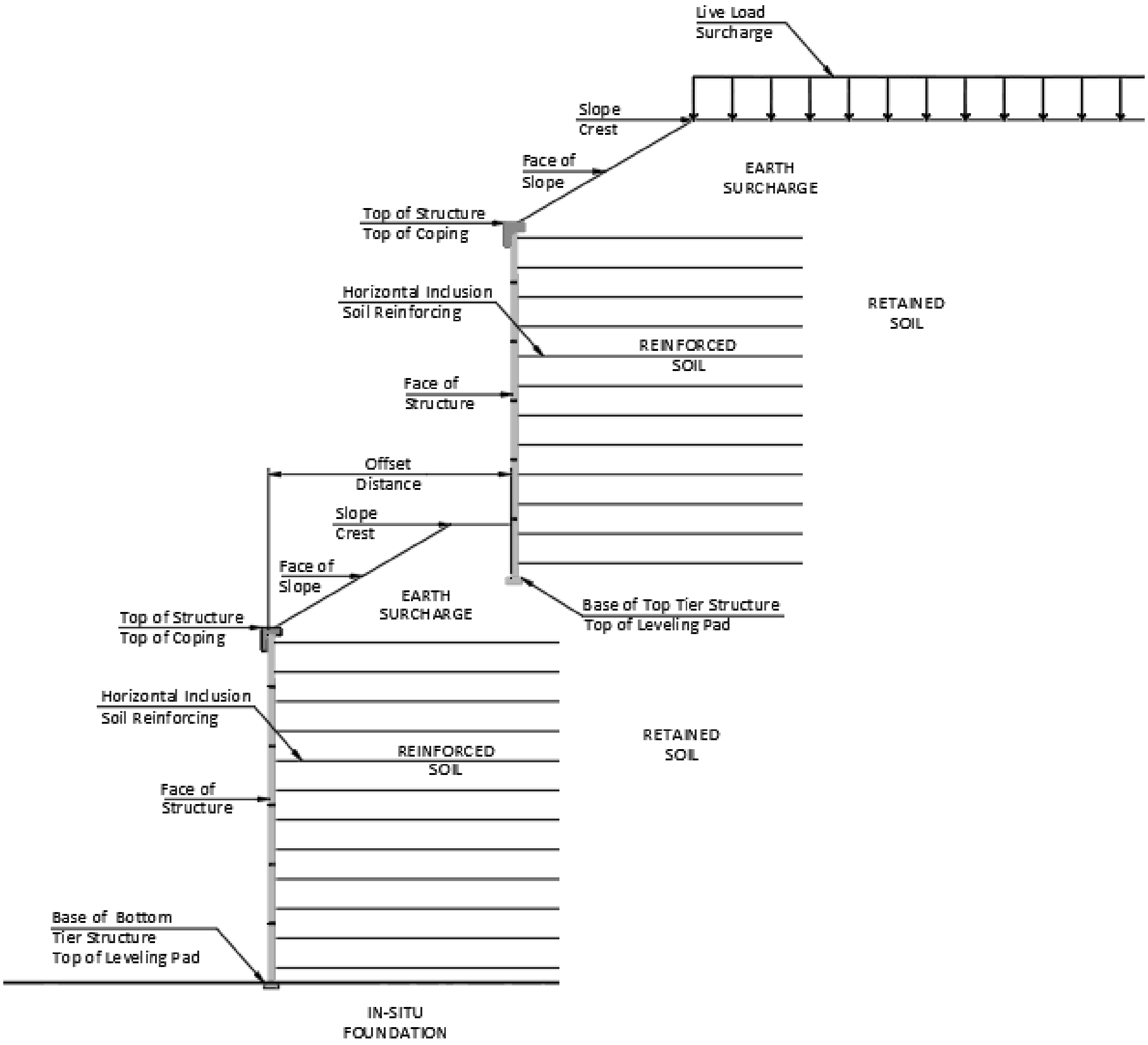

Fig- 2. Typical Tiered MSE Wall

Stability Requirements

MSE walls must be designed to satisfy bearing capacity, global stability, external stability, internal stability, and compound stability. Standard soil mechanics principles apply. Global and external stability considers that the combined wall facing, and the reinforced soil zone, functions as a coherent gravity mass that is typically modeled as a rigid block. Global stability is the overall stability of the composite structure where the failure surface falls outside the reinforced soil zone. External modes of failure of the coherent gravity mass include sliding, overturning, and bearing. The external stability of the MSE structure follows classical design methods used for gravity retaining wall structures. Internal stability modes of failure include tensile failure and bond failure of the soil-reinforcing elements. Bond failure is commonly referenced as pullout failure. In the internal stability analysis, the failure surface is assumed based on clear code requirements, and the location is a function the extensibility of the soil reinforcing element. Compound stability modes of failure considers failure surfaces that pass through two or more soil zones (reinforced soil, retained soil, foundation soil). Compound failure surfaces can be circular, log-spiral, bi-linear, multi-linear or a combination thereof. Limit equilibrium (LE) software programs are typically used in the analysis of global and compound stability. Circular and non-circular failure surfaces should be checked in global and compound stability analysis. Deterministic software programs or spreadsheets are used to analyze the external and internal stability. Sample failure surfaces and their locations for a standard and two-tiered MSE wall are respectively shown in Fig- 3 and Fig- 4.

It is obvious by the comparison of Fig- 3 and Fig- 4 that the design of a tiered MSE wall is more involved than that of a standard MSE wall. The actual shapes of the failure surface will depend on the unique geometry and soil conditions for a given wall. It is important that a range of failure surface search parameters be considered in the software program being used to check stability. For a standard MSE wall, there is typically one critical failure surface; for a tiered MSE wall, there may be multiple critical failure surfaces.

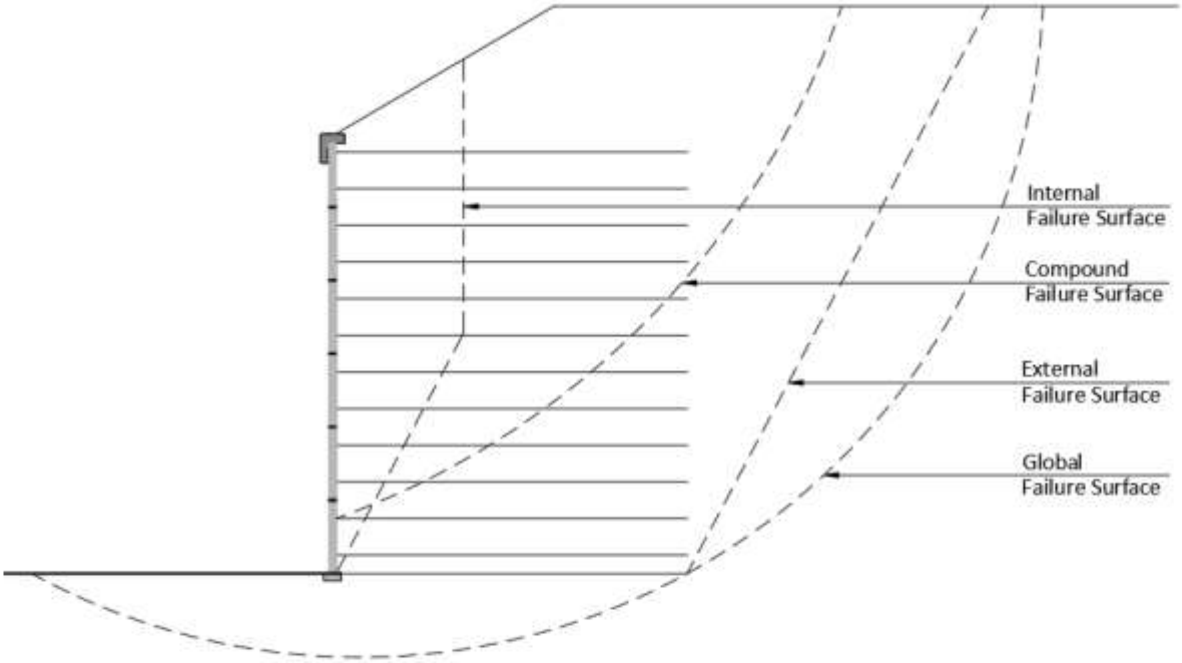

Fig- 3. Typical Failure Surfaces for an MSE Wall

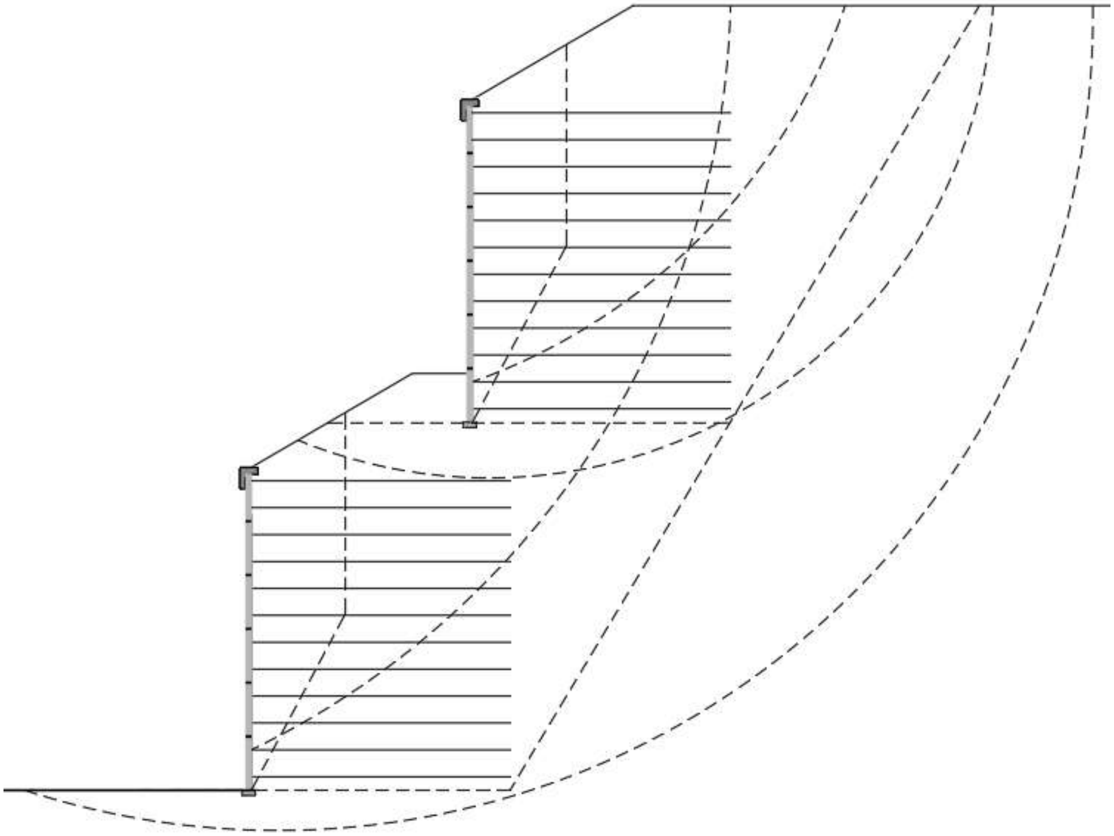

Fig- 4. Typical Failure Surfaces for a Two-Tiered MSE Wall

Many computer software programs can be used to design a tiered MSE wall. The definition and input of the soil parameters and MSE wall component parameters are essential to correctly determine the critical failure surfaces. The design process for a complex tiered MSE wall requires communication and interaction between the MSE Engineer and the Geotechnical Engineer. The MSE Engineer is typically responsible for defining the soil reinforcing, facing element, and reinforced soil strength parameters. The Geotechnical Engineer is typically responsible for performing the global stability and compound stability analysis. This includes estimating the soil parameters for the retained soil and the foundation soil. The MSE Engineer nor the Geotechnical Engineer can assess compound stability without discussion, interaction and coordination through the design process.

Tiered Wall Design Methodology and Challenges

In typical highway projects, there is often limited, to no coordination, between the MSE Engineer and the Geotechnical Engineer. For simple, single tier MSE walls, the design is typically straight forward and defined in the specification and geotechnical report and limited, to no coordination is necessary. In most applications, the MSE Engineer is only responsible for the internal and external stability of the structure. Global stability is the responsibility of others, typically the project Geotechnical Engineer. Compound stability analysis for simple, single tier MSE walls faced with segmental concrete panels is generally not a governing mode of failure and therefore is not a required design consideration.

During the initial design concept developed by the Geotechnical Engineer before the project goes to tender, it is typically unknown what MSE wall system will be utilized. The MSE wall system is not selected until after project award. It is common practice that during the pretender design phase, the global stability analysis completed by the Geotechnical Engineer assumes the reinforced soil zone has a very high strength. By setting the reinforced zone with a very high strength in the global stability analyses, failure surfaces pass outside the reinforced soil zone. Therefore, there are no compound stability failure surfaces generated. For simple, single tiered MSE walls this is a valid assumption that has little impact on the stability of the wall.

In contrast, a tiered MSE wall requires analysis and investigation of the interaction between each of the tiered MSE walls. As shown in Fig- 4, there are several possible failure surfaces, some which extend into the reinforced soil zone and must be analyzed. This requires knowledge of the strength parameters of the soil reinforcing. As previously stated, before the award of the project, the MSE system that will be constructed is unknown. Therefore, modeling the MSE reinforced soil zone with a very high strength that prevents the failure surfaces from passing through the reinforced soil zone cannot properly assess compound stability for a tiered wall. In other words, the MSE system that is selected may not be able to satisfy the strength and pullout requirements to resist failure surfaces that passing through the reinforced soil zone. Because of this, the initial geometric configuration of the MSE walls may have to be modified to satisfy compound stability requirements.

The new TAC “Design, Construction, Maintenance, and Inspection Guide for Mechanically Stabilized Earth Walls” provides some guidance on the roles and responsibilities between the MSE Engineer and Geotechnical Engineer. The TAC guide shows the responsibilities graphically. Table 1 lists the responsibilities of the MSE Engineer and the Geotechnical Engineer and the overlapping shared responsibility. Table 1 indicates that ICS (Internal Compound Stability), is a shared responsibility between the MSE Engineer and Geotechnical Engineer. For complex structures, this could be problematic for the reasons just discussed. This may create an economic hardship for the contractor, MSE supplier, geotechnical engineer, and the owner. This is contemplated by TAC as can be seen in the last shared responsibility that states that an *Economical compromise to best serve the Owner’s interest*. This is an unfair burden to place on the MSE Engineer and the Geotechnical Engineer, particularly when discussions related to shared responsibilities come after a tender has been awarded.

Table 1. Spheres of Responsibilities

Geotechnical Engineer Responsibilities	Shared Responsibilities	MSE Engineer Responsibilities
Global Stability	Overlap of ICS-Global slip surfaces	Internal Compound Stability (ICS)
Preliminary MSE Sizing	Effect of reinforced soil zone size on bearing capacity, settlement and global stability	Final MSE sizing
External Sub-Surface Drainage	Residual flows from external sources into the reinforced soil zone	Internal Sub-Surface Drainage
Ground improvement of weak or compressible foundation	Economical compromise to best serve the Owner’s interest	Design to meet external ultimate limits and serviceability

Because the MSE wall system is unknown at the time of design concept, it is not a realistic expectation that the MSE Designer and the Geotechnical Engineer be jointly responsible for global and compound stability. Further, specifications that require the MSE Engineer to assume responsibility for global and compound stability are also unrealistic. The MSE Engineer has no control over the in-situ soil parameters nor is it reasonable for an MSE Engineer to have knowledge of local soil conditions. The MSE Engineer only has control over the backfill that is placed in the reinforced soil zone, the soil reinforcing, the facing and the means and methods of installation. It is for this reason that MSE Engineers only assume responsibility for internal stability.

Project Description - St Jacques-Pullman MSE Walls

The St. Jacques-Pullman MSE walls were required for the widening of Pullman Boulevard and Rue Saint Jacques, a portion of the larger Turcot Interchange redevelopment in Montreal being delivered by MTQ. The site is located between L'Avenue de Carillon to the east and Rue Girouard to the west. The project was awarded to L.A. Hébert in the fall of 2013; construction commenced in 2016 and the walls were completed in 2018. Rue Saint-Jacques is at the crest of an existing escarpment with slopes that vary between 20° and 45° from the horizontal. To accommodate the widening, a series of five, tiered MSE walls located between Pullman Boulevard and Rue Saint Jacques were required. The five tiered walls were identified from top to bottom as A-E and were designated 18401/MS2-SJ(A), 18405/MS2-SJ(B), 18404/MS2-SJ(C),18403/MS2-SJ(D&E) and 18402/MS1-PULL. The tiered walls had a complex geometry with variable heights, offsets and intermediate slopes for aesthetic reasons. The upper MSE wall, 18401/MS2-SJ(A), needed to be constructed in front of an existing pile supported CIP wall built in the 1960s.

The total height of the five tiers was about 30 m, with the highest tier being up to 6 m. The total area of the combined MSE walls was approximately 4800 square meters consisting of a total of 1200 concrete facing panels. A cross section of the walls is shown in Fig- 5. This cross section is shown with MSE reinforcement lengths typical of simple walls and no consideration for compound stability. The final configuration used to satisfy compound stability is shown in Fig-6, which is significantly more complicated than the configuration in Fig-5. The design process used to develop the solution shown in Fig-6 is described below.

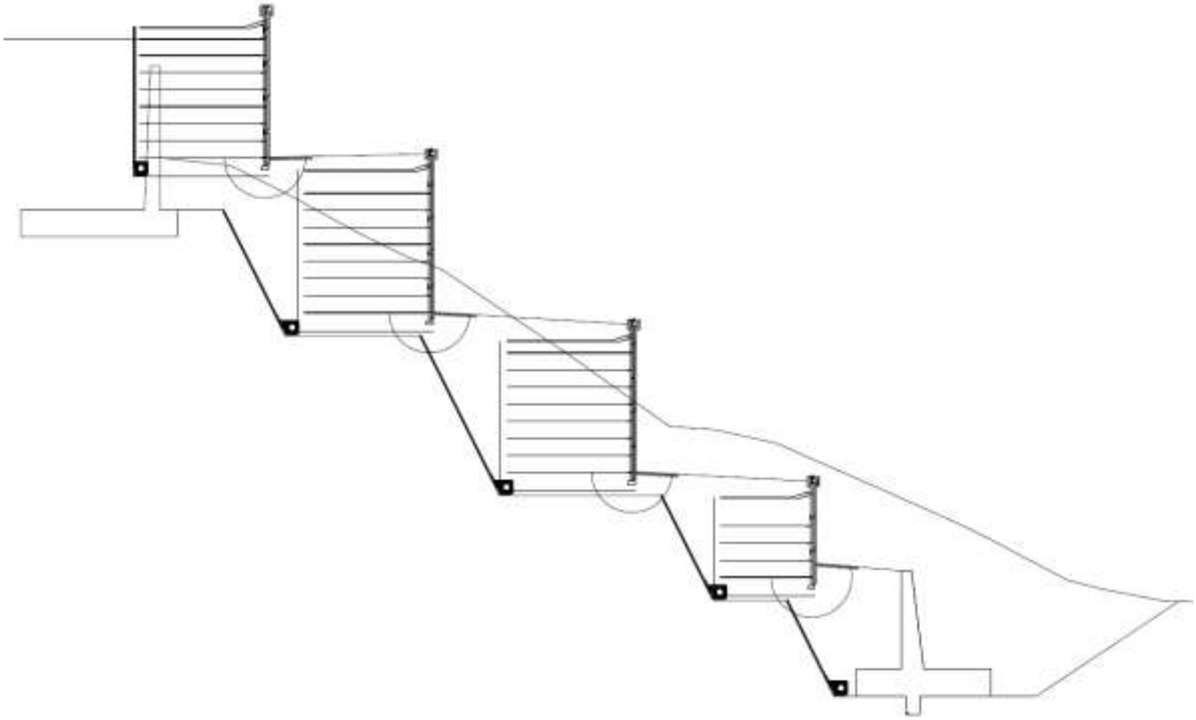

Fig- 5. Typical Cross Section of Tiered Walls for St-Jacques-Pullman

St Jacques-Pullman MSE Walls – Hybrid Stabilization Concept

The St Jacques-Pullman project specification required that the MSE Engineer accept responsibility for global and compound stability, although some initial global stability analysis had been completed by the owner prior to tender. Due to the complexity of the project, the MSE Engineer retained a Geotechnical Engineer who worked as a coordinated team, each with clearly defined responsibilities. The responsibilities of the MSE Engineer was to provide the material design parameters for the MSE components. This included the strength parameters, pullout parameters, length of soil reinforcing, number of soil reinforcing, and facing parameters. The responsibility of the Geotechnical Engineer was to use these parameters to perform a compound stability analysis of the combined MSE walls. The wall configuration presented in the tender documents is shown in Fig-5. To satisfy compound and global stability for the wall configuration shown in Fig-5, it was necessary to either increase the length and strength of the MSE soil reinforcing elements or introduce additional structural elements. If longer and stronger MSE soil reinforcement were only used to address compound and global stability for the cross section shown in Fig-5, a large excavation into the existing escarpment would have been required.

Completing large excavations for installation of MSE soil reinforcement in this case was not desirable since it would have involved excavating additional soil (which would need to be disposed elsewhere), importing more MSE wall backfill (which was expensive) and installing temporary excavation support elements (typically soldier piles and lagging in the Montreal area).

A hybrid solution was developed involving a combination of nominally longer and stronger MSE soil reinforcement in combination with soil nails, as shown in Fig-6. The soil nails were configured to also act as temporary excavation support for installation of the MSE walls. This project was one of the first uses of soil nails on an MTQ project.

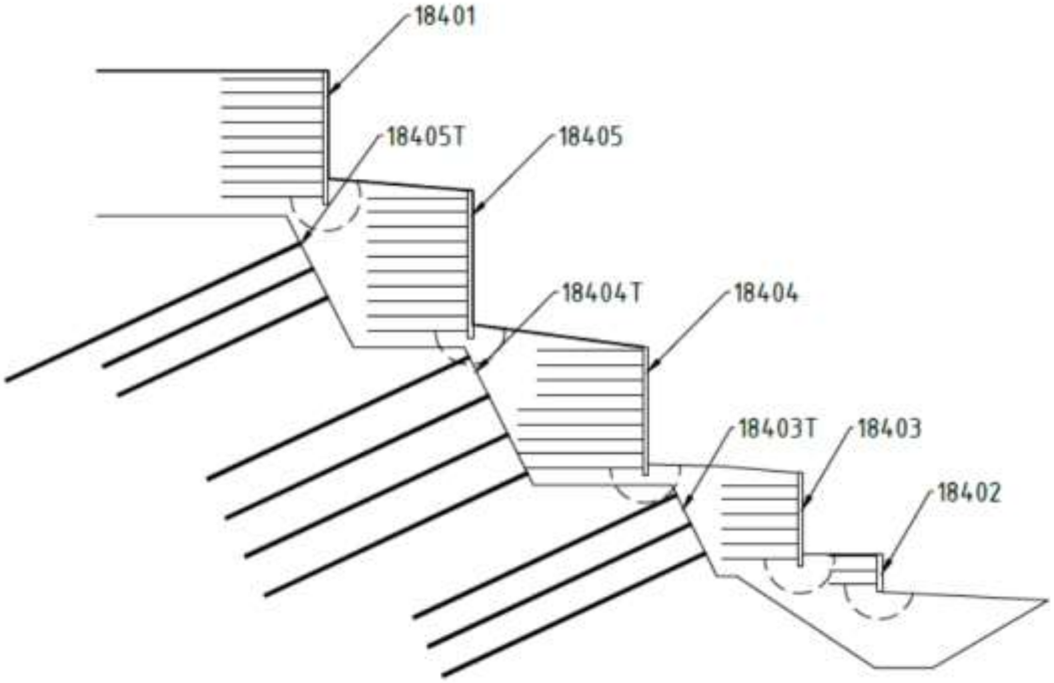

Fig-6. Hybrid Soil-Nail MSE Wall Solution for St Jacques-Pullman Walls

Soil nailing is a technique that uses grouted, tension-resisting steel bars (nails) to reinforce the soil. Soil nail behaviour is similar to MSE reinforcement, but soil nails have a large steel cross section compared to MSE wall reinforcement and tend to be much stiffer. Soil nails are commonly used for slope stabilization, temporary excavation support, and repair of existing retaining walls experiencing distress or failure. Soil nails can comprise solid thread bars or hollow core bars. Hollow core bars were selected as they are installed in a single step using smaller drill rigs. A typical hollow core soil nail for a retaining wall application is shown in Fig-7. Soil nails when used for temporary excavation support are installed in a top-down construction sequence. After each excavation stage, inclined soil nails are drilled into the exposed soil cut face at horizontal spacings of to 1 m to 2 m. To provide temporary excavation face support, the soil nails were connected to the wire mesh facing system with spike plates. A nominal tension load was applied to the soil nails to actively engage the mesh face. The completed soil nail slope is shown in Fig-8.

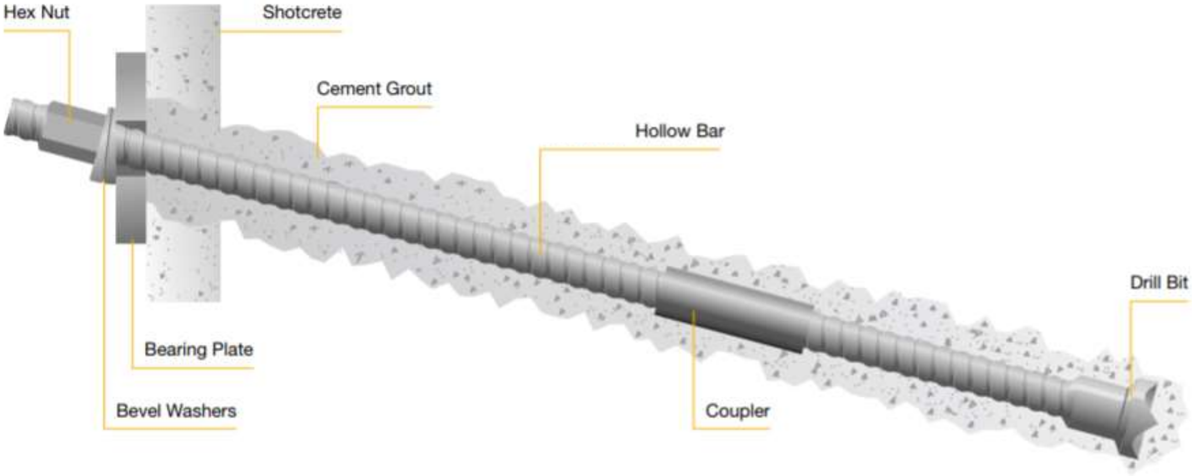

Fig- 6**.** Typical Cross Section of a Hollow Core Soil Nail

Fig- 8**.** Completed Soil Nail Stabilized Excavation Slope

St. Jacques-Pullman MSE Walls - Analysis Methods

The MSE wall design was completed in accordance with the *AASHTO LRFD Bridge Design Specifications, 7th Edition* (AASHTO 2014) and the *FHWA-NHI-10-024 Design and Construction of Mechanically Stabilized Earth and Reinforced Soil Structures* (FHWA 2009). Design consideration for the interaction between the MSE wall and soil nails was completed in conformance with the recommendations described in the FHWA-CFL/TD-06-001 – *Shored Mechanically Stabilized Earth (SMSE) Wall Systems Design Guidelines*.

Due to the complexity of the hybrid soil nail – MSE wall solution the compound and global stability was assessed using both limit equilibrium methods using the program Slope/W and finite element analysis (FEA) methods using the program Plaxis2D. The use of FEA methods was critical to examine the deformation pattern of the hybrid system, understand strain compatibility between the soil nails and MSE soil reinforcing and confirm the slip surface search parameters used in the limit equilibrium analysis appropriately captured the complex behaviour.

Plaxis2D analyses were first completed at two representative cross sections along the wall. The factor of safety for compound and global stability was computed in Plaxis2D using a limit displacement approach. A limit displacement approach involves incrementally decreasing soil strengths from initial values in a finite element model and checking the model stability after each incremental decrease in soil strength using convergence. At some incremental decrease, the model becomes unstable and cannot converge because of excessive irreversible stain and plasticity. At this point the structure is assumed to fail. This is the value that is used to produce a factor of safety.

Slope/W analyses were then completed at the same cross sections for comparison to the Plaxis2D analyses. Slope/W analyses were then completed at twelve other representative sections to adjust the soil nail configuration and MSE reinforcement details across the entire length of the wall. The number of cross sections analyzed was higher than normal because of the major changes in wall geometry along the length of the wall (complex wall layout for aesthetic purposes). The limit equilibrium slip surface search parameters required consideration of multi-linear composite failure surfaces to properly capture the complex compound failure surfaces for the hybrid system.

Select Slope/W and Plaxis2D model geometries and analysis outputs are shown in Fig-9 to Fig-13. The Plaxis2D analysis outputs in Fig-11 to Fig-13 demonstrate the complex behaviour of the hybrid solution.

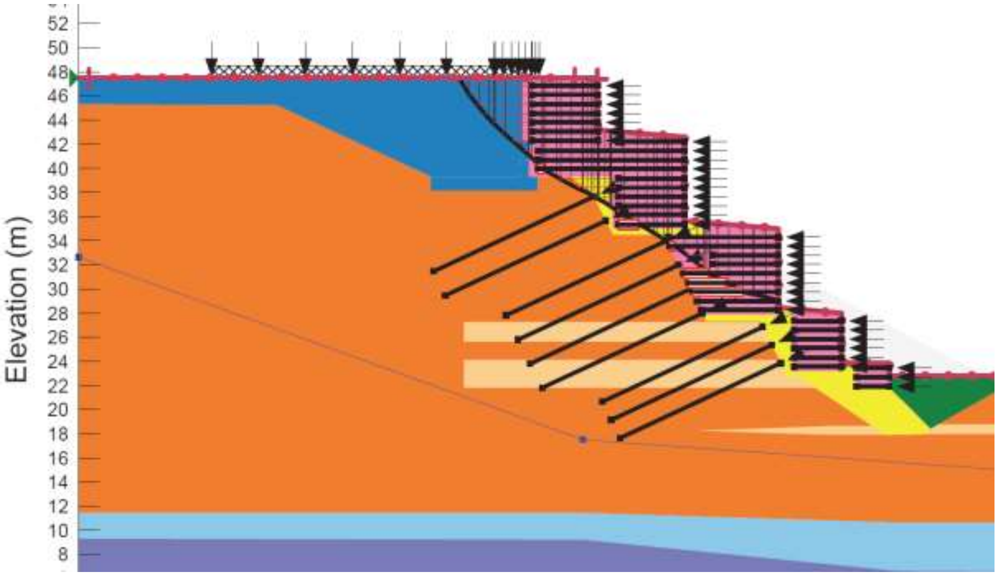

Fig-9. Slope/W Model Geometry

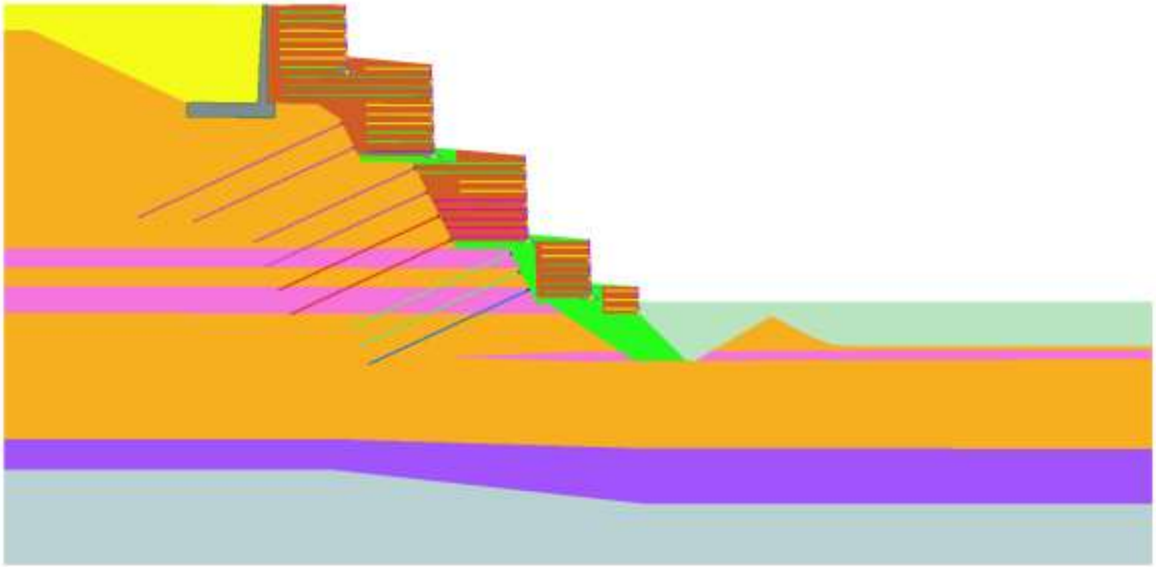

Fig-10. Plaxis2D Model Geometry

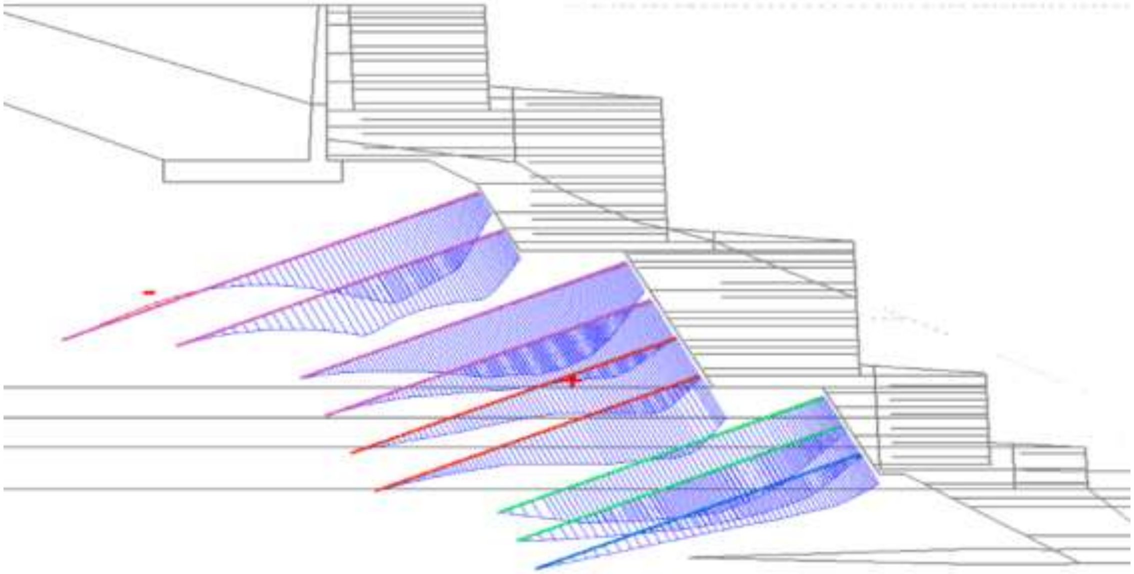

Fig-11. Plaxis2D Soil Nail Force Distribution

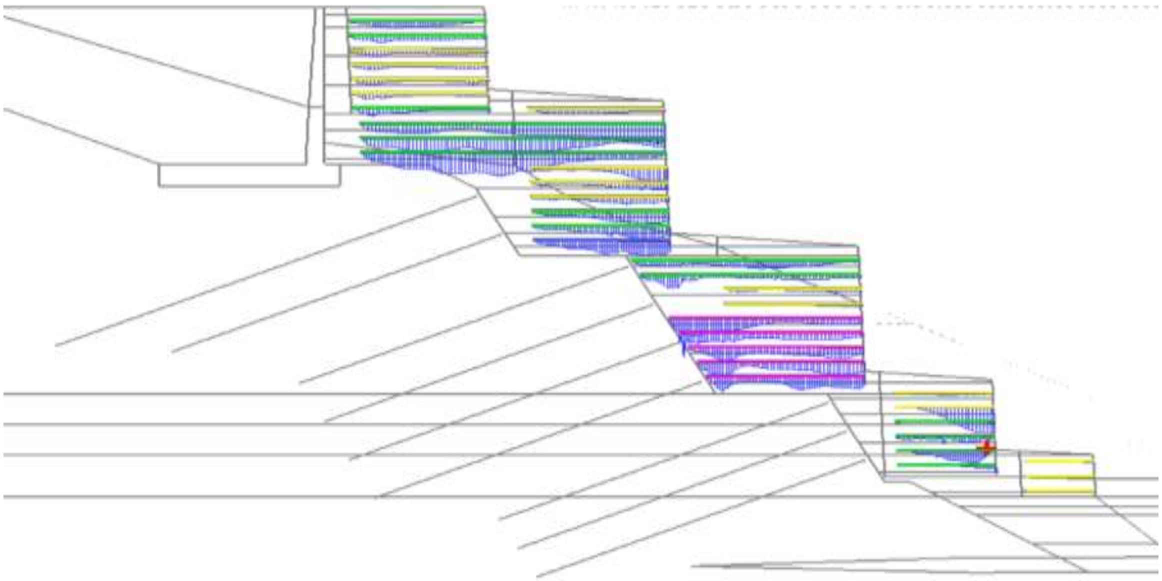

Fig-12. Plaxis2D MSE Soil Reinforcement Forces

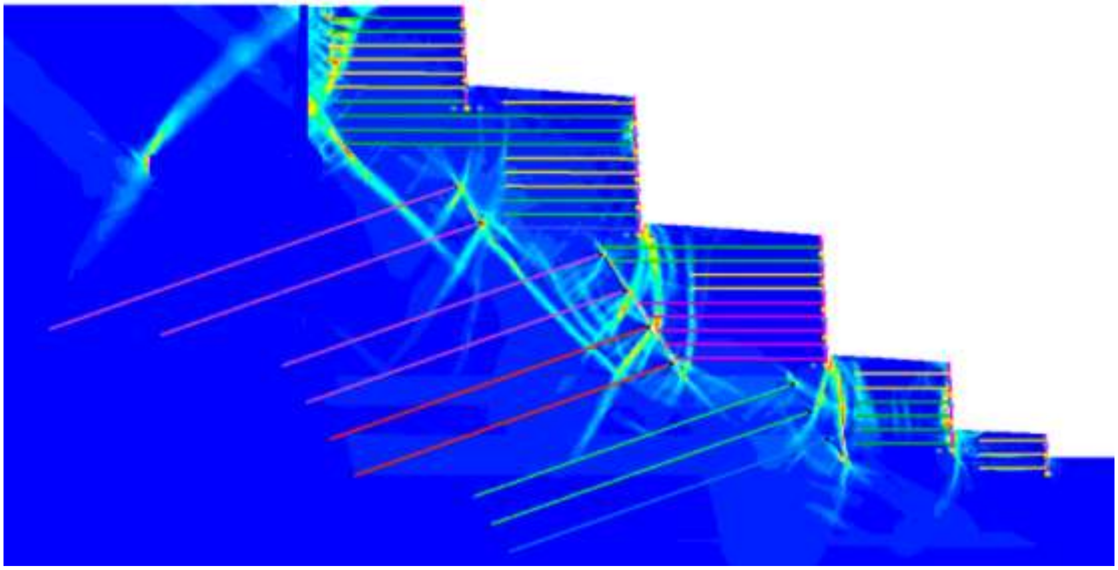

Fig-13. Plaxis2D Shear Zones

Discussion

The St. Jacques-Pullman MSE wall project is an excellent case history demonstrating the complexity of addressing compound and global stability for tiered MSE walls. A hybrid solution was developed that addressed the economic interests of all parties involved in the project. This solution could not have been developed without close coordination and cooperation between the MSE Engineer and Geotechnical Engineer. It is not reasonable to assume and MSE Engineer, if they are made responsible for compound stability, would be able to develop such a solution with a full understanding of local soil conditions and alternative geo-structural elements (soil nails, piles). It would be extremely difficult to develop a set of specifications for tender to cover a hybrid solution of this complexity. Requiring the MSE Engineer to retain a Geotechnical Engineer is not ideal given the typical timelines and communication protocols involved in the tender process.

Conclusions

In situations where tiered walls are required or compound stability is anticipated to be an issue, it would be advantageous to have potential MSE wall suppliers and their MSE Engineers engaged with the Owner's Geotechnical Engineer earlier in the design process, as part of the tender document preparation. Using this method, the Geotechnical Engineer would take responsibility for compound stability with explicit input from MSE Engineers at a more logical stage in the design and construction process. This would reduce the potential for major changes being needed to address compound stability after the tender has been awarded, when economical compromises to best serve the Owner's interest may not be possible due to construction schedule or other challenges.

Fig-14. Photos of Completed Wall

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