Geogrid-reinforced Earth Structures for Transportation Projects in the Vancouver Region – Case Histories

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ABSTRACT This paper describes several case histories of geogrid-reinforced, Mechanically Stabilized Earth (MSE) structures, including walls and slopes, that were designed and constructed for three of the major transportation projects carried out in the Vancouver Region in the last eight years: The Port Mann Highway 1 project, South Fraser Perimeter Road and Low Level Road. The reinforced soil structures were built for grade separation purposes at multiple locations encompassing the various geotechnical environments present in the region varying from highly competent glacial soils to soft, compressible and/or liquefiable soils. The design of the earth structures had to meet performance criteria under seismic conditions and in some cases under exceptionally high loads resulting from the interaction with bridges. The retention systems included varied configurations such as vegetated reinforced soil slopes at diverse inclinations which in many cases blended with the surrounding landscape, vertical or nearly vertical MSE walls and two-stage walls that allowed the construction of bridge abutments on compressible soils. Post-construction performance of the reinforced soil structures has been satisfactory under the working conditions and has met the goals established by the project owners.

Introduction

Since their introduction to the North American market in the early 1980s, polymeric geogrids have been increasingly used in the construction of reinforced soil structures for grade separation applications thanks to benefits resulting from their use, such as cost effectiveness, adaptability to varying and challenging geotechnical and environmental conditions, among others.

The structures described in this paper were built using reinforced soil proprietary systems where the primary reinforcement consisted of High Density Polyethylene (HDPE) uniaxial geogrids, and in the case of reinforced soil slopes, secondary reinforcement using polypropylene (PP) biaxial geogrids was also used. These geogrids are integrally formed through a manufacturing process that includes extrusion, punching and drawing of these polyolefin materials.

The projects where the subject structures were implemented include the British Columbia Ministry of Transportation and Infrastructure's Port Mann/Highway 1 Improvement Project (PMH1) and South Fraser Perimeter Road (SFPR), the City of North Vancouver's and Port of Metro Vancouver's Low Level Road (LLR).

Terminology

A geogrid, as defined by Koerner (1998), is a geosynthetic material consisting of connected parallel sets of tensile ribs with apertures of sufficient size to allow strike-through of surrounding soil, stone, or other geotechnical material

It is also important to distinguish between Mechanically Stabilized Earth Walls (MSEW) and Reinforced Soil Slopes (RSS). A common definition that has become an industry standard is that of Elias et al. (2001): RSS "are a form of reinforced soil that incorporate planar reinforcing elements in constructed earth-sloped structures with face inclinations of less than 70 degrees", while MSEW are inclined at 70 degrees or more. The inclusions can be geogrids or other man-made elements incorporated in the soil to improve its behaviour.

Case Histories

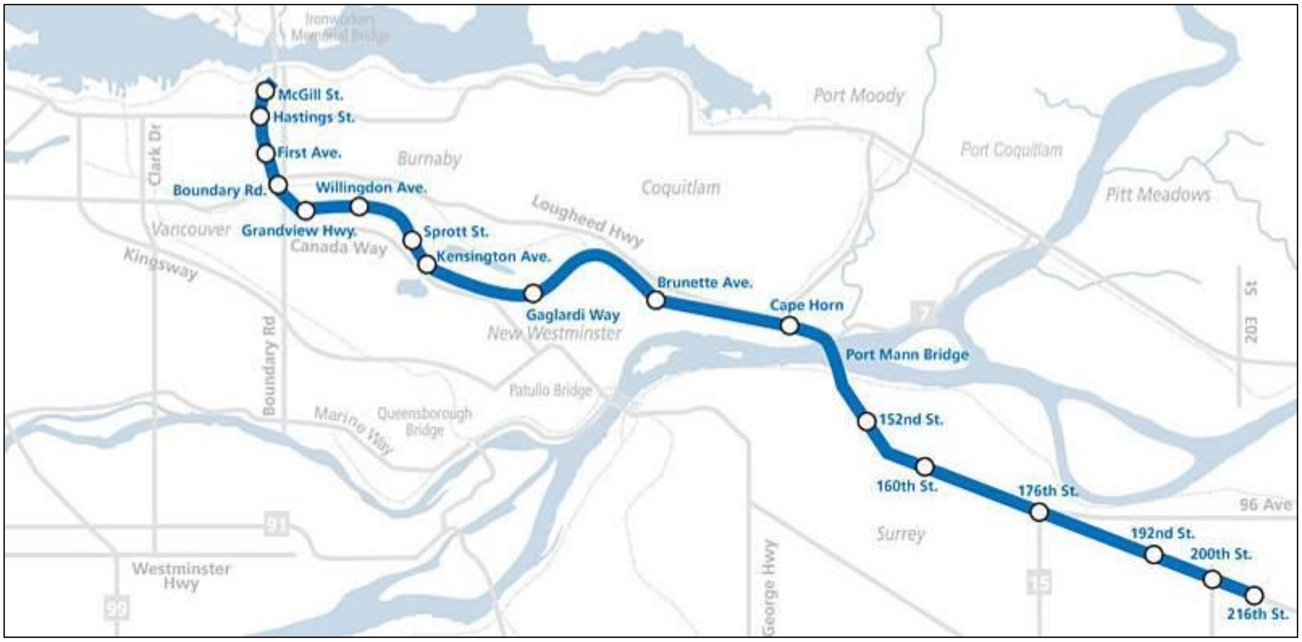
Port Mann Highway 1 Improvement Project

Highway 1 is part of the of the Trans-Canada Highway in the Province of British Columbia, traversing the Lower Mainland from West Vancouver to Chilliwack, crossing the Fraser River over the Port Mann Bridge.

The PMH1 project consisted of the improvement of the Highway 1 along a 37 km stretch between the cities of Vancouver and Langley (see Fig. # 1). The works, carried out by the Kiewit/Flatiron consortium between 2009 and 2014, included the widening of the highway by adding one or two lanes in each direction, the upgrading or construction of new interchanges and the construction of a new 10 lane, 2 km long bridge to replace the existing Port Mann Bridge.

Reinforced Soil Slopes were generally built as permanent retaining structures for the support of new lanes in sloping terrain, or for fill retention in bridge approach embankments in areas where the available right of way required the steepening of the fill slopes, providing, in addition, an environmentally friendly alternative to concrete facing walls. Wire facing MSE walls were also used for the same purpose where steeper inclinations at the face were required or as temporary retaining structures to allow traffic on existing lanes during the construction operations.

Fig. 1. Location of the Port Man Highway 1 Improvement Project (Source: BCMOT)



Geotechnical Conditions

The section of the highway that was part of the improvement project traverses a wide range of soils including glacial and postglacial sediments. Among the main soil deposits that provided foundation conditions for the reinforced soil structures, as described in the relevant geological maps by the Geological Survey of Canada, are:

- Postglacial Salish Sediments (Sae, SAh), consisting of bog, swap, and shallow lake deposits with lowland peat overlying Vashon drift and Capilano sediments; lowland stream channel fill and overbank sandy to clayey silt with organic sediments;
- Postglacial and Pleistocene Deposits (SA-C), consisting of marine shore and fluvial sand;
- Postglacial Fraser River Sediments (Fc), consisting of overbank silty to silt clay loam overlying deltaic and distributary channel fill sandy to silt loam;
- Pleistocene Capilano Sediments (Cd) consisting of marine and glaciomarine stony to stoneless silt loam to clay loam with minor sand and silt;
- Pleistocene Vashon Drift and Capilano Sediments (VC), consisting of lodgement and minor flow till with lenses and interbeds of sand to gravel and stony silt, overlain by glaciomarine and marine deposits consisting of stony to stoneless clayey silt;
- Pleistocene Vashon Drift (Va) consisting of lodgement till (with sandy loam matrix and minor flow till) containing lenses and interbeds of glaciolacustrine laminated stony silt;
- Pleistocene Pre-Vashon Deposits (PVa,PVc), consisting of Quadra fluvial channel fill and floodplain deposits, crossbedded sand containing minor silt and gravel lenses and interbeds; Quadra marine interbedded fine sand to clayey silt; Semiahmoo till, glacio-fluvial, glaciomarine and glaciolacustrine deposits.

Generally speaking, the pleistocene soil deposits provided good foundation conditions for the reinforced soil structures in terms of bearing capacity and settlement. On the other hand, the postglacial deposits presented a series of challenges for the construction of the structures due to a number of geotechnical issues including low bearing capacity, high compressibility (primary and, in some cases, secondary) and liquefaction potential.

Another important geotechnical condition considered in the design of the reinforced soil structures is the high seismicity of this region. As has been documented in numerous studies (e.g. Atukorola & Viji, 2007), the seismicity in the area is a result of the subduction of the Juan de Fuca plate beneath the North American plate. Subsequently, there are three basic sources of earthquakes: (i) relatively shallow crustal earthquakes, (ii) deeper earthquakes within the subducted plate, and (iii) very large inter-plate earthquakes known as “mega-thrust” or “subduction” earthquakes. The magnitude of a subduction earthquake affecting the Vancouver region is expected to be in the order of M8.2+.

Design of the RSS and MSEW

The design of the RSS, including internal and compound stability, was conducted by Tensar International generally following the methods and guidelines stated in Elias et al. (2001), employing commercial software based on Bishop’s Modified Method of limit equilibrium slope stability analysis.

The internal and external design of MSEW used the Allowable Stress Design (ASD) approach following the guidelines of AASHTO (2002) and Elias et al. (2001).

Interaction between the designer of the reinforced soil system and the geotechnical consultants was essential since the geogrid reinforcement needed to meet the minimum requirements to satisfy global stability. It is an industry practice to delegate the analysis of the global stability to the geotechnical engineer due to their in-depth knowledge of the site conditions

Numerical analyses of representative RSS structures were carried out to verify the compliance with the seismic performance requirements of the project, as described below.

Reinforced Soil Structures

Sixteen thousand square meters (vertical face area), approximately, of reinforced soil structures using HDPE uniaxial geogrids and PP biaxial geogrids, were designed and built for the PMH1 project as an alternative to concrete-facing MSE walls originally planned for the project. The geosynthetic materials were supplied by Nilex Civil Environmental Group.

The Tensar® Sierra® reinforced slope system was used for most of the structures with geometries varying in inclination from 42 degrees to the horizontal (1.1H:1V) to 69 degrees (3H:8V) and heights to a maximum of 9 m. These geometries were possible in areas where enough right of way was available. In other cases, MSE walls built at nearly vertical inclinations were built using the Tensar® SierraScape® system.

Uniaxial geogrids installed at vertical spacings of 0.5 m, typically, were used as primary reinforcement. The reinforced slopes were vegetated at the face through the installation of biaxial (BX) geogrid wraps that provided confinement to the backfill and increased the surficial stability (secondary reinforcement). Pockets of plantable fill (top soil) are installed at the face and seeded to develop a vegetative cover.

A black steel, welded wire form is used at the face as a lateral confinement aid during the placement and compaction of the backfill of RSS; however, its structural benefit is not accounted for in the design of the structure. Fig. # 2, shows a typical facing detail employed in the project.

The reinforced backfill in most cases consisted mainly of sand and gravely sand imported from different sources in the Lower Mainland, with friction angles varying from 34 deg. to 40 deg. However, in some cases RSSs were built using sandy silt fills from excavations nearby the job sites.

Among the advantages of the RSS systems is their flexibility and capacity to tolerate differential settlements; for this reason, they were used in the construction on compressible soils.

Fig. # 3 shows an example of 1.1H:1V reinforced slopes built on the North Side of the highway, in the city of Coquitlam in proximity to the Cape Horn Interchange.

Fig. 2. Typical facing detail of a Sierra® RSS

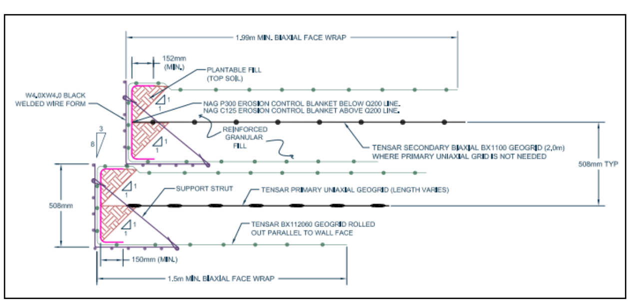


Fig. 3. Reinforced Soil Slopes built on soft, compressible soils

These slopes were built on each side of an existing drainage ditch on soft, compressible soils with presence of organic content. Preload surcharge was placed on top of the south slope (supporting the highway lane) to accelerate the consolidation of the foundation soil. Vegetation developed on the slope face and provides a natural blend with the adjacent, shallower, channel slopes.

In some cases, due to the extremely soft conditions of the foundation soil, subgrade improvement was required by using biaxial geogrids to build a granular pad that would allow the construction operations. Fig. # 4 shows an example of this situation; the reinforced slope supporting the added south lane of Highway 1 at Schoolhouse St, was partially built into the channel bed whose flow was temporarily diverted; once the construction was completed and removal of the preload took place, the channel was flooded back again. Fluctuating water levels were considered in the design of this slope and many others along the project. The flexibility of these systems allowed for obstructions of utilities, culverts, lightning poles, and other roadside elements.

Other applications of RSSs in this project included the construction of bridge approach embankments. Such is the case of the one built in proximity of the west abutment of Port Mann bridge. Due to the height of the fill, of approximately 9 m, large settlements were expected in this area; for this reason and to mitigate the potential effects of liquefaction, the ground was improved using deep stone columns. Fig. # 5 shows the reinforced slope once completed and vegetated.

This retaining structure was one of the cases selected for analysis using numerical modelling to assess its response under earthquake conditions. Given that the project required meeting some performance criteria expressed in terms of deformation and extent of the damage after the occurrence of the design earthquake, which in this case was that with a probability of exceedance of 5 percent in 50 years (975-yr return period), representative structures were modelled using the FLAC finite difference program, in addition to the conventional pseudo-static analyses.

Fig. 4. Construction of RSS into water body.

Fig. 5. Reinforced slope at Port Mann Bridge embankment with vegetative cover developing

One of the advantages of green faced steepened slopes is that they can blend into their surroundings while mitigating the visual impact they cause, especially in urban environments. One good example is the reinforced slopes built to retain the embankments of the highway at the height of Government Street. As shown in Fig. # 6, the steepened, vegetated slope serves its purpose as approach embankment for the underpass built for the buses of the Skytrain system, located just across the street in a residential area in the city of Burnaby.

A key aspect to achieve a good visual impact is the selection of proper species, adequate for the environment and location of the wall. The slopes in Figure 6 were located north-facing, and therefore required vegetative species that would grow under little sun exposure. Opposite to this is the case of the south-facing slope shown in Fig. # 7. In both cases a specialist was retained by the constructor in the selection and planting of the appropriate vegetative cover.

Fig.6 Reinforced slopes in urban environments

Fig. 7. South-facing reinforced slope, a few weeks after completion of construction

South Fraser Perimeter Road (SFPR)

The SFPR, also known as Highway 17, is a crucial piece of British Columbia's transportation network, devised as part of the Gateway Project that also involved the improvement works of Highway 1.

This four lane, 80 km/hour route extends for a distance of 40 kilometers along the south side of Fraser River. As noted in Fig. # 8, it extends from Deltaport Way (SE) to Highway 15 (NW), and provides a key route for commercial truck traffic commuting along highway 17 between the Ferry Terminals, Fraser River Industrial Areas, with connection to highway 15 leading to the USA border. The project was built by Fraser Transportation Group (FTG) between 2010 and 2014, approximately.

Geotechnical Conditions

The project was divided into eight segments, starting with Segment 1 at the Tsawassen Ferry Terminal in southwest Delta and finishing with Segment 8 at 176 Street in Surrey. The structures described in this paper were built along Segments 2, 4, 5, 6 and 8, located in the cities of Delta and Surrey.

Fig.8. Alignment of South Fraser Perimeter Road (Source: BCMOT)

Most of the walls along Segments 2, 4 and 6 were founded on quaternary deposits as described below per the GSC Maps 1484A and 1486A :

- Postglacial Salish Sediments: bog, swamp and shallow lake deposits (SAb) consisting of peat, organic silt loam and silty clay loam overlying Fraser River Sediments.
- Fraser River Sediments (Fc): deltaic and distributary channel fill sediments and overbank sediments, consisting mainly of sand, silt, silty clay, sandy silty and clayey loam, organic silt.

Walls along Segments 5 and 8 were built on Glacial deposits including:

- Prevashon deposits: glacial, nonglacial, and glaciomarine sediments (PVa,c) consisting of sand, gravel and clayey silt.
- Vashon Drift: lodgement till (Va) with a sandy loam matrix and lenses of silt, sand and gravel.

The presence of Salish sediments underlying many of the bridge structures implied challenges: due to their compressibility, large settlements were anticipated at the abutments. On the other hand, the Fraser River Sediments are susceptible to liquefaction and medium to high compressibility.

As is common to this region, seismicity is an important element affecting the performance of the retaining structures.

Design of MSEW

The SFPR project made extensive use of MSEW and RSS that specifically utilized HDPE and PP geogrids as soil reinforcement to address the multiple challenges that the geotechnical conditions of the project offered.

The design of these structures was performed by Tensar International and Braun Engineering, and followed the same approach described above for PMH1, this time using also Tensar's proprietary software. FTG selected GeoPacific Consultants Ltd. to conduct the numerical modelling of selected MSE structures to verify their compliance with the seismic performance requirements of the project.

All the permanent MSEW of the project were designed for a service life of 100 years. Due to the presence of piles supporting the bridge abutments embedded into the reinforced soil mass, a wide range of pile loadings due to temperature and earthquake, among the main sources, had to be considered in the design.

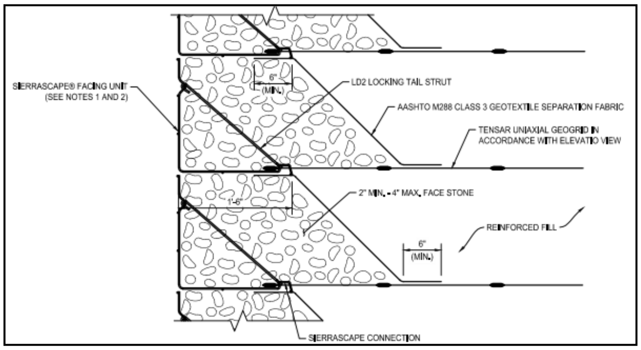
Reinforced Soil Structures

Most of the retaining structures described below involve the use of the Tensar® SierraScape® system, which is a galvanized wire-faced wall system as illustrated in Fig. # 9, whose components were supplied to the project by Nilex Civil Environmental Group.

It is key to note that this is referred to as a connected wall facing system, whereby the soil reinforcement is attached to the lower facing return by use of a connector strut. This assures full load transfer between the primary soil reinforcement (uniaxial grid), and the wire facing element.

MSE walls were built at vertical or nearly vertical inclination to heights of up 14 m. For a permanent wall application such as required on this public highway project, a facing stone, more commonly known as rock-fill, is placed immediately behind the facing cage. The use of rock-fill behind such a facing system affords for easier installation, as well as better overall alignment of the final facing system. The facing stone is separated from the structural backfill (river sand in this case), by the use of a non-woven geotextile separator.

Fig. 9. SierraScape System Detail



One of the main applications of MSEW in this project was that of grade separation and lane widening; on Fig. # 10 a detail of the SierraScape wall built to raise the grade of River Road above the new Highway 17 in Segment 5 is shown. A detail of the construction of new lanes on MSE walls at the Cannery intersection, also in Segment 5 is shown on Fig. # 11. The soils found in this area were competent and no special foundation treatments were required.

Construction of bridge abutments was one of the main uses of MSE walls in this project. Examples of those applications are the false abutments built at the BNSF Sunbury railway intersection in Segment 4 (See Fig. # 12) where the SierraScape walls were used as false abutments, i.e., the bridge abutment was built on piles embedded into the reinforced zone of the MSE wall. Another example of false abutment is shown in Fig. # 13, corresponding to the BNSF Viaduct at River Road in Segment 5 where the wall was shaped to meet the project geometric requirements.

The MSEW systems were used in the construction of multiple bridge approach embankments and abutments, often combined with vegetated reinforced slopes such as those built at the Tannery Road intersection in Segment 6, as shown in Fig. # 14. In this case, the abutment was sitting on a Load Transfer Platform (LTP) which consists of a geogrid reinforced granular platform sitting on timber piles, designed by EXP, the geotechnical consultant of the project, to minimize the long-term settlement of the embankment. The flexibility of the MSEW systems allow for the occurrence of total and differential settlements without affecting the performance of the structure.

In areas where the restrictions of the right of way allowed for, reinforced slopes were built at maximum inclinations of 69 deg. (3H:8V). Such is the case of the Sierra slope built to support new highway lanes in Segment 8, just east of the crossing under the Port Mann Bridge, as shown in Fig. # 15. The foundation and retained soils in the area consisted of competent, glacial, cohesive and granular deposits.

Seven bridge sites located in Segments 2, and 4 of the highway are sitting on areas where soft compressible soils are present. To overcome the geotechnical challenges resulting from the ground condition and to meet the deadlines of a tight construction schedule, two-stage walls were selected as the optimal solution.

Fig. 10. SierraScape wall to raise River Road in proximity of Gunderson Road

Fig. 11. Construction of new lanes supported on MSE walls at Cannery intersection

Fig. 12. False bridge abutment at BNSF Sunbury intersection

The two-stage MSE wall construction process consisted of a 1st stage wall initially erected, which is comprised of a wire faced wall, with HDPE geogrid reinforcement, which allowed the contractor to continue with the earthworks bridge approach fill placement, while the 1st stage wall undergoes settlement, under the applied preload surcharge. This first stage wall is then allowed to settle under until achieving primary consolidation of the soils. One benefit of using a flexible wire-facing wall is that it can accommodate differential settlement generally in the range of 1/50, with no adverse effects to the wall facing system. After primary consolidation was completed the installation of a 2nd stage facing, which is effectively a false-fascia precast panel was placed in front of the 1st stage wall.

Fig. 13. Construction of false bridge abutment at BNSF Viaduct at River Road

Fig. 14. Bridge abutment at SFPR Tannery intersection combining MSEW and RSS

The construction of first stage MSE walls is depicted in Figs. # 16 through 18 below. The rock fill of the face in the first stage walls was replaced with the sand used as reinforced backfill which was confined with a non-woven geotextile installed behind the welded wire form. Settlements in the range of 1 m were measured by the constructor at the face of the wall upon completion of the primary consolidation.

Once the geotechnical engineer of the project approved the removal of the preload surcharge, installation of the precast concrete panels supplied by Lockwood Bros. Concrete Products took place as shown in Fig. # 19. A completed 2-stage MSE wall is shown in Fig. # 20.

Fig. 15. Construction of reinforced slopes for new highway lanes (courtesy of FTG)

Fig. 16. Construction of the first stage of 2-stage MSE walls

Fig. 17. First-stage MSE wall preloaded to accelerate construction settlement

Low Level Road

The Low Level Road (LLR), located within the City of North Vancouver, had a project value of $106 million and opened to traffic in November of 2014. The project was designed to improve rail and port traffic, by providing a vertical grade separation, to separate congested municipal roads from port and rail activities.

Fig. 18. Installation of the false fascia after completion of construction settlements of the first stage MSE wall

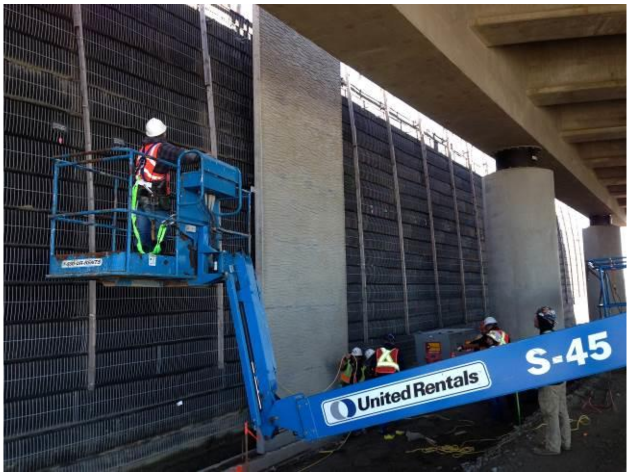


Fig. 19. 2-stage MSE wall after installation of precast concrete panel false fascia and copings

This involved the realignment and elevation of 2.6 kilometres of the LLR in North Vancouver, B.C., while creating room for two new rail tracks. The project eliminated three existing road and rail crossings while providing a new overpass to access the port terminals. The site topography generally rises up steeply when proceeding to the northeast. This added to the challenge of realigning road and rail, along an established port/rail facility, while proximal to foreshore of Burrard Inlet, with diverse geotechnical conditions.

Geotechnical Conditions

Foundation materials and retained soils for most of the walls of this project involved competent soil deposits of Pleistocene age of the Vashon Drift and Capilano Sediments (VCb) geological unit per the GSC Geological Map 1486a. These deposits consist of glaciolacustrine sand and gravel and lenses and interbeds of glaciolacustrine stony silt.

The exception to the above is the area of the Neptune/Cargill overpass, underlain by mountain stream marine deltaic Salish Sediments (Sai) consisting of sand, silt, silty clay.

Reinforced Soil Structures

A diversity of MSE walls and reinforced soil slopes were required to achieve the final realignment and widening of LLR, while safely isolating the lower port and rail activities noted along the southern extent of Fig. # 20. The project involved road realignment, MSE walls, earthworks, sewer, water main, and utility relocations, as well as the Neptune/Cargill overpass.

The above was generally achieved by building a Downslope wall (RW-A) which elevates the LLR creating grade separation from the railway and an upslope wall (RW-B) which supports road, bike, and pedestrian pathways above the LLR, as shown in Fig. # 20, below.

Wall RW-A was built using the SierraScape® wire-faced system described above, while the reinforced slopes employed the Sierra® reinforced slope system. Both systems were designed following the design methodologies described previously.

The MSE walls were built at vertical or near vertical inclinations at the face and maximum height of 14 metres. The vegetated reinforced slopes were built at inclinations of 69 deg. (3H:8V) at the face and maximum height limited to 5 m to facilitated maintenance activities; where higher slopes were required, wire-faced walls were built on top to achieve the desired grade elevations.

Fig. # 21 shows an aspect of the construction of wall RW-A, raising the LLR grade above the railway tracks; the Neptune/Cargill overpass above the existing rail can also be seen; this structure helped improve the safety and efficiency of industrial truck traffic accessing the port side, as well as the local travelling public. A detail of the construction of the southwest abutment of the overpass is shown in Fig. # 22.

Due to geotechnical challenges associated with existing soil sloughing/unraveling at steep slopes in some areas of the north side of the roadway, Stantec, the prime consultant for the project, decided to use a non-uniform geogrid layout that helped minimize the excavation into such problematics slopes. This non-uniform geogrid reinforcement layout, also known as trapezoidal layout, which allows the reduction of the geogrid length at the base and mid height portions of the wall while increasing the length of the layers above, was implemented at several locations for both, MSE walls and RSS. Fig. # 23 shows a typical trapezoidal section for a wire-faced wall.

A detail of the construction of a segment of hybrid retaining structure combining a vegetated reinforced slope topped with a wire-faced wall, built upslope of the lower wall RW-A is shown in Fig. # 24. Notice that vegetation is starting to develop on the face of the reinforced slope.

Conclusions

Geosynthetic reinforced structures have gained increased popularity over the last decades and have been used extensively and successfully in the construction of transportation and infrastructure projects in the Vancouver region.

Fig. 20. General Retaining Wall Arrangement (Courtesy of Stantec)

Fig. 21. Construction of wall RW-A above the railway grade

Fig. 22. Detail of the Neptune/Cargill Terminal Overpass during construction

Generally accepted design methodologies are available for the design of Mechanically Stabilized Earth structures and Reinforced Soil Slopes. Properly designed and built MSE and RSS have proven adequate performance under varied geotechnical conditions present in the Vancouver region.

Fig. 23. Cross section of a trapezoidal geogrid layout of an MSE wall (Courtesy of Tensar International)

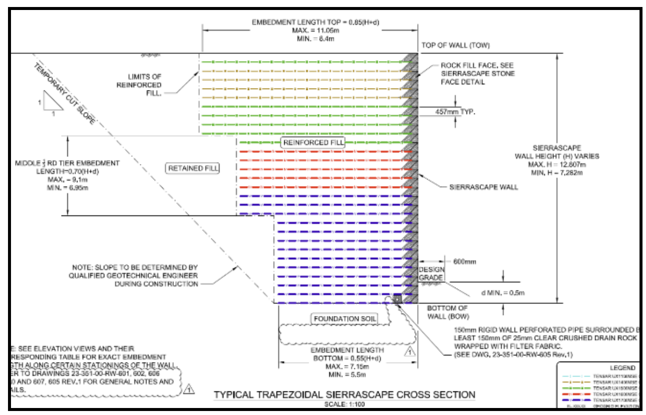


Fig. 24. Detail of hybrid structure combining a reinforced slope topped with an MSE wall

The versatility of these systems allows their use under a wide range of geometries, environmental and loading conditions. Tolerance to deformations make them a good choice in projects where geotechnical conditions may lead to large settlements or in the case of seismic shaking.

Reinforced slope systems have great environmental value as they can blend with the surrounding landscape or minimize the visual impact when built in urban areas. They also offer the possibility, in some cases, of using excavated materials from the construction sites, resulting in economies and reduced environmental impact.

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