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The design challenges of mechanically stabilized earth wall structures in extreme rainfall conditions for commercial operating owners

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Abstract. Mine owners demand that structures perform optimally at the primary point of commercial mining operations, which force the designers' attention to the critical contributions of the material characteristics. The extreme rainfall conditions and high loads exerted on the structures, required careful consideration of the design methodology and parameters used to cause the least amount of disruption during the full operating life span of the Mechanically Stabilized Earth Wall (MSEW) structures, through the varying conditions present on site. To design the low risk MSEW structures in Liberia, where the most common backfill construction material used is often of a lower grade laterite, combined with a rainfall condition classed as monsoon (above 4,000mm rain fall per annum), generated a scenario that forced the design approach and choice of geosynthetic materials to exclude any compromised solutions. Simplicity in the construction installation using geosynthetics and gabion materials have satisfied design requirements and minimized risk to mine operators and management.

1. Introduction

The continuing need for high performing infrastructure to support greater loads and withstand inclement site conditions is a common challenge faced in the mining industry. Two tall tipwalls were required to support the new Run of Mine (ROM) dump hopper pads that would form part of the expansion project of the concentrator processing plant at the Liberia iron ore mine, 270km North-East of the Liberian capital Monrovia. Previous studies established that the area was a monsoon region that often-experienced rainfall in the order of 4,000mm per annum. The project demands were met by using the Terramesh Mechanically Stabilized Earth Wall (MSEW) System.

MSEWs are defined as composite structures that are bound together by alternate layers of compacted soil and reinforcing elements confined by a vertical facing. These types of structures are often considered as an alternative to mass gravity concrete structures and can easily be adapted to its surroundings depending on the type of facing used. In comparison to

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traditional concrete panel MSE structures, these coherent gravity structures are flexible and can accommodate a greater degree of differential settlement.

Terramesh is a proven flexible MSEW system that has drawn its popularity from its ease of installation and reduced costs. This system comprises a 3m wide rectangular gabion-like facing with an integral 3m 'tail' to which high strength polymeric geogrids are fixed as reinforcement (Figure 1). The facing consists of pre-assembled units that are manufactured with double twisted wire mesh (Type 80 – 8x10). Long-term durability is ensured by galvanizing the wire mesh with *Galfan (Zn95Al5)* and polymer coating, thus increasing its resistance to chemical abrasion. Previous compression tests have been conducted on the Terramesh units showing that a filled Terramesh basket is resistant to approximately 600kPa of surcharge directly applied on top of the unit. In the field, the Terramesh basket is confined above/below, either side and behind, further increasing its resistance to surcharge loading. The high strength polymeric geogrids provide structural stability to the reinforced mass by transferring the destabilizing forces from the active zone to the passive zone through the frictional bond between geogrid and soil.

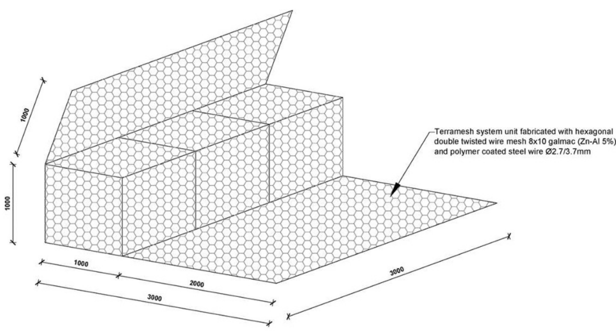

Fig. 1: Typical Terramesh Unit

2. The Liberia Project

The required Crushing Pocket at ROM 1 was approximately 19.7m in height and had a total of five loading bays, while the required Crushing Pocket at ROM 2 was approximately 16m high with two loading bays. Both headwalls had a maximum surcharge of 165kPa. The previously mentioned 4,000mm of annual rainfall also impacted the design requirements of the MSEW structures and, as such, drainage became a critical aspect of the project.

2.1 Design Challenges

Aside from the heavy loading and risks associated with monsoon conditions, it was further discovered from the borehole logs that the in-situ material on site contained 7m thick layers of Saprolitic soils, underlain by competent Gneiss. Other borehole logs indicated that the water table was at surface level with the presence of weak soils in the foundation material. These conditions were believed to be a result of anthropogenic (perched) groundwater, related to previous construction works on site.

2.2 Design Approach

For the design of the two MSE structures, both the FHWA-NHI-10-024 [1] and the BS 8006-1: 2010 [2] codes were adopted to mitigate the risks to the project as best as possible. Both, the FHWA and BS codes utilize partial factor principles to achieve a safe design. The FHWA uses the Load and Resistance Factor Design (LRFD) approach that is based on AASHTO [3], and the BS uses the Limit Sate Design (LSD) approach based on EuroCode 7 [4]. In addition to these codes, the client further required for the materials to be specified in accordance with the Client's Project Specification Document, that outlined the material specifications for the base and subbase materials which related to pavement design. The applicability of these materials for use in MSE design was confirmed by checking requirements in FHWA, BS, and the new South African COTO - Standard Specifications for Road and Bridge Works [5].

2.3 The Design

Considering the design challenges and requirements of the project, the Terramesh System was the most suitable MSE system due to its flexibility and free draining facing. The amount of water on site and the variability of both loading and ground conditions placed a premium on these aspects. A cost- and time-effective approach was selected whereby a combination of 1m and 0.5m high Terramesh units were used with high and low strength geogrids (depending on the level and loading conditions). The Terramesh units were supplied with Polimac polymeric coating to resist foreseen hydraulic and environmental conditions. As for the reinforcing elements, two types of polymeric geogrids were considered: ParaGrid 200 (UTS = 200kN/m) and the MacGrid WG8 (UTS = 80kN/m). Two types of fill materials were designed for, to comprise the ROM 1 and ROM 2 MSEW structures; a fill in the reinforced area (Structural Fill), and a backfill between the natural slope and reinforced area (General Engineering Fill). The specifications for these materials, as well as the modelling parameters used for MSE design and finite element (FEM) are presented in Table 1.

Table 1. Material specifications and modelling parameters.

Material Specifications	**CBR (95% Mod. AASHTO**	**Fines (<0.075mm)**	**Plasticity Index**		
Structural Fill (SF)	45%	< 15%	< 6		
General Engineering Fill (GEF)	-	< 25%	-		
Modelling Parameters	φ' (°)	c'(kPa)	γ (kN/m^3)	E (MPa)	υ
Structural Fill (SF)	36	0	20	60	0.3
General Engineering Fill (GEF)	30	0	20	15	0.3

Founding conditions were variable as some areas showed shallow gneiss, where others had deep saprolitic soils. The profile at the front of the wall was generally found to have shallow rock and, where not present, a granular subgrade was introduced to improve bearing characteristics. Foundation material was therefore conservatively modelled as GEF. A cross section of the ROM 1 headwall is presented in Figure 2.

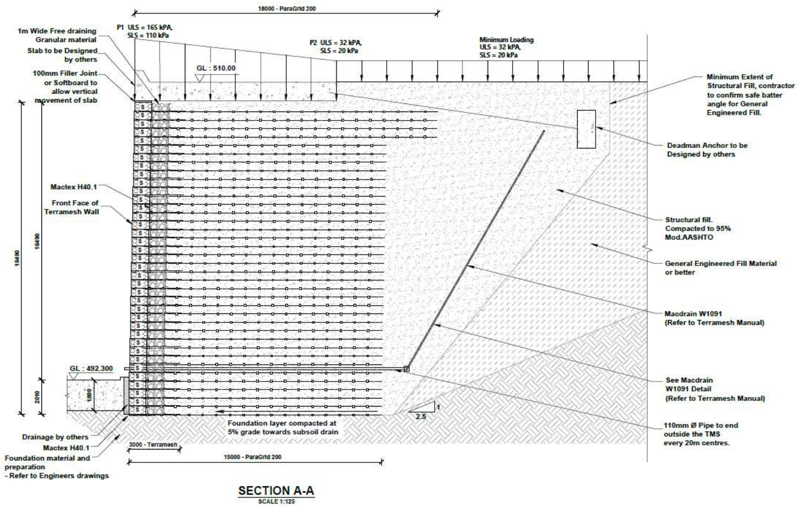

Fig. 2. Typical Section of an MSEW Terramesh Wall.

The head wall sections comprised of 0.5m units with 18 and 15m lengths of ParaGrid 200 reinforcement for the full height of wall. The combination of 0.5m units with ParaGrid 200, yielded the strength which was necessary for the 165kpa load applied below the head wall vehicle slabs. In the top two layers the minimum reinforcement lengths were increased by 1m to mitigate the risks of tension cracks forming between the structural and back fill zones post-construction or as a result seismic effects (as per FHWA). The MSEW structures were designed for a service life of 25 years. The resultant internal and external design checks for the ROM 1 headwall (the highest loaded area) are presented in Table 2.

Table 2. MSEW design checks for ROM1 Headwall.

External Stability	Bearing	Overturning	Base Sliding
Driving Force/Moment	-	12,600 kN/m	1,600 kN
Resisting Force/Moment	-	48,900 kN/m	4,000 kN
Minimum Capacity Required	1,500 kPa	-	-

Internal Stability	
Max. Geogrid Tension Calculated	74 kN/m
Ultimate Allowable Geogrid Tension	109 kN/m
Pull Out Force	28 kN/m
Adherence Capacity	59 kN/m

From the FEM serviceability checks conducted, it was further noted that the 0.5m units had the greatest effect on limiting the amount of bulging on the front facing of the wall, and reduced the allowable displacement to below 500mm, in accordance with the design criteria outlined in the FHWA. The forces acting on the loading slab were reduced to a per metre

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force to account for the 2D nature of the FEM analysis. The results of the FEM analysis on the ROM 1 headwall are presented in Figure 3.

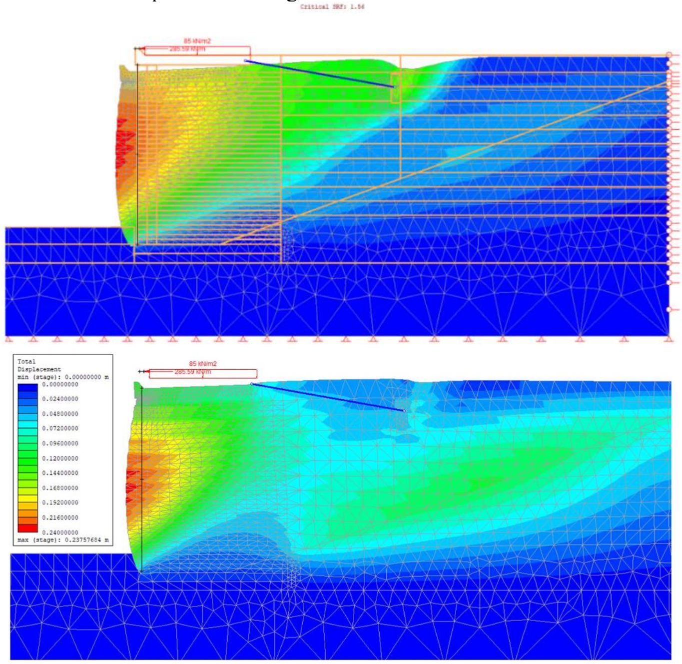

Fig. 3. FEM analysis (Top) ULS check: SRF 1.56, (Bottom) SLS check: expected displacements.

The traditional MSEW checks in codes (internal & external stability) cannot account for the global stability, which in this case includes a 15m long Deadman Anchor (DMA). The global stability was analysed using the strength reduction factor (SRF) in the FE model. The SRF reduced the shear strength parameters in the model until non-convergence (i.e. failure) was obtained. This is analogous to the Factor of Safety, and therefore a value of 1.4 was desirable. The SRF of 1.56 in the ultimate load case therefore showed that the DMA was successful in providing a safe global design. The force in the DMA was determined as 532kN/m. The displacements presented in Figure 3 are total displacements and represented the predicted (exaggerated) deformed shape of the facing. Calculation of differential displacements at the base of the wall showed displacements within allowable limits: a 300mm slot with granular infill was planned at the base of the structure to convey stormwater and prevent load transfer from MSEW to crusher slab. Only 14mm of lateral movement was calculated in this area.

For the wing walls, a different combination of the grids and units were used to suit the varying heights and load requirements of the structure as the wall height tapered down. It appeared to be more cost effective to use a 1m unit with a stronger grid and a 0.5m unit with a weaker grid due to the additional time required to install shorter units and their associated geogrids. By utilizing these configurations, similar strengths could be achieved without compromising the design methodology or exceeding the client's budget.

3. Drainage

The management of both, surficial and subsurface water was a key consideration in the long-term stability of the MSEW structure. The monsoon rains and shallow perched groundwater drove the requirement for the drainage systems to intercept surficial water before infiltrating the fill as far as possible and conveyed infiltrated water away from the MSEW structure to prevent pore water pressure build-up. Figure 4 presents failure modes resulting from inadequate water management.

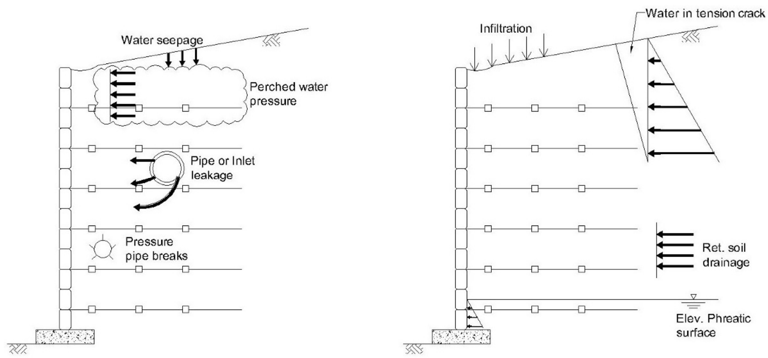

Fig. 4. Typical failures (left) due to internal water and (right) due to external water.

The following measures were put in place to mitigate risks posed by surficial water:

- An additional 1m free-draining layer consisting of sorted gravel located behind the vertical facing – this layer also increases the stability of the facing as per FHWA.
- A subsoil drain at the back of the reinforcement combined with a continuous drainage strip (Macdrain W1091).
- A drainage system on the base of wall consisting of Φ110mm geopipes at 20m centers.
- Berms were added at the top of the wing walls to provide a cutoff and channel surficial water to prevent overtopping on the structure as far as possible.
- As a mitigating measure for scour protection, Reno (Castoro type) Mattresses were inserted at the base of the wing walls if overtopping did occur, as per FHWA recommendations. Overtopping at headwall sections were not much of a concern due to concrete slabs at the base.
- Geomats (MacMat R) were recommended on top of the tip walls to prevent any surficial erosion of the structural fill material.
- A herringbone drainage system was constructed below the MacDrain, in the foundation area, to facilitate drainage of the subsurface water.

4. Installation

The Terramesh units are unpacked and assembled according to the Terramesh installation manual [6]. Once assembled, the individually laced units are then aligned to create the front facing of the wall with the Gabion portion on the outer side and the double twisted mesh tail towards the inner side. The adjacent units are connected along the vertical top and bottom edges with bracing wire. Connection of the tails are not essentially necessary, the frictional transfer of load between the tail and the geogrid suffices. This is considered in the design similarly to geogrid pullout, instead of a soil-grid frictional reduction factor, a soil-mesh and mesh-grid factor can also be used to check the pullout capacity of the tail. The Terramesh / geogrid interface is presented in Figure 5

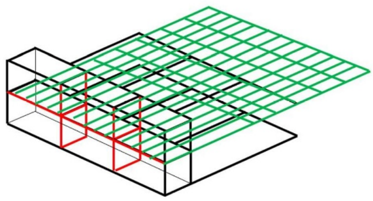

Fig. 5. Units connected with Grid.

The units shall be filled in accordance with the guidelines set out in the Terramesh manual and to ensure an aesthetically pleasing appearance, all visible faces should be hand packed. The diameter of the stone or crushed rock used to fill the unit, should be greater than the mesh aperture size of the Terramesh basket to prevent the individual pieces from passing through the mesh. For a Terramesh system with an 83mm mesh opening size, it is recommended to use 100-200mm diameter stones. As a further recommendation, the units should be overfilled by 30-50mm to allow for natural settlement of the rock fill.

At the interface between the back face of the Terramesh unit and the structural soil fill, a non-woven geotextile was included extending 250mm towards the backfill at top and bottom. The stone filled Terramesh basket is an important drainage path, and the non-woven geotextile prevents fouling of the free draining facing by infiltration of the fill material. The lack of the geotextile is generally detrimental to the integrity of the structure.

For the placing of grids and layering of structural fill material, it is essential to slope the final layer of fill at the end of every working day, to not less than 4% away from the front face of the wall to ensure the surface runoff is directed away from the area without the risk of ponding within the structural fill material. If the fill does get saturated, the layer should be removed, re-layed and recompacted.

FHWA notes that geopipes exiting through the facing must be installed in such a way as to not compromise the stability of the facing or allow the migration of fines out the wall, nor transfer load from wall to pipe due to settlements.

5. Conclusion

The current case study shows the benefits of using the flexible facing systems due to their utilization in a highly loaded and adverse environmental conditions when proper design is implemented. In the current study the external and internal design was determined as safe according to the BS and FHWA codes with the use of the Paragrid 200 reinforcement. The addition of a DMA helped to achieve a global stability SRF of 1.56, which met the minimum requirement for geotechnical structures. Furthermore, despite the flexible nature of the facing, differential displacement at the base of the structure was limited to well below what was required. The Terramesh MSEW System is particularly suited for high rainfall areas due to its free draining vertical facing. The Liberia Project was one of Maccaferri's largest projects with a total wall area 3,683m². A final layout of the ROM 1 and ROM 2 crusher walls is presented in Figure 6.

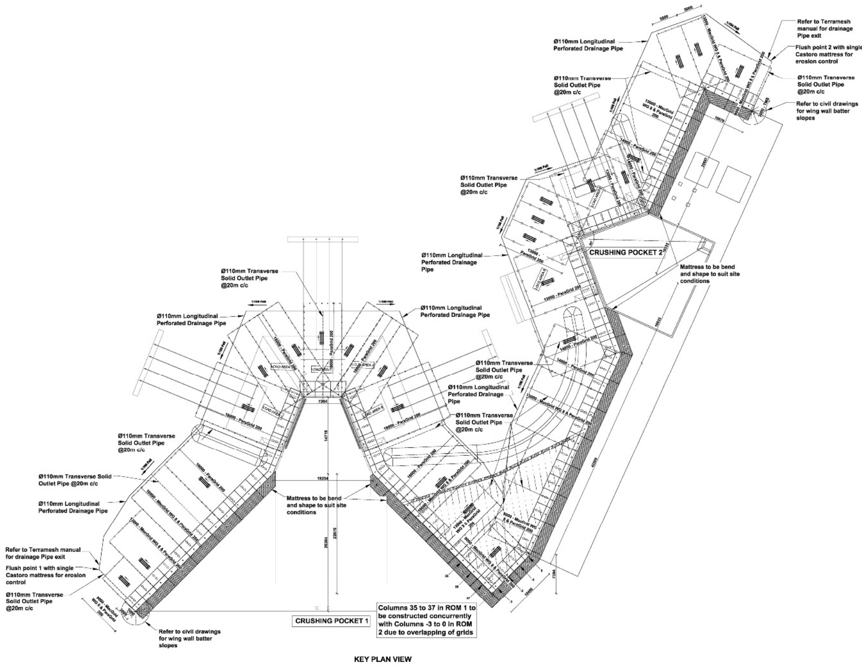

Fig. 6. Liberia Project Final Layout.

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