The problem with MSE walls – a case study in support of integrated geotechnical engineering design


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INTRODUCTION

Mechanically Stabilised Earth (MSE) walls have a growing application in place of conventional retaining systems for varying reasons, most notably economy and constructability. However, there have recently been a number of failures or instances of poor performance of these systems throughout the southern African region. An evaluation of these indicates that there are two fundamental causes for poor performance. The first relates to the nature in which MSE structures are planned, designed and constructed. The second relates to the need for the geotechnical designer to develop a clear understanding of the subsurface conditions, together with a need for routine verifications of the ground conditions, design, construction and materials during the process of construction. This article presents a case study of the planning, design and construction of an MSE wall, in this case a Reinforced Earth® wall, which was successfully constructed over a poor subgrade in Durban. In the context of the preceding discussion, the case for integrated design by geotechnical engineers is made, given the uncertainties with the "design and build" procurement model which is typically used for the supply of MSE systems.

MR458 ROAD-OVER-RAIL BRIDGE

Located approximately 20 km north of Durban, connecting JG Champion Drive to the Cornubia Industrial and Business Estate (CIBE), lies the new MR458 road-over-rail bridge which leads motorists directly to the main entrance of the estate. CIBE forms part of the Cornubia development, which is a multi-billion rand integrated human settlement incorporating industrial, commercial, residential and open space use. It is being developed by Tongaat Hulett Developments and the eThekwini Metro Municipality, and has been adopted by the Cabinet as a national priority project.

The dual bridges, each 88.5 m in length, comprise four spans with slanted piers and an integral deck consisting of pre-tensioned beams. The abutments to the bridges are also slanted and include some 200 m of MSE wall (MSEW) approach fills. The site is situated in an alluvial plain, with the western portion of the site previously cultivated as a watercress farm, while the eastern portion was used as a dump site for sludge from a nearby wastewater works.

The site offered poor founding conditions for the MSEW and bridge structures, with over 120 mm of settlement

Completed Cornubia Bridge and MSE walls – MSEWs are the ultimate geotechnical structures, as they have an incontrovertible link with the soils within, around and below

Cornubia Bridge west abutment – the abutments were slanted, which would have visually accentuated the effect of any downward settlement behind the abutment

Ground improvement comprising dynamic replacement craters

Load transfer platform designed in accordance to EBGEO

predicted for the 9.5 m high abutments. The bridge abutments are buttressed walls, leaning back at a 1 in 4 slope. The fact that the abutments were slanted implied that any settlement between the bridge (which is founded on rock-socketed piles) and the MSEW would be accentuated and immediately visible in the architectural feature of the bridges. The development of negative skin frictions on the piles for the abutments was also a concern, due to the poor subgrade. Dynamic replacement stone columns were thus required to improve the founding conditions below the MSEW.

OVERVIEW OF MSE WALLS

MSEWs in the broadest sense comprise concrete block or panel façades connected with multiple layers of inclusions acting as reinforcement in the soils placed as fill. The complexity begins with the wide array and ever-developing soil reinforcement technologies, suppliers, materials and even connection and construction methodologies, which implies that the performance of any MSE system hinges on the application for which the system is selected.

Added to this, is the multifarious interaction that occurs with the founding soils *on* which it is built and the soil materials *with* which it is built. MSEWs are the ultimate geotechnical structures; the structure has an incontrovertible link with the soils within, around and below. The stresses developed and strain encountered in the soils and the structural system itself, influence each other and cannot be designed independently of each other.

The case for the use of the MSE systems can be strongly motivated when the cost and time taken to construct such systems are considered. Cost benefit comparisons undertaken on recent bridge projects have shown that only once walls exceed 20 m in height should consideration be given to the replacement of sections of MSEW with additional bridge spans if there are no other considerations affecting the bridge length.

An inherent problem with MSE systems is the way in which they are procured, planned, designed and constructed. In trying to account for the varying patented systems, the most common approach is to allow the contractor to supply the design based on usually very limited information by the designer. For example, drawings could very simply state "wall design by others" with limited or inappropriate specification, and no guidance on design, design specification or parameters. This option is selected to encourage competition between suppliers, and is generally welcomed by suppliers, despite the self-inflicting problems caused.

Consequently, this procurement model has led to the following unintended consequences which undermine the effectiveness and credibility of the MSEW system:

- The elimination of proper geotechnical investigation and almost no involvement by geotechnical engineers as part of the principal design or owner's consulting team. This is supposedly under the assumption that the contractor (or supplier) assumes the risk, which is not the case.
- Without specifications provided by the owners, or if such specifications are too broad, it is not possible to compare MSEW on any basis other than on price. Hence, the least robust design will produce the lowest cost. Lack of a design basis memorandum may result in liberal soil strengths, optimistic loading conditions, and favourable groundwater conditions. Additionally, some proprietary design approaches eliminate or alter minimum standards of practice (e.g. facing connection, bearing capacity, corrosion protection, internal failure surface orientation, and global stability) (Simac *et al* 2007). This is particularly true in South Africa, where even unreinforced block retaining walls are confusingly marketed as technically equivalent to MSEWs.

Returning to the issue of risk, and with reference to the GCC and COLTO specifications, the design consultant retains responsibility for overall stability and design criteria. The system thus actually involves a shared design responsibility between the owner, design consultant, supplier and/or contractor.

It is not a design-and-build method, which is the method that the owner and designer usually believe they are getting, even though none of the procedural, contractual and legal criteria necessary to invoke a design-and-build scenario are put into place. This leads to confusion before, during and after construction regarding exactly which party assumes engineering responsibility (and liability) for important design decisions and quality assurance.

The above highlights that there is significant responsibility assumed by the owner and his designer when specifying MSEW systems, and in the case of the new Cornubia Bridge, the poor subgrade conditions and a bridge design which accentuates any settlement of the MSE walls behind the abutment, necessitated that an integrated geotechnical design approach was required for the success of the project. This integrated geotechnical design entailed the following:

- **Geotechnical investigation** in accordance with the SAICE Geotechnical Division Code of Practice for Site Investigations, and led by a registered geotechnical engineer;
- An **initial detailed design** to establish technical and performance criteria, and select suitable MSEW systems;

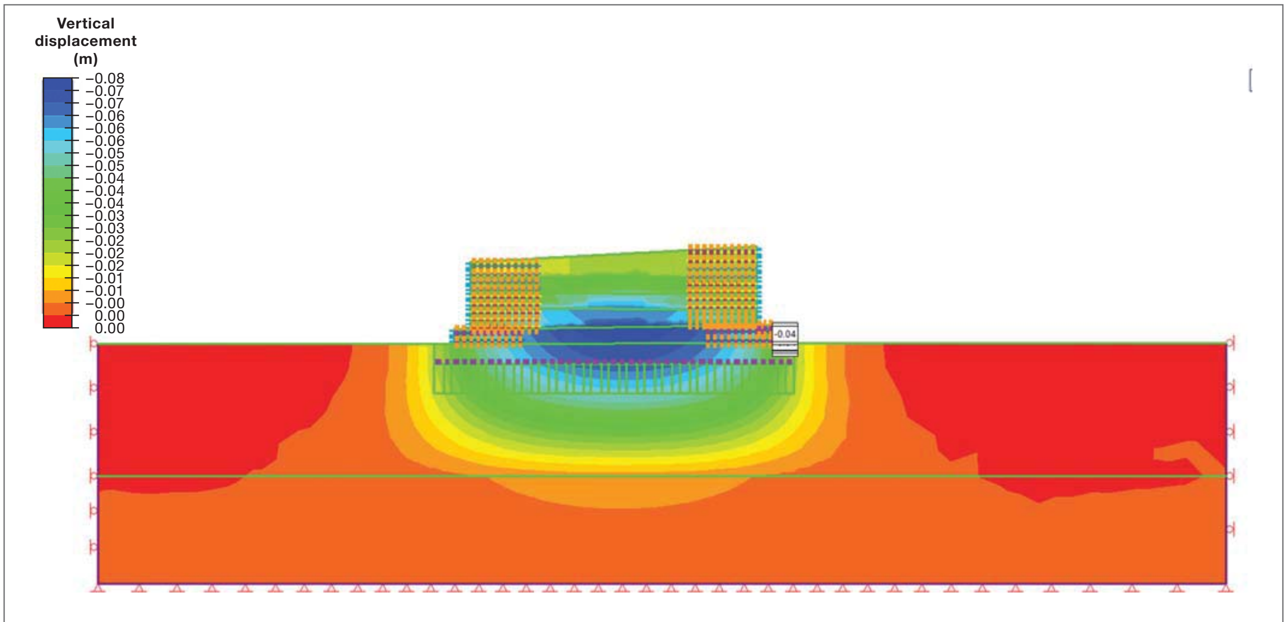

Figure 1: Staged finite element analysis – the analyses corresponded well to the surveyed settlements measured on targets placed on the MSEW panels

- Development of **tender and design specifications**, appropriately considering the various design constraints;
- **Finalisation of design** and design interfaces, with consideration of the final selected MSE system (by winning tenderer, Reinforced Earth), including peer review of respective designs; and
- Implementation of an appropriate **quality assurance**, testing, construction and performance monitoring regime. This included an appropriate level of construction supervision by the geotechnical designer and the supplier.

The above steps are expanded upon further below in the context of the project.

Geotechnical investigation

A comprehensive investigation was conducted, appropriate to the geotechnical conditions and structure proposed, and adhering to the SAICE Code. Investigations were undertaken by ARQ Consulting and comprised several rotary core boreholes to depths of up to 17 m, in-situ testing (SPT and DPSH) and laboratory testing on soils and rock.

The DPSH tests showed very little resistance through the alluvial materials, with the probe progressing some 200 mm per blow in some instances. The SPT results, using cautious estimate SPT-N blow count, was in the order of 8 over the top 5 m, and SPT-N blow count of 13 from 5 to 10 m. Mudstone and dolerite were encountered at depths exceeding 10 m.

Initial detailed design

An initial detailed design was undertaken using typical and varying parameters for the MSE structure to account for different systems which could potentially be used. This required the selection of a number of performance criteria against which various MSE technologies could be evaluated, and a cost benefit and optimisation exercise. This optimisation duly considered various influencing elements – such as ground improvement on overall stability and settlement, and the availability and selection of fill material on internal stability.

Due to the poor founding soil stiffness values, associated low bearing capacity and expected high settlements, ground improvement measures were implemented for the foundations of the MSEW. This ground improvement was achieved by means of dynamic replacement with the rapid impact compaction (RIC) method. The RIC specially adapted machine uses a 9 ton weight from a drop height of 1.5 m.

The stone column raft was capped with a load transfer platform, consisting of a high-strength bi-directional geotextile, and a granular raft consisting a G6 material. The platform was reviewed in accordance to methods described in SANS 207:2006 and the Recommendations for Design and Analysis of Earth Structures using Geosynthethics Reinforcements (EBGEO). The two methods differ in the way the soils between stone columns are analysed, where the one ignores the subgrade provided between stone columns and the other incorporates the subgrade.

The MSEW consisted of a tiered walkway system with specially made panels, 3 m wide and 1.5 m high, according to the architectural requirements. The settlement performance was modelled in finite element software to establish the improvement that could be expected in the overall behaviour of the system whilst using a dynamic replacement stone column foundation with a granular platform. The offset between the two tiers implied that the top and lower tiers would influence each other. The maximum tension line would, however, be at a flatter angle when compared to a non-tiered system, and therefore strip lengths need to be reviewed for pull-out, differently to methods used for a non-tiered system.

Without any soil improvement, some 120 mm of settlement was expected due to the fill placement. The dynamic replacement stone columns and G6 platform were shown to improve the settlement behaviour in a staged finite element analysis to some 50 mm, while the estimated self-weight settlement was estimated to be negligible at some 12 mm.

Tender and design specifications

Considering the design limitations, development of a specification for the supply and internal design of the system, with due consideration of the SANS 10160 and SANS 207 requirements, was undertaken. Specific attention was given to design safety factors, design loads, design responsibility, supplier involvement and responsibilities during construction, including verification testing.

Technical specifications thus set out minimum technical and performance criteria required by the supplier, allowing for the assessment of the tenders on adherence to criteria first, followed by price.

Finalisation of design

Although performance criteria were set at tender stage, these governed the range of several design parameters important to the design. The finalisation of the design was dependent on having discrete design values, which were only known once the final MSE system was selected (i.e. successful tender is known).

This stage also included peer review and collaboration on the design with the suppliers on their internal stability designs and compliance with specification. Similarly the supplier was able to review the owner's external stability designs. This ensured that design assumptions

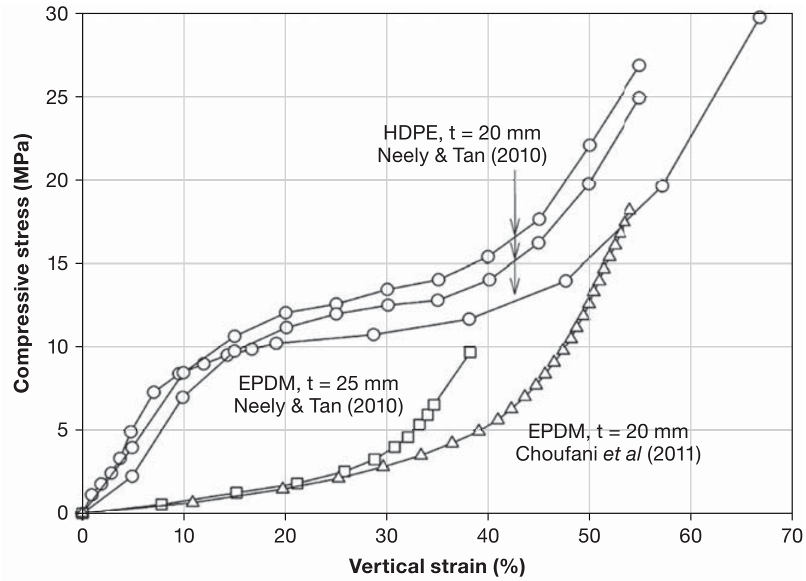

Figure 2: Compression behaviour of HDPE and EPDM bearing pad materials (Damiens *et al* 2013)

Although performance criteria were set at tender stage, these governed the range of several design parameters important to the design.

Bearing pads placed on vertical joints between panels

and interfaces were understood. One such example was the internal or inter-panel settlement:

As settlements were very much driving external design and performance criteria, it was important that this was communicated and considered in the internal design, and in particular the concrete panel façade and the larger-than-normal panels used. Bearing pads are utilised to absorb internal (as a result of settlement of the fill) and some external settlement (as a result of foundation settlement). These are placed in horizontal joints of discrete precast concrete panels in order to allow the panel and the reinforcement to move down with the reinforced fill as it is placed, and settles. This mitigates downdrag stress and provides flexibility to the façade to account for differential foundation settlements. SANS 207:2006 states that for discrete panels the vertical movement capacity of the system should be a minimum of 1 in 150 relative to the panel height.

Ethylene propylene diene monomer (EPDM) bearing pads of 25 mm were placed in the joints between the discrete panels at a spacing of 0.75 m. The expected stress-strain relationship is provided in Figure 2 for three different types of bearing pads.

The foundation and internal settlements, panel rotation and weight of the panels were all modelled in geotechnical finite element software to analyse the number of bearing pads required on the vertical joints between panels. Additionally, the loads in the steel strips were reviewed to compare them to the capacities they have been designed for and to establish if additional or higher loads are attracted to the strip at the facing-strip interface (T_{conn}).

Quality assurance

The final and most important stage of a fully integrated geotechnical design is the implementation of an appropriate quality assurance, testing, construction and performance monitoring regime. This must include an appropriate level of construction supervision and oversight by the geotechnical designer.

For the ground improvement, quality assurance was undertaken by reviewing the continuous number of blows versus penetration plots, plate load tests, DPSH and continuous surface wave (CSW) testing, which all provided verification of the subsoil conditions and the performance of the ground improvement. This was in addition to standard quality assurance and testing of the concrete, backfill, layerworks, materials supplied, survey, line and levels.

Settlement was monitored on panels and in the roadway, and limits set which governed the timing for placement of final road layer works and ancillary features.

CONCLUSION

It is essential that professionals charged with the responsibility of planning, designing and implementing MSE retaining systems understand the application, limitations and costs associated with such technologies, which are ever developing and advancing. This responsibility is often exacerbated by difficult subsurface conditions, restricted right-of-way and marginal sites with challenging topography, variable climatic conditions and other environmental constraints.

The notion that in projects where public money is involved these systems are procured on a design-and-build basis, thus absolving the owner and/or consultant of any responsibility, is not correct. Notwithstanding the fact that the contractual mechanisms enabling a design-and-build approach are seldom put into place, there are highly complex interactions between internal and external design factors, and between the soils and structural members making up the MSE system. If failure occurs, the responsibility will invariably need to be shared, as it will always be difficult to identify a single causational factor which led to the failure.

Furthermore, the recent trend by owners and consultants of providing contractors with limited or inappropriate investigation, design specifications and parameters, and performance criteria, unfairly jeopardises the entire industry. It is a clear dereliction of design responsibility.

Whilst it is understood that both COLTO and SANS 207 are currently under review, limitations to these will remain. The requirement for adequate ground information and an integrated approach to the geotechnical engineering design of MSE represents best practice and reduces the risk for all project participants. Likewise, the introduction of new and conflicting technologies implies *more* involvement of geotechnical design engineers in defining the problem and levelling the playing field, not less.

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REFERENCES

A full list of references can be provided by the authors on request. ◻

PROJECT DATA	
Client	Co-funded by eThekwini Municipality (60%) and Tongaat Hulett Developments (40%)
Consultant	SMEC South Africa
Contractor	Fountain Civil Engineering (FCE), with Reinforced Earth as MSE supplier
Project value	R145 million