In the past decade Mauritius has implemented major road and traffic infrastructure upgrade projects with the aim of alleviating ever-increasing traffic congestion. In October 2015, the Minister of Public Infrastructure and Land Transport (MPI) announced the implementation of a new Road Decongestion Programme (RDP) over a period of five years, starting in the 2016/2017 financial year. The overall aim of the RDP is to provide an efficient, high-quality road network supporting the socio-economic development of Mauritius by alleviating congestion, improving road safety and enhancing the overall level of service offered to road users.

The Government of Mauritius pledged an investment of 15.5 billion Mauritian Rupees (MUR) (~ZAR6.2 billion), entirely financed by the government. Reportedly, this figure recently increased to MUR37 billion, mainly due to international grants, which also include implementation of the Metro Express project. Growth in the construction sector is projected to rise to 9.5% in the 2018/2019 financial year, while overall economic growth is forecast at 3.9%.

For these massive capital investments, acquisition of land is required to expand existing traffic networks, ultimately leading to the planning and alignment of some roads over very challenging topographical, hydrological and geological terrain and environments. Ring Road Phase 1 served as one of the forerunners in providing an initial solution for a much-needed alternative route into the capital city, Port Louis, from the south. The first phase, constructed from 2010 to 2013, comprises a 4.9 km dual carriageway and one large bridge over the St Louis River, with access roads to industrial and retail areas and their National Convention Centre. The successful completion of Phase 1 of this project was therefore paramount to the implementation of Phase 2.

**PROJECT INTRODUCTION**

For Phase 1 of the Ring Road, steep natural topology necessitated the construction of several large cuts and fills. Space restrictions justified implementation of large mechanically stabilised earth (MSE) walls instead of traditional fills. In early 2014, cracks appeared on the northbound carriageway, followed by the collapse of a 15 m high MSE wall portion of the fill (Figure 1). Observations pointed to a textbook circular slope failure with "slip at the lip" and "bulge at the toe", indicating that deep-seated movement had occurred. ARQ (Pty) Ltd was appointed to identify the mechanism of failure, design remedial measures and oversee implementation of these solutions.

These remedial measures consisted, inter alia, of a vertical secant piled wall supported by seven-strand, three-level, high-strength ground anchors, coupled with a geosynthetically reinforced fill section behind the reconstructed MSE wall (Figure 2). An article discussing the investigation and design aspects of this remedial work was published in the April 2016 edition of *Civil Engineering*, and this article now summarises the construction of the remedial solutions.
DEMOLITION

Where possible, backfill material excavated during demolition was stockpiled and reused in the remedial work. All contaminated failure material was tested beforehand to confirm its suitability for reuse in the structural backfill.

During demolition and excavation, the contractor excavated to behind the theoretical failure plane (Figure 3) into residual material to ensure long-term stability.

Safe slope angles were required to ensure the safety of people and plant during construction. The most critical section of the slope was identified as that where the slope height was greatest. A 1:1 batter angle was calculated as being acceptable for temporary works (Figure 4). Slope stability was continuously monitored during construction via visual assessment.

Care was taken to check for any signs of instability or movement following periods of significant cyclone rainfall. No instabilities or collapse occurred during construction.

SECANT PILE WALL

For secant pile wall installation, a guide beam (Figure 5) was required to ensure accuracy and interlock between the piles. The site sloped away from the wall and...
along the road alignment approaching the St Louis River. This necessitated two platforms for piled wall installation to optimise pile lengths and minimise temporary lateral support requirements. The curved alignment of the road further added to the complexity, and necessitated concave construction of the beams and other elements.

The secant pile wall consisted of 1080 mm diameter cased augered piles to bedrock, at 925 mm c/c spacing. Piles were installed in alternating “hard” ($f_{cu} = 40$ MPa) and “soft” ($f_{cu} = 10$ MPa) sequence, with hard piles reinforced with 18Y32 bars. Sockets of 3 m and 1 m deep were required for the hard and soft piles respectively to ensure that the piles would resist bending moments and shears imposed by the high MSE wall. The piles were installed to minimum and maximum depths of approximately 10 m and 25 m. A total of 47 hard and 46 soft piles were installed, with total lengths of 779 m and 757 m respectively.

**CHALLENGES ENCOUNTERED**

Several challenges were faced during construction, of which a few are mentioned here. Cyclonic weather conditions, constant rain, high temperatures and humidity in the closed mountain valley proved challenging for health, safety and quality of work. Teams worked double shifts to ensure compliance with the construction programme. Augering into hard rock and working night shifts led to noise pollution of the neighbouring residential areas. Concrete supply was limited to outside peak traffic hours, as regulations restrict heavy vehicles on main roads during these times. This factor, combined with high temperatures, severely hampered continuous concrete operations. Casing segments of 3 or 4 m meant that it was often necessary to construct temporary ramps for concrete tremie-pipe pouring. Restricted space, wet platforms and steep slopes further contributed to the unique challenges.

Medium-hard rock was assumed, as it was encountered in borings behind the failure plane from the top of the MSE wall. However, during auger drilling/casing installation, it was found that the bedrock strength varied significantly, with the unconfined compressive strength (UCS) ranging from 110 MPa to 250 MPa. This placed severe strain on the equipment, causing a decrease in production.

To mitigate the strain, reduced socket lengths were proposed. The design was altered to allow sockets of 0.5 m to 1.0 m, depending on the bedrock UCS, for the unreinforced/soft piles. The reinforced piles required a socket length of >1 m, plus 2 m of a heavily reinforced 350 mm pile rock socket where the UCS was >70 MPa to ensure adequate moment/shear capacity.

Upon completion of the pile installation, a capping beam was constructed with shear stirrups tying guide beams to the piles. This continuous reinforcement induced another level of system reliability for a small additional cost and minimal construction delay.

Quality assurance was implemented by pile echo tests (PETs) and cross-hole sonic logging (CHSL). Any anomalies were investigated via core drilling.

**MSE WALL AND EMBANKMENT FILL**

The secant pile wall/capping beam installation was followed by MSE wall and embankment fill construction concurrently with the excavation in front of the pile wall and ground anchor installation. It was a client requirement that the remedial MSE wall be exactly the same as the original design. A sequence of fill height versus anchor installation was followed to ensure adequate system reliability at all times.

The bottom MSE wall panels were placed on top of the capping beam. Steel strips connected to the panels reinforced the graded rockfill placed behind these panels. The upper portion of the embankment consisted of compacted G8 material. In order to limit differential settlement between the existing and new fill and to increase overall stability, a high-strength 100 kN/m bi-axial geogrid, combined with a layer of non-woven needle-punched geosynthetic, acted as both reinforcement and separation between the rockfill and the normal fill and was placed every 750 mm in the new fill.
During construction, progress of the rockfill and normal fill was synchronised to ensure a minimal step height between the two (Figure 6). Due to frequent rain on site, the embankment fill was often ripped and left to dry before recompaon. This resulted in the embankment fill governing overall progress, as rockfill compaction is practically insensitive to moisture content and therefore much quicker to place, even though steel reinforcing strips were placed within this layer.

GROUND ANCHORS

Remedial work comprised the installation of three rows of seven-strand anchors through the soft piles of the secant pile wall and into the bedrock some distance behind. The load from the ground anchors was distributed to the hard piles via reinforced continuous steel waler beams. Altogether 128 anchors were installed with a total length of 3,938 m – the longest anchor being 51 m in length. The height of the fill above the pile capping beam was some 15 m and the bottom row of anchors was some 6 m below the top of the capping beam. The maximum height difference between the top of the fill and the lowest anchor was therefore around 21 m.

Soil conditions were very challenging for the drilling of anchor holes (Figure 7), as the in-situ material included highly plastic soft clays with boulders, groundwater and a rapid transition from soft clay to very hard basalt rock. The anchor tips were fixed into this latter rock for about 8 m. These challenging conditions reduced drilling accuracy and this, together with a slight curve on one portion of the wall alignment, resulted in a slight alteration in the trajectory of alternating anchors being specified to prevent collision.

Initially, a construction sequence was determined relating the allowable fill height to the progress of anchor installation. This sequence was determined by limiting the movement of the pile wall to <20 mm and also considering the loads on anchors and pile moments. It was necessary to determine this sequence, as the loads on the pile wall would change constantly with the fill height above the wall, the excavation in front of the wall and the progress of anchor installation. This sequence necessitated two-stage stressing for all anchors, with the anchor stressing loads for intermediate stages being roughly 30 to 50% (depending on
the anchor position) of the stressing loads for the final stage.

During construction this sequence proved time-consuming and, as the movements of the capping beam (surveyed weekly) were <20 mm, an accelerated programme was instituted. This entailed stressing each anchor only once (to some 85% of its final design load). This new design load was chosen such that the wall was still able to move slightly outward (but still less than the 20 mm requirement) without exceeding the allowable anchor loads. As part of the observational approach adopted, the frequency of the capping beam surveys was increased to twice a week and additional lift-off tests were also conducted on selected anchors to monitor whether their increase in load was acceptable. Fill height sequence versus anchor installation progress was also adjusted accordingly. Adopting the observation method proved to be successful, as the movement never exceeded 20 mm and the final anchor loads did not exceed their safe, allowable loads.

After completion of anchoring (Figure 8), the excavation was backfilled to the top of the capping beam. As the backfilling of the excavation progressed, the waler beams and anchor heads of each row of anchors were cleaned and subsequently cast in a lightly reinforced concrete beam for corrosion protection (Figure 9). The beams were cast using self-compacting concrete and included breather pipes to ensure that all voids were filled with concrete. Bituminous paint was applied to the outside of the beams and the pre-formed joints were sealed.

### ROAD AND EMBANKMENT

After completion of the MSE wall, the road embankment for the dual carriageway was constructed above, together with the road drainage, street lamps, pavement layers, asphalt surfacing and other road ancillary works (Figure 10), resulting in the road being reinstated to its original alignment and pavement design.

### CONCLUSION

Remedial work to the Port Louis Ring Road was completed in mid-2017 (Figure 11) after the resolution of several design and construction challenges. This project highlighted the value of having an experienced geotechnical engineer, intimately familiar with design, on the site full-time. In a complex and ever-evolving construction project, in-depth construction monitoring, as well as facilitating and commissioning design changes, is imperative to achieve success. At the end of the day all challenges were overcome and the road was returned to its original state by implementing state-of-the-art geotechnical solutions.

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