DESIGN AND CONSTRUCTION OF BRIDGE No. 4163 OVER CRAVENS CREEK AT EAST-WEST ARTERIAL STAGE 2 (ACT). A NEW APPROACH TO TRADITIONAL MASONRY ARCH BRIDGES.

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ABSTRACT

The Reinforced Earth Company, engaged by Brown Consulting, undertook a detailed design of a bridge over Cravens creek at the East-West Arterial Rd. ACT.

Bridge No. 4163 is a twin arch bridge designed for the SM1600 live load. The bridge has a straight alignment over the creek.

This paper covers the design and construction techniques of an arch bridge using only precast elements and Mechanical Stabilised Earth walls (MSE walls), with the exception of the in-situ arch footings. Arches, spandrel walls, abutments, wing walls, parapets and balustrades were developed to replicate a traditional masonry arch bridge. Concrete panels for the spandrel walls, abutment and wing walls were cast and assorted architectural finishes using varied coloured concrete mixes to simulate the stone finish. The funicular shape of the three-pin precast arches and the MSE walls aimed to provide a reliable and cost effective solution for the project requirements.

PROJECT BACKGROUND & OVERVIEW

The Reinforced Earth Company (RECO) was awarded the design and supply of two TechSpan® precast arch structures with MSE TerraPlus® retaining walls as part of the East West Arterial Stage 2 Project.

The combination of both structures conforms a bridge that will be supporting the arterial road crossing at Cravens Creek which is located in ACT's central west. The arch structures are installed in parallel; each with a length of 36m (bridge width) and a span of 18m each. MSE retaining walls are installed at each arch entrance to retain the arch backfill.

The precast wall facing panels have a Reckli® 2/168 Somme tobacco finish that replicates stonework, and the balustrade panels have a smooth charcoal finish.

This major infrastructure project has been contracted to Woden Contractors Pty Ltd by SMEC for the ACT Government and should be completed by late 2015.

TRADITIONAL MASONRY ARCH BRIDGES

The main load-bearing structures of a traditional masonry arch are made from natural stone, brick, or concrete blocks. Such a bridge is always arched, with large supports. The main load-bearing element of a masonry bridge is the arch, over which is built the spandrel, which in turn supports the bridge roadway. The spandrel is made from a gravel or crushed stone backing held in by lateral (side) walls made from concrete masonry or stonework (see Figure 1).

The design of the arch naturally diverts the weight from the bridge deck to the abutments. Arch bridges are meant to be under compression. The force of compression is pushed outward along the curve of the arch toward the abutments.

On the other hand, tensional forces in arch bridges are virtually negligible. The natural curve of the arch and its ability to dissipate the force outward greatly reduces the effects of tension on the underside of the arch. The greater the degree of curvature (i.e. - the larger the semicircle of the arch), the greater the effects of tension on the underside of the bridge.

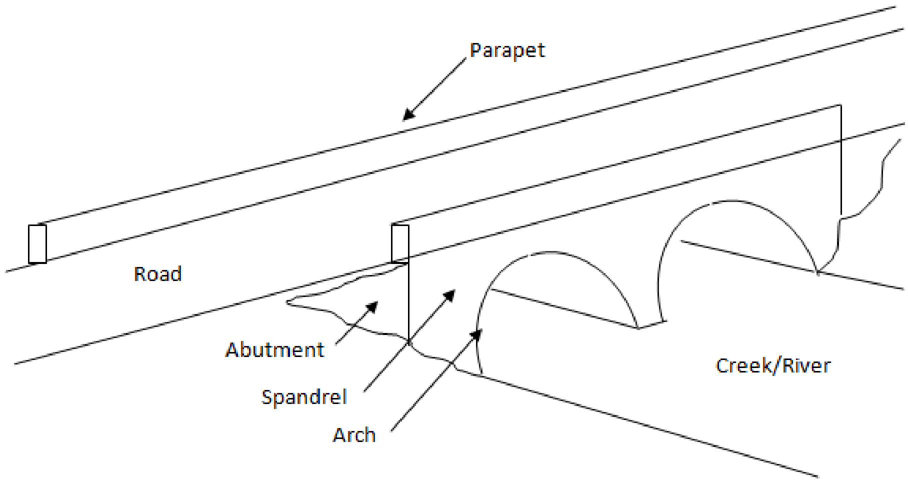

Figure 1 – Traditional Masonry Arch Bridge

As previously mentioned, the shape of the arch itself is dissipates the weight from the centre of the deck to the abutments. As with the beam bridge, the limits of size will eventually overtake the natural strength of the arch.

Traditionally, the arch is really a beam curved to form a semicircular shape made from a series of blocks carefully cut to fit together perfectly. These blocks are wedge-shaped, and gradually take the curve of the arch from the central and vertical 'keystone' down to the outermost and horizontal 'footers' (see Figure 2).

The key feature by which the arch improves on the simple beam is the partial dissipation of vertical forces horizontally. This means, however, that for an arch to work it requires substantial material to the sides, to stop the arch spreading and the central section collapsing inwards. This is what makes early arch bridges so massive in form.

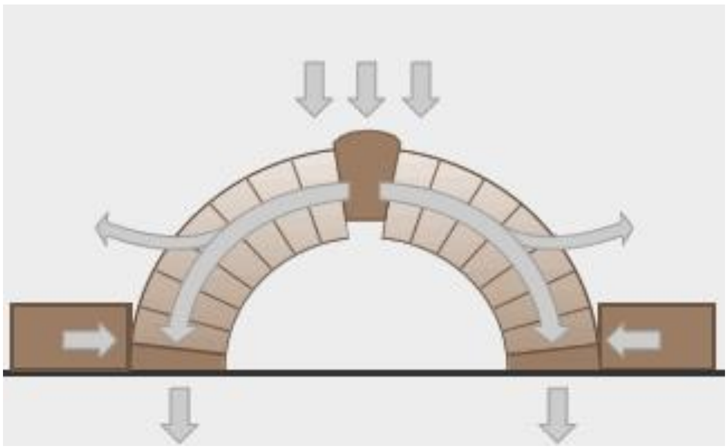

Figure 1 – Schematic arch diagram
(Arrows suggest forces acting on the structure)

While there is a lot of cosmetic variety in arch bridge construction, the basic structure doesn't change. There are, for example, Roman, Baroque and Renaissance arches, all of which are architecturally different but structurally similar.

It is the arch itself that gives its namesake bridge its strength. In fact, an arch made of stone doesn't even require mortar. The ancient Romans built arch bridges and aqueducts that are still standing today. The tricky part, however is building the arch, as the two converging parts of the structure have no structural integrity until they meet in the middle. As such, additional scaffolding or support systems were typically needed.

THE PRECAST APPROACH TO TRADITIONAL MASONRY ARCH BRIDGES

The main advantages of a masonry bridge are its durability and its architectural attractiveness. Masonry bridges are known that have been in use for more than 2,000 years. The basic short comings that limit the use of masonry bridges are their complexity and labor-intensiveness of construction. A new variation of a masonry bridge is the concrete bridge, where its components have been replaced in the design by precast concrete elements.

Basically, this system consists of two main components:

1. Precast Arches.

2. Spandrel walls & Abutments (MSE walls)

1. Precast Arches

1.1 Introduction

Precast arch geometry and loading are evaluated, as a funicular curve, to generate an arch that will create the most optimal and economical shape, minimizing tensile forces, thus creating an axially loaded structure. The Arch cross section consists of segmental precast arches units forming a three-hinged arch structure (see Figure 3).

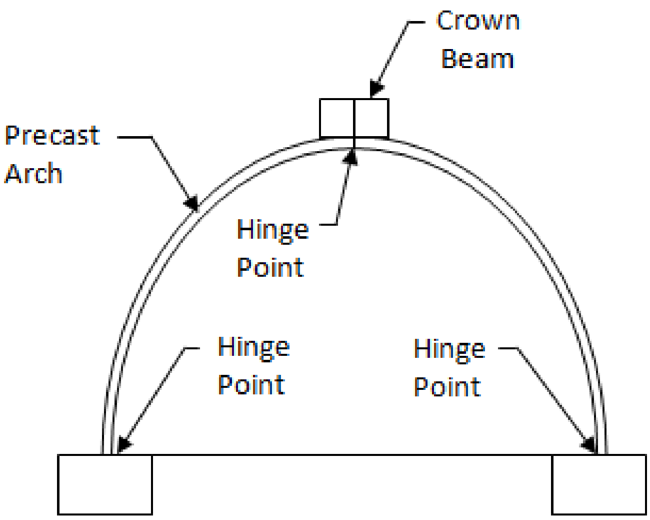

Figure 3 – Three-Hinged Arch Structure

This technology is a rapid and simple method of construction and can cross the waterway without temporary channel relocation. Another attractive benefit is the appearance of precast arches complimented with MSE head walls, allowing for unique architectural features suitable for its surroundings.

1.2 Design of Precast Arches

The design approach used for TechSpan® precast arches is aimed at determining the most cost efficient arch shape meeting the project specifications, including the clearance box required inside the arch and the geometry of the surrounding soil. (See Figure 4).

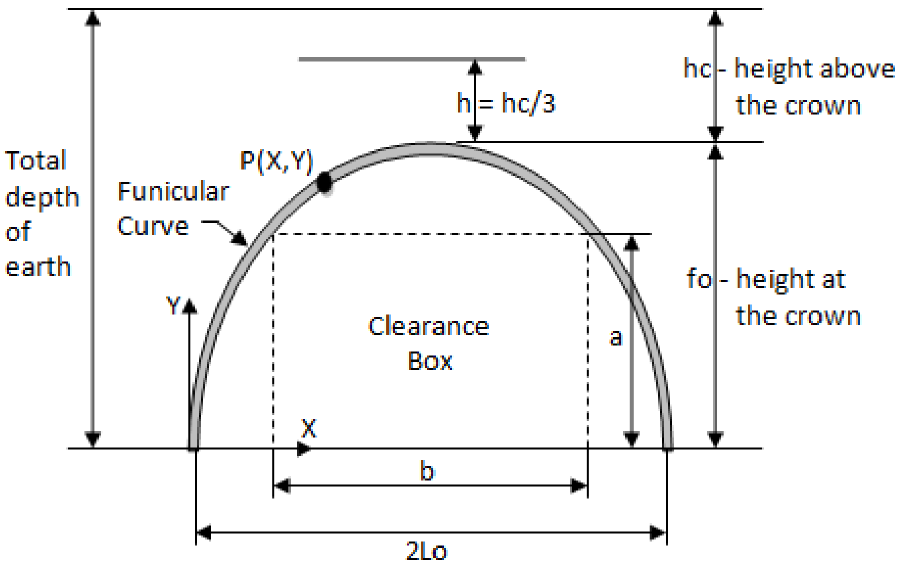

Figure 4 - Arch Geometry

The first step in the design process is to develop the arch shape. The coordinates of the funicular curve, or arch shape, are calculated by incrementing the ordinate y and resolving the fourth degree equation in x (see equation below), where ‘λ’ is the usual earth pressure coefficient: λ = tan2 (π/4 - ϕ/2) and ‘ϕ’ is the internal friction angle of the fill.

$$\frac{\lambda}{6}y^3 - \frac{\lambda(h+f_0)}{2}y^2 - \frac{f_0}{12L_0^2}x^4 + \frac{f_0}{3L_0}x^3 - \frac{f_0+h}{2}x^2 + L_0\left(h+\frac{f_0}{3}\right)x = 0$$

In general, the increment ‘y’ is chosen such that we know a point on the funicular curve having the same ordinate as the clearance box (y = a), ensuring the clearance box lies within the shape of the arch. This paper will not discuss the derivation of the funicular curve equation as the funicular curve is only a starting point that begins the design process of the arch. For developing the x and y coordinates or geometrical characteristics of the arch, it is assumed no bending moment occurs in the arch. *Terre Armee International (1990)*[1]

The next step in the design of the arch is calculating the forces developed in the elements at the various stages of construction. The lifting of the arch for handling and construction create forces in the arch that need to be considered. The maximum bending moment occurs when the arch is resting on its ends just before being lifted into position. The minimum (negative) bending moment occurs during construction or assembling before the earth fill is added. Any effects of the wind load can render this case even more critical.

The forces developed in the arch from handling and the assembly loads may be readily calculated. However, the forces due to the earth fill and surcharge loads are not as easily calculated but responds to the deformation of the arch to modify the overall stress condition and strain response. The key phenomenon is the relative stiffness of the arch and the earth backfill.

In Figure 5, a concentration of vertical stresses, due to negative friction resulting from down-drag, leads to an increase in vertical load on a stiff structure. Conversely, a flexible structure may have a decrease in vertical load.

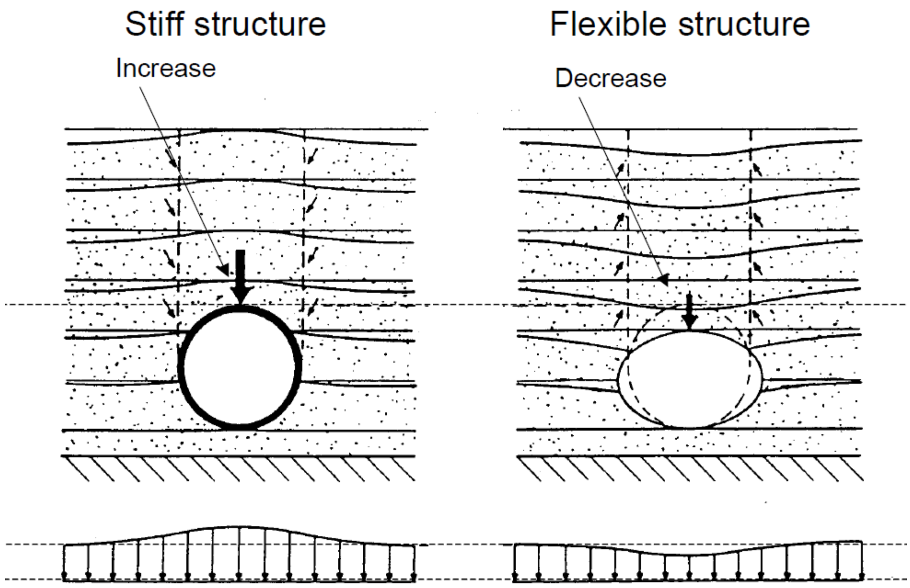

Figure 5

There are many finite element programs that could probably analyse the arch shape. However, specific needs were required such as having the flexibility to analyse many different arch shapes quickly and to analyse the backfilling lifts around the arch. Reinforced Earth Group developed a specific finite element program called AZTECH to model the soil & arches together. AZTECH is a non- linear elasto-plastic program.

This finite element software uses six different types of materials: concrete arch, foundation soil, general backfill around the arch, backfill immediately surrounding the arch, soil/concrete contact elements, and hinge elements (at footing and crown). The backfill around the arch is by far the most complicated material to model. The fill material around the arch has the greatest effect on the arch loading. To best model this material, the Young's Modulus and Poisson's Ratio are both presented as a function of stress in accordance with the relationship defined by Duncan et al (1980)[2] . The Young's Modulus and Poisson's Ratio are calculated in accordance with equations in this reference as a function of the constants, Ki, Kb, n & m.

The finite element analysis is carried out for a number of load cases. The initial load case is the arch erected and resting on its footings, without backfill at each side. Subsequent load cases represent the phases of backfilling, which take place in asymmetric 1.0m layers on both sides of the arch (See Figure 6). The 1.0m layers ensure the allowed maximum differential height of 0.5m.

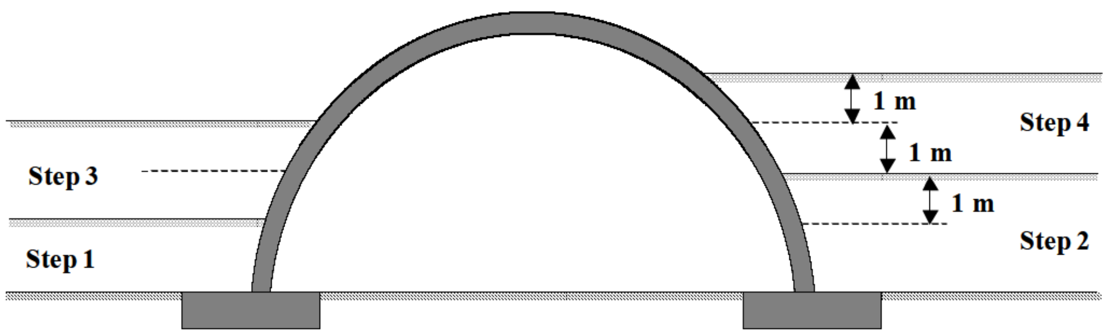

Figure 6 -Backfilling Load cases

The compaction of each layer of fill is modelled by applying an initial load of 10kN/m2 to the layer. Subsequently, a (negative) load of $-10kN/m^2$ is applied to the layer and is superimposed on the stress state resulting from the previous load. Even if the efforts applied to the system are then the same as those which were applied before the compaction, the stress/strain state finally obtained is different from the initial state due to the non-elastic behaviour of the soil. There is an irreversible decrease in volume.

The final load cases analysed by the finite element model correspond to live loads on the surface. The most critical cases are for asymmetric live loads, as shown on Figure. 7.

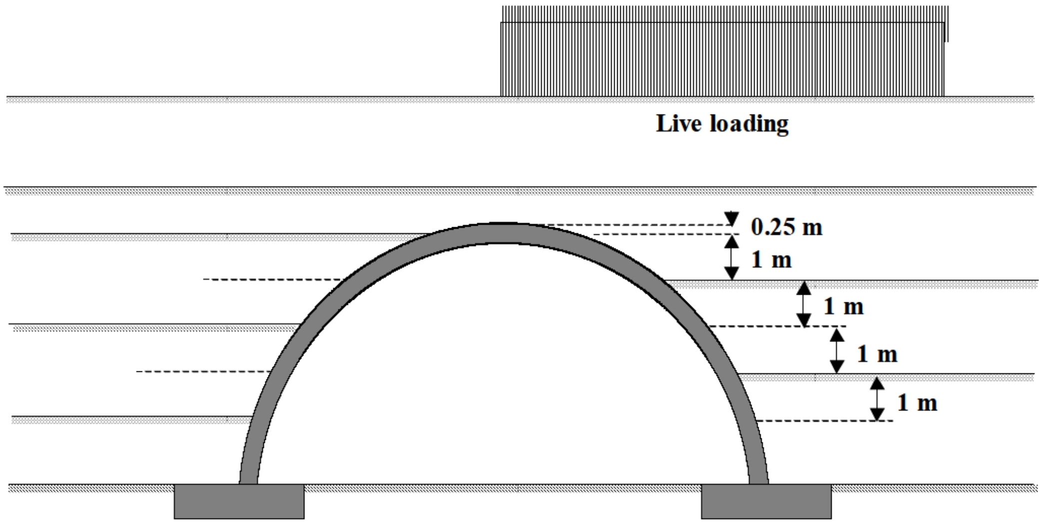

Figure 7 – Live Load Cases

Concrete design complies with AS3600. Figure 8 shows the amount of reinforcement and required thickness for this project.

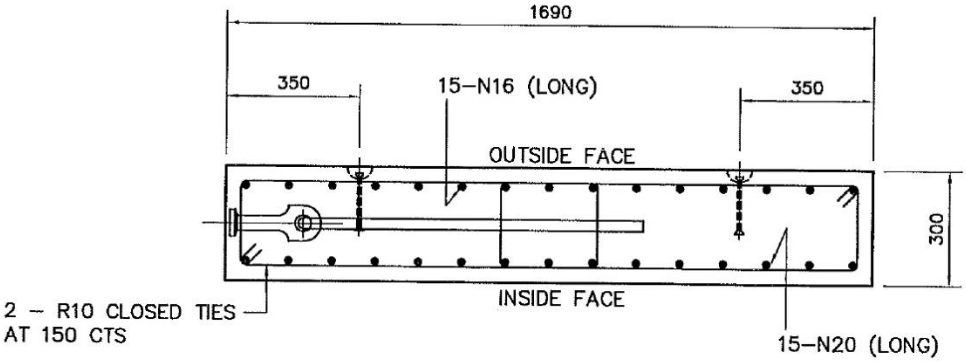

Figure 8 - Typical Section through Arch

Another aspect of the TechSpan® design is the crown beam. The crown beam is a continuous beam on top of the arches that structurally supports the arches against longitudinal loads. Longitudinal loads occur when the TechSpan® arches are placed on a grade or a high stockpile that is on top of the arches. The crown beam is designed to resist the shear load that develops when the arches are loaded longitudinally. See Figure 9 for the crown beam design.

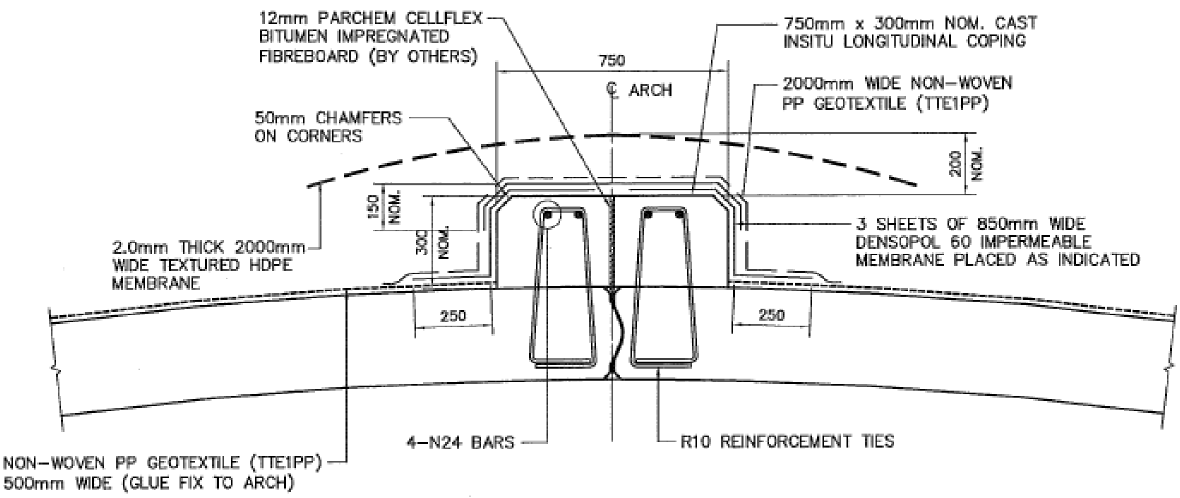

Figure 9 -Crown Beam Section

1.3 Construction of Precast Arches

After the site is prepared, the cast in-situ concrete footing and keyway for arch units are constructed. The position of each arch unit is marked along the keyway to help ensure proper placement.

Then the first two opposite arch units are placed by first bringing the first arch unit into position according to the marked location in the footing keyway, as shown in Figure 10.

Vertical and horizontal tolerances are critical to the ease of construction. Close attention to detail at the pre-construction stage can help ensure a trouble free rapid construction.

Figure 10 – Arch unit in footing keyway

With the arch still held by the crane, the first arch acts as the support for the second arch, which can be positioned using a second crane (see Figure 11). The remaining arch units are then placed similarly and on completion, the keyway is grouted. Required waterproofing and geotextile is placed over the arch joints.

Next, the backfilling sequence around the arches is carried out. To avoid misalignment of the arches and excessive eccentric loading of individual arches or the entire structure, the backfilling sequence requires differential level of backfill between opposite sides of the structure.

Figure 11 – Positioning the first two arch units using two cranes

There are 3 zones of backfilling required around the arch as shown in Figure 12. Zone 1, select granular material, is placed 0.5 m around the perimeter of the arch and can only be compacted by hand compacting equipment. Zone 2 consists of a fill material placed vertically and horizontally around Zone 1. This material can be compacted with heavy compaction equipment but is limited to any vibration. Zone 1 & 2 must also conform to the MSE wall backfill specifications. Zone 3 is the remaining fill required around the arches. In this zone, heavy compaction equipment may be used. Once the backfill reaches the crown of the arches, the in-situ crown beam is then cast in place.

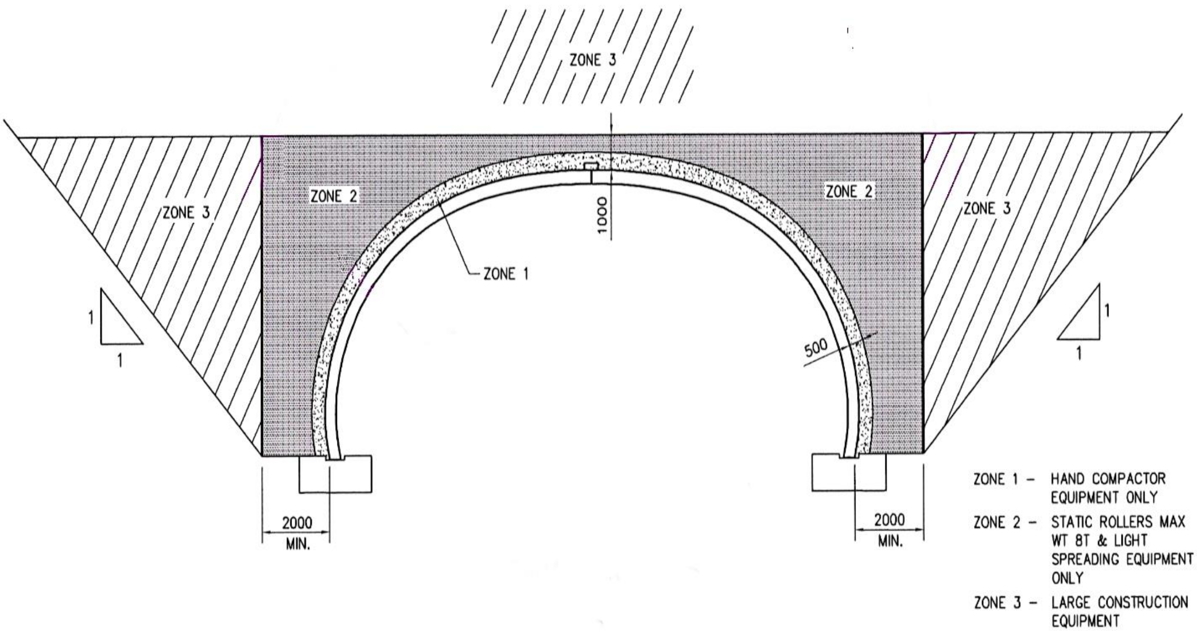

Figure 12 - Different Zones of Backfill

2. Spandrel Walls & Abutments (MSE walls)

In Bridge No. 4163, the spandrel walls, wingwalls and abutments were designed as MSE walls.

2.1 Mechanically Stabilized Earth Walls.

Mechanically Stabilised Earth, or Reinforced Earth, is a composite material formed by the interaction of a cohesionless and granular soil, and reinforcing strips. The reinforcing strips resist stresses produced within the soil mass, which are transferred by friction to the strips. Precast Concrete panels, with cast in tie points, are used at the facing for the reinforced structure, or reinforced earth block (see Figure 13), preventing erosion of the backfill while providing an attractive, finished exterior.

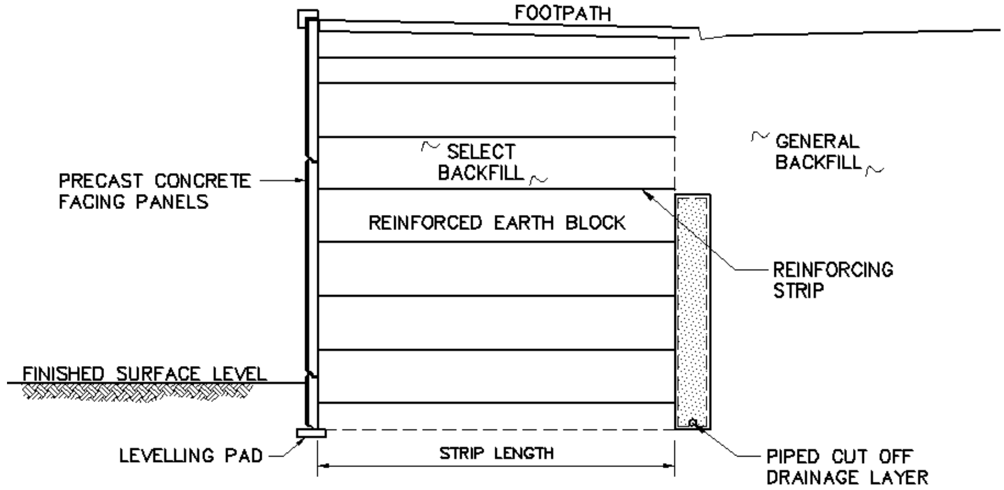

Figure 23 – Typical Cross Section

2.2 Design of MSE Walls

The failure Mechanisms to be considered in designing MSE include:

- Sliding along a plane through the block or at the base
- Overturning of the entire block
- A wedge or circular slip circle type failure through or behind the block
- Bearing capacity of foundation
- Excessive settlement

Firstly, the internal and external stability are checked using VALDEZ, a program developed by The Reinforced Earth Group. This program considers three limit state load cases.

VALDEZ uses basic equilibrium equations to check the overturning, sliding and bearing capacity of the MSE block, analysing the active pressure at the rear of the reinforced earth block, self-weight of the block, Meyerhof pressure and any applied loads.

The internal stability analysis checks the maximum applied forces at each layer of reinforcing strips. The horizontal pressure at each strip layer is calculated from the Meyerhof pressure. Stresses in the strips are higher at the top of the wall and lower at the base showing a variation of the tension with depth. The line of maximum tension considered divides the active and resistant zones of the block (see Figure 14). The portion of strip in the resistant zone will work in tension, while the full length of the strip can be considered for frictional strength.

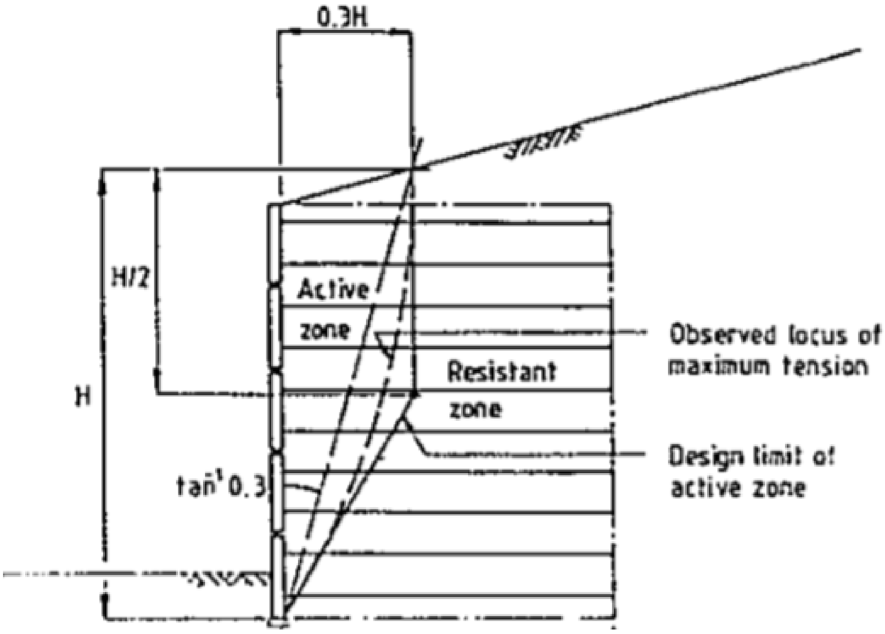

Figure 14 – Zone Definition in MSE Block

Allowing for all load and safety factors, frictional resistance and tensile strength of each strip is calculated. The number of strips required is developed by comparing these results to strip capacity to attain to an overdesign factor greater than 1.

The MSE block is then modelled using STARES program to check the working stress load case. This is a slip failure analysis using Bishops equation of slices which develops the resultant forces in vertical slices within the generated circle of slip failure. The reinforcing strips restrain the forces through slices, as shown in Figure 15.

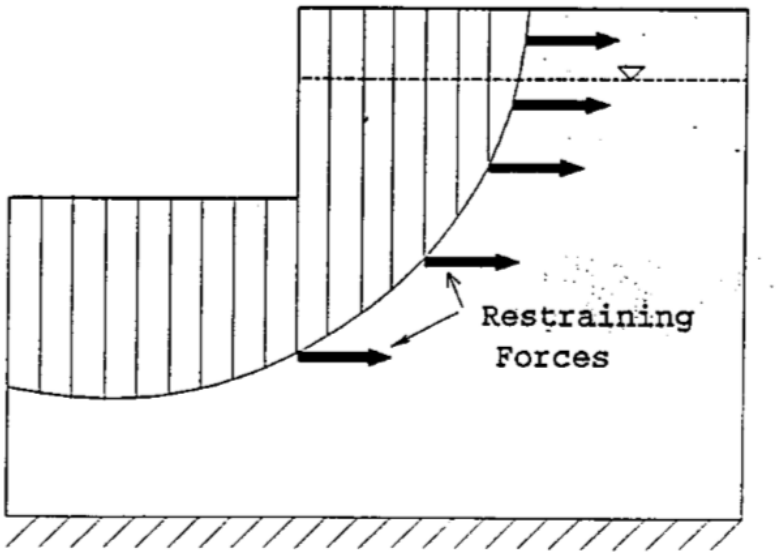

Figure 15 – Restraining forces acting on slices

2.3 Main Components of MSE Walls

Precast Concrete Facing Panels – Standard rectangular panels are used for the majority of the wall and sloping panels are used as required by the geometry of the structure. Tie points are cast in to the rear of the facing panels for reinforcing strips connection.

Reinforcing Strips – The ribbed steel strips are supplied in varying lengths and cross-sections, determined by the design of the structure. The strips are hot dipped galvanised and are designed to bolt to the facing panels tie strips.

Select Backfill – Backfill complying with Contract Specifications shall be used within the Reinforced Earth block.

2.4 Construction of MSE Walls

After the site is prepared, the facing panels are founded on a cast in-situ concrete levelling pad. Initial course of panels are placed, alternating full and half height panels. These are braced and clamped in position and panel joints are covered by specified geotextile.

Close attention to detail and accuracy in setting out and vertical alignment checks, at the initial course panels, will help ensure a speedy construction process and a desirable finished appearance.

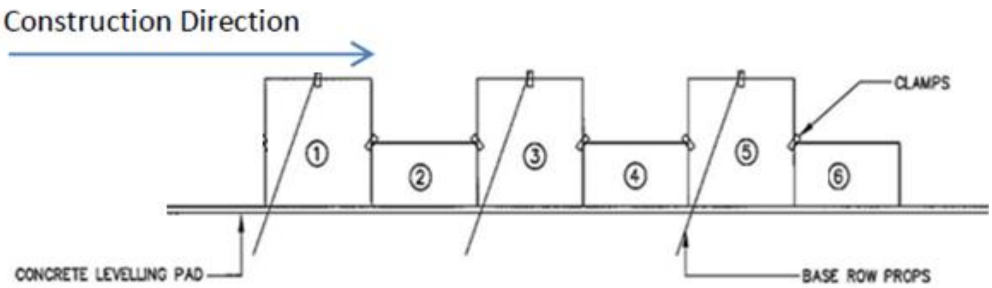

Figure 16 – initial Course Sequence

The select backfill is then spread and compacted in 300mm lifts, while connecting reinforcing strips to panel tie points between lifts, bearing pads are placed on top of initial course panels and then second course can be set.

The cycle of backfilling and compacting in lifts, connecting strips, placing geotextile and bearing pads and setting panels is repeated until the design height is reached.

When backfilling and compaction is complete and all clamps are removed, the capping units are installed.

BRIDGE No.4163. BUILDING SEQUENCE

1. Arch footings: Cast in situ footings are installed prior to erecting the precast arch units.
2. Arch units are placed in position as described previously.
3. Arch joints are waterproofed.
4. Installation of base row precast panels forming the spandrels and abutments.
5. Backfilling of the arch and MSE walls in consecutives lifts as described previously.
6. Crown beam to be cast when backfilling reaches the crown level.
7. Spandrels and abutments to be backfilled up to bridge road level.
8. Installation of capping units.

Figure 17 – Bridge No. 4163 in Cravens Creek Bridge under construction

CONCLUSION

Traditional masonry arch bridges have been popular in bridge design for over 2000 years due to their durability and architectural attractiveness. Bridge No. 4163 achieves both of these features with the use of precast arches and together with MSE walls.

This system proves to be a faster and simpler construction method, while still achieving the desirable finish of a traditional masonry arch bridge. The use of precast elements saves time and is more economical than the block laying required in construction of masonry arch bridges. Flexible design methods used also ensure the development of the most economical shape.

REFERENCES

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2. Duncan, J.M., Dunphy, Byrne, P., Wong, K. and Mabry, P. (1980) “Strength, stress-strain and Bulk modulus parameters for finite element analysis of stresses and movements in soil masses” Report No. UCB/GT/80-01. Department of Civil Engineering, University of California, Berkeley USA.