Masonry Arch Bridges with Reinforced Soil Spandrel Walls

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ABSTRACT *In the United Kingdom, most masonry arch bridges were built before the beginning of the twentieth century and many are more than 250 years old and of architectural significance. Masonry arch bridges are simple structures with a stone or brick arch supporting outer spandrel walls infilled with soil or granular material. Originally built to carry horse and cart traffic, they have proved to be able to support modern traffic loadings. However, constant traffic can lead to the spread and even the collapse of the spandrel walls due to distortion of the fill. The general maintenance cost of masonry bridges has proved to be lower than most modern structures, and the construction of new masonry arch bridges is encouraged in the United Kingdom. This paper provides two linked case histories relating to (i) the first use of reinforced soil to repair a 250-year-old masonry arch bridge in 1984 and (ii) the introduction of reinforced soil into the basic design of a new masonry arch bridge constructed in 2000.*

KEYWORDS: Reinforced soil, masonry arch bridge, spandrel walls, geogrid

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INTRODUCTION

At first glance, there appears to be little in common between masonry arch bridges and reinforced soil. However, in one area they are linked: both are formed using soil as a major material in their construction. Until recently, this common factor had no practical relevance. The recent developments in reinforced soil construction technology, including the development of polymeric reinforcing materials, have provided situations where reinforced soil can be applied to the maintenance of masonry arch bridges and to the advancement of the design of new masonry arch bridges.

The paper provides details of the developments in reinforced soil which have made it possible to apply the technology to reduce the repair costs of arch bridges and to improve the design of newly constructed arch bridges. Two case histories are provided: (i) describes the first use of reinforced soil to repair a 250-year-old masonry arch bridge in 1984 and (ii) describes the introduction of reinforced soil into the basic design of a new masonry arch bridge constructed in 2000.

DEVELOPMENTS IN REINFORCED SOIL

Earth retention methods are generally organized according to two principal categories of *externally* or *internally* stabilized systems. An *externally* stabilized system uses an external structural wall, such as a gravity wall, against which stabilizing forces are mobilized. An *internally* stabilized system involves reinforcements installed within and extending beyond the potential failure mass. Within this second system, shear transfer to mobilize the tensile capacity of closely spaced reinforcing elements has removed the need for a structural wall and has substituted a composite system of reinforcing elements and soil as the primary structural entity. A facing is required on an *internally* stabilized system, but its role is to prevent local raveling and deterioration rather than to provide primary structural support.

Early man-made examples of reinforced soil structures can be found in the Great Wall of China and the ziggurat of the ancient city of Dur-Kurigazu, constructed of clay and sand with reeds for reinforcement. The earliest known use of reinforced soil in

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the United Kingdom is by the Romans, who constructed a 1000 m wharf in London formed with timber facing and reinforcement. In 1822, Col. Pasley introduced canvas-reinforced soil for military construction to the British Army (Pasley, 1822). The lack of durable reinforcements meant that the use of the technique up to the 1960s was limited to short life structures, such as the support of roof packs in the Yorkshire coalfield where steel netting was used as reinforcement.

The modern form of reinforced soil was introduced in the 1960s, following the development by Vidal (1966) in France of a form of retaining wall (called reinforced earth), which used flat steel strips as reinforcing members embedded between horizontal layers of particulate material tied to a facing to form a vertical structure. The principle upon which it rests was that the friction acting on the metal strips buried within the soil induced tension in the strips forming ties across any slip plane that may otherwise have developed in the soil. The Vidal System is illustrated in Figure 1, where:

- Fill material must be frictional,
- It must be laid and compacted horizontally,
- The reinforcing members must be pliable and in-extensible, and
- The facing must be vertically flexible to accommodate settlement of the fill.

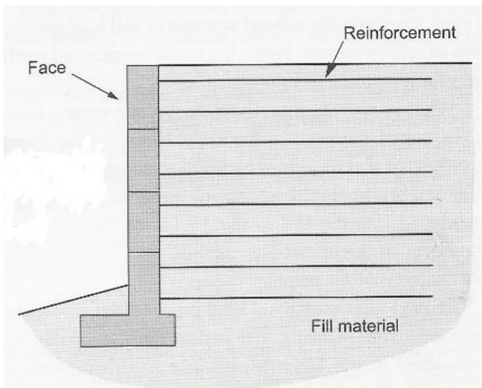

Figure 1. Vidal reinforced earth system.

REINFORCED SOIL CONSTRUCTION METHODS AND MATERIALS

The use of soil deposited in layers to form the structure results in settlements within the soil mass caused by gravitational forces. These settlements result in the reinforcing elements positioned on discrete planes moving together as the layers of soil separating the planes of reinforcement are compressed. Construction techniques capable of accommodating this internal compaction within the fill are required. Three methods of construction which meet the settlement criteria are shown in Figure 2.

Concertina Method

The constructional arrangement of the Concertina Method initially developed by Vidal was formed using pliant U-shaped sheet steel channel sections which could deform in the form of a concertina, shown in Figure 2. This is also the form of construction used with planar reinforcing materials such a geotextiles or geogrids where the material is also used to form the facing. The method is often referred to as “wraparound.”

Telescope Method

In 1970, Vidal introduced a facing formed by reinforced concrete panels, which could “telescope” together to accommodate the settlement of the fill. This is made possible by supporting the facing panels by the steel strip reinforcing elements and leaving a discreet horizontal gap between each facing panel (i.e., the facing panels hang from the reinforcing elements), as shown in Figure 2.

Sliding Method

In 1973, a third method of accommodating the settlement of the fill was developed by the United Kingdom Department of Transport. It is known as the Sliding or York Method, in which settlement within the soil mass is accommodated by having the reinforcements embedded within the soil slide down the facing while remaining connected to the facing (Jones, 1978; Motorway Archive Trust, 2002). The facing may be made up of discrete elements or may be single full height units. The latter are particularly suitable for reducing the construction time of bridge abutments. The reinforcement may be of any form: strip, geotextile, geogrid, or anchor. This method is also outlined in Figure 2.

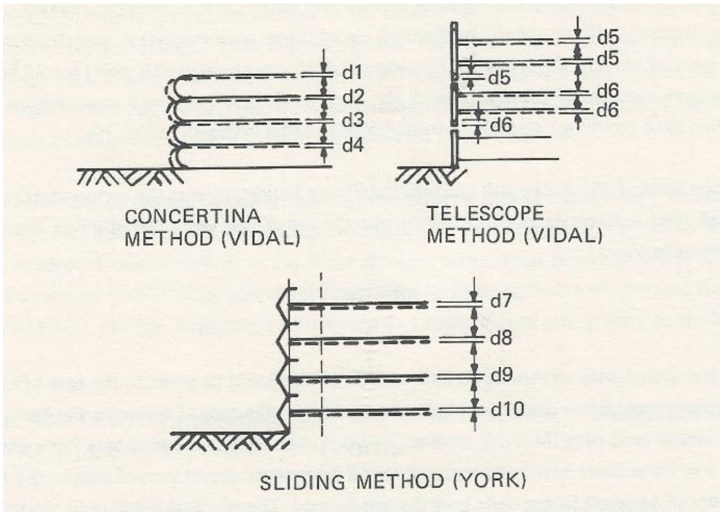

Figure 2. Construction methods for reinforced soil (GEO, 2002).

Hybrid Methods

In some situations, it is possible to combine elements of both *externally* and *internally* stabilized systems, such as the improvement of gravity structures. Figure 3 specifically illustrates a development of the Norwegian Tronderblock wall system, in which precast concrete facings are used for the construction of low height (circa 3 m) gravity retaining walls. Following the development of polymeric geogrid reinforcement, the versatility of the method was improved by introducing horizontal layers of geogrid reinforcement connected to separate facing elements, enabling retaining structures up to 10 m to be constructed. When using a hybrid method of construction, care must be taken to reduce the internal settlement of the fill to a minimum, as the facing cannot accommodate settlements. This is generally achieved using high-quality fill and restricting construction to cases of firm foundations (i.e., not constructing hybrid reinforced structures on weak soil).

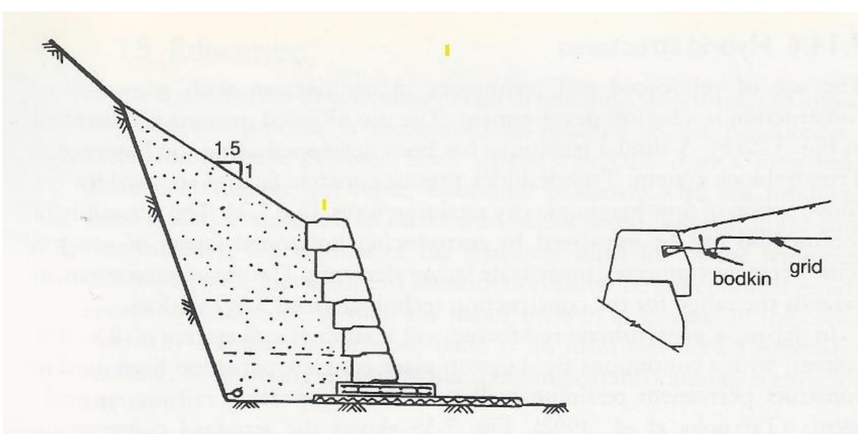

Figure 3. Reinforced soil hybrid wall, based upon Tronderblock precast facing (Jones, 1996).

Polymeric Reinforcements

Reinforced soil using steel reinforcing elements requires good quality cohesionless material to ensure long-term durability. The development of the York or Sliding Method of reinforced soil in 1973 also included the introduction of non-metallic reinforcements in the form of glass fiber strips and polymeric tape, which could be used with a wide range of fill (including recycled waste materials). In the late 1970s, polymeric geogrid reinforcement was developed by Brian Mercer and introduced to the construction industry in 1984 at a Geosynthetics Symposium at the Institution of Civil Engineers (ICE, 1984). It has since been identified as one of the top 100 British inventions of the 20th century. The first use of polymeric geogrid reinforced soil was in 1979, to construct an elevated railway facility at Newmarket/Silkstone Colliery in West Yorkshire, United Kingdom, using mine waste as the fill (Jones and Doulala-Rigby, 2014). The structure was the subject of the BBC cultural affairs program "Tomorrow's World."

LABOR AND PLANT

The labor and plant requirements for the construction of reinforced soil structures are minimal, and no specialist equipment or skills are required. The erection of a small vertical reinforced soil structure can be undertaken by a team of three people deployed to cover the main construction elements, erecting the face, placing and compacting the fill, and fixing the reinforcement. A comparison of the labor requirements for different forms of retaining walls has been given by Leece (1979). For reinforced soil, a labor content (manhours/m^2) for facing is typically 4, while that for mass concrete is 11.2. The plant requirements during construction normally include aids to the placing and compaction of soil, and some form of small crane or lifting device, although the latter is not required when a non-structural facing is used. Construction is often based on a method specification such as United Kingdom Department of Transport Memorandum BE 3/78, where the compaction plant used within 2 m of the facing consist of the following forms (Department of Transport 1978):

- (a) vibrating tampers;
- (b) vibrating plate compactors with a mass < 100 kg; and
- (c) vibrating rollers with a mass/m width < 1300 kg and a total mass < 1000 kg.

Good compaction of the soil is desirable, as it has beneficial influence on behavior and reduces internal differential movements while also providing the most stable environmental conditions which are important to durability. Uniform compaction is achieved by using fill layers of 100-300 mm in depth.

RATE OF CONSTRUCTION

Construction of reinforced soil is normally rapid. Construction rates of vertical structures of 40-200 m^2 per day are usual, and typically the speed of construction is determined by the rate of placing and compaction of the fill. In some cases, the economic production of facing units may determine the construction rate, particularly if an original or unique facing is required.

MASONRY BRIDGES

There are over 90,000 masonry arch bridges in the United Kingdom. Most were constructed as part of the development of the canal system in the 1700s and the railway network during the Industrial Revolution in the 1800s, but a significant number are much older and of historic importance. The materials used in the construction of masonry bridges reflect the terrain and the local geology. Where stone could be found, this was used; elsewhere, bricks were made from local clays.

Masonry arch bridges are simple structures with a stone or brick arch supporting outer spandrel walls infilled with soil or granular material, as shown in Figure 4. Originally built to carry horse and cart traffic, they have proved capable of supporting modern traffic loadings, although constant traffic can lead to the spread and even collapse of the spandrel walls due to distortion of the fill. The general maintenance cost of masonry bridges has proved to be lower than most modern structures. Where appropriate, the construction of new masonry arch bridges is encouraged in the United Kingdom with the development of a new code of practice for their design and construction (Highways England, 2020).

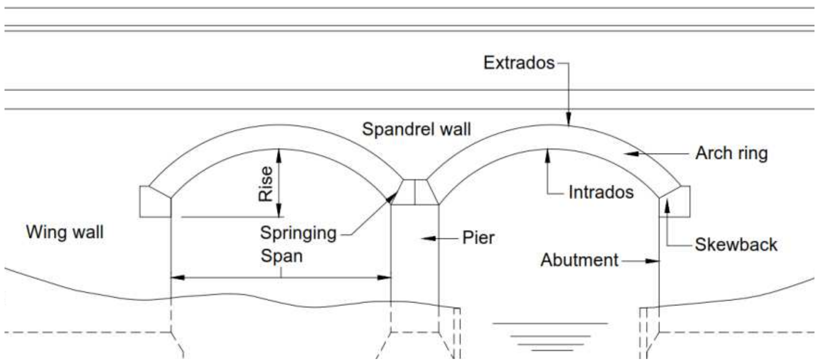

Figure 4. Long section of an arch bridge (Highway England, 2020).

SPANDREL WALLS

Masonry arch bridges are susceptible to an outward movement of the spandrel walls; unserviceability arises more commonly from the collapse of such walls than from the condition of the arch barrel. United Kingdom Standard BA 16/84 gives scant advice on the stability of spandrel walls, beyond stating that they are not amenable to calculation and must be assessed qualitatively by considering the condition of the structure and the significance of any defects (Department of Transport, 1984). This aspect of arch bridge assessment has been largely neglected, and the mechanism of failure is not fully understood, so the relative significance of defects is obscure.

Spandrel walls are an example of an *externally* stabilized method. The movement of spandrel walls may take the form of tilting, bulging, or sliding over the extrados of the vault, possibly accompanied by horizontal shearing at different levels or a fracture through the end of the arch barrel may open, as depicted in Figure 5. There are various potential causes for this movement. Vertical live loading on the arch may initiate separation between its extrados and the stiffer spandrel wall and parapet acting together as a beam, or it may lead to longitudinal fracture near the end of the vault. Lateral forces tending to push the spandrel wall outwards may be exerted by the fill, especially if it becomes saturated and freezes or if the road/rail track levels are raised appreciably. The forces may be due to traffic: either vertical live loads generating horizontal pressures from a "Poisson ratio" effect on the fill, or centrifugal forces on curves being transmitted through the fill. The position of traffic relative to the spandrel wall is often significant.

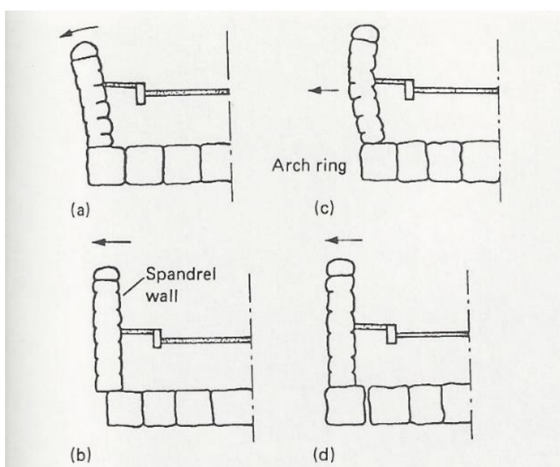

Figure 5. Movement of spandrel walls: (a) outward rotation; (b) sliding; (c) bulging; and (d) outward and cracked arch (Sowden and Jones, 1990).

Instability may result from any of the above factors or some combination of them, but few studies have been undertaken to determine which are most likely to be critical. An accurate analysis of lateral pressures generated by modern traffic within the fill is difficult and may be impossible. Owing to the wide range of infill materials encountered and the fact that adequate records are rarely available, investigations into the characteristics of the fill material are rare. It is noticeable that, when spandrel walls collapse, the exposed faces stand almost vertically, suggesting that over time the fill compacts into a cohesive mass which tends to retain its shape despite a complete lack of side support.

STABILIZATION OF SPANDREL WALLS

The traditional method of increasing the resistance of spandrel walls to outward movement involves the use of tie-bars with appropriate methods of distributing the stabilizing effect; the results are reasonably effective if inelegant, as shown in Figure 6.

An effective alternative method for strengthening spandrel walls is by thickening them on the inner faces—usually using reinforced concrete—to add mass and stability while increasing their potential to act as horizontal beams. This work must be undertaken with care and with the bridge at least partially closed to traffic. An excessive head of newly placed concrete has been known to cause collapse of the spandrel wall it was being provided to support. Concrete lifts should be limited to one meter high with accelerating agents added to reduce intervals between pours. Another method to reducing the effective lateral pressure acting on spandrel walls is the construction of a concrete saddle. The concrete can be brought up to provide a complete infill over the arch. This provides a permanent solution to the problem but can have drawbacks, including increasing the load on the foundations (which can result in settlement, causing additional problems). Ducts may be required to provide for the inclusion of services across the bridge (Ridings and Jones, 1981).

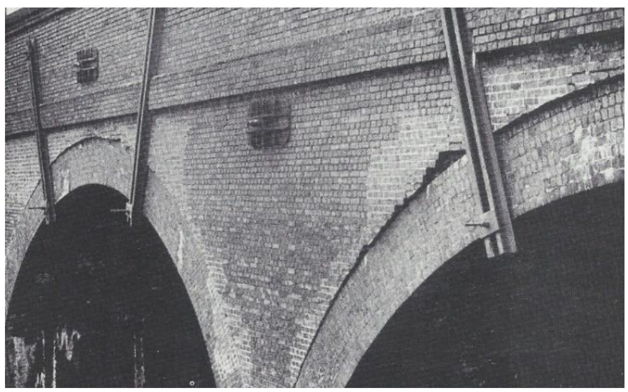

Figure 6. Tie-bars and spreader beams used to stabilize spandrel walls (Sowden and Jones, 1990).

The development of polymeric geogrid reinforcement introduced the concept of stabilizing spandrel walls using reinforced soil as the infill between the walls, shown in Figure 7. The advantages of this technique are twofold: total relief is provided to the walls; and the method is economical since the primary construction material is soil, which is compatible for long-term use with polymeric geogrid, which is non-metallic and hence not susceptible to corrosion.

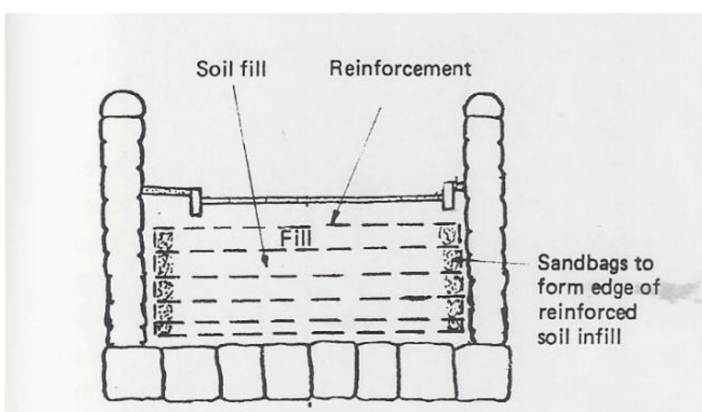

Figure 7. Reinforced soil infill used to relieve lateral pressure on spandrel walls.

KETTLEWELL NEW BRIDGE, NORTH YORKSHIRE, UK

Kettlewell New Bridge is a "listed" dual span masonry arch bridge over the Wharfe River in North Yorkshire constructed in the 18th century, shown in Figure 8. A listed building, structure, or environment is one that is recognized as being of national importance and part of the United Kingdom's heritage. Listed structures are legally protected from being demolished, extended, or altered. Kettlewell New Bridge was the first to be repaired using geogrid reinforced soil to stabilize its failing spandrel walls.

In 1984, the spandrel wall on one side of the bridge failed due to bulging and lateral sliding, though the infill soil remained intact (see Figure 9). Repair was undertaken with geogrid reinforced fill between the spandrel walls, designed in accordance with United Kingdom Memorandum BE 3/78, using the concertina method of construction of reinforced soil, seen in Figure 10. Lateral loading from the reinforced fill onto the reconstructed spandrel walls was eliminated by forming a small permanent gap between the reinforced fill and the back of the spandrel walls, shown in Figure 7. The Concertina Method of construction accommodates difficult geometries particularly if the face is formed by wrapping geogrid reinforcement over sandbags. The 3D shape of the void above the arch results in the shape of the facing changing and the vertical spacing of the reinforcement varying. This is easily accommodated during construction by hammering the sandbags into the desired shape using a wooden mallet.

The required vertical spacing of the reinforcement is at a maximum at the springing of the arch; thus, if this section is stable in accordance with the design Memorandum BE 3/78, no other sections need to be checked. Construction in the confined space over the arch between the spandrel walls is possible, as construction is primary by hand using minimum construction equipment. The geogrid used in the repair of Kettlewell Bridge was the newly developed 1-meter-wide high-density polyethylene (HDPE) uniaxially oriented geogrid with a tensile strength of 80 kN/m identified as SR1. The spacing of the reinforcement at the springing of the arch was 400 mm. The original soil fill removed to undertake the repair was reused (if in suitable condition, e.g., unsaturated). As part of the repair, a waterproof membrane was applied to the extrados of the arch with a positive drain provided at the springing.

Figure 8. Kettlewell New Bridge, North Yorkshire, UK (Photo © Stephen Craven (cc-by-sa/2.0).

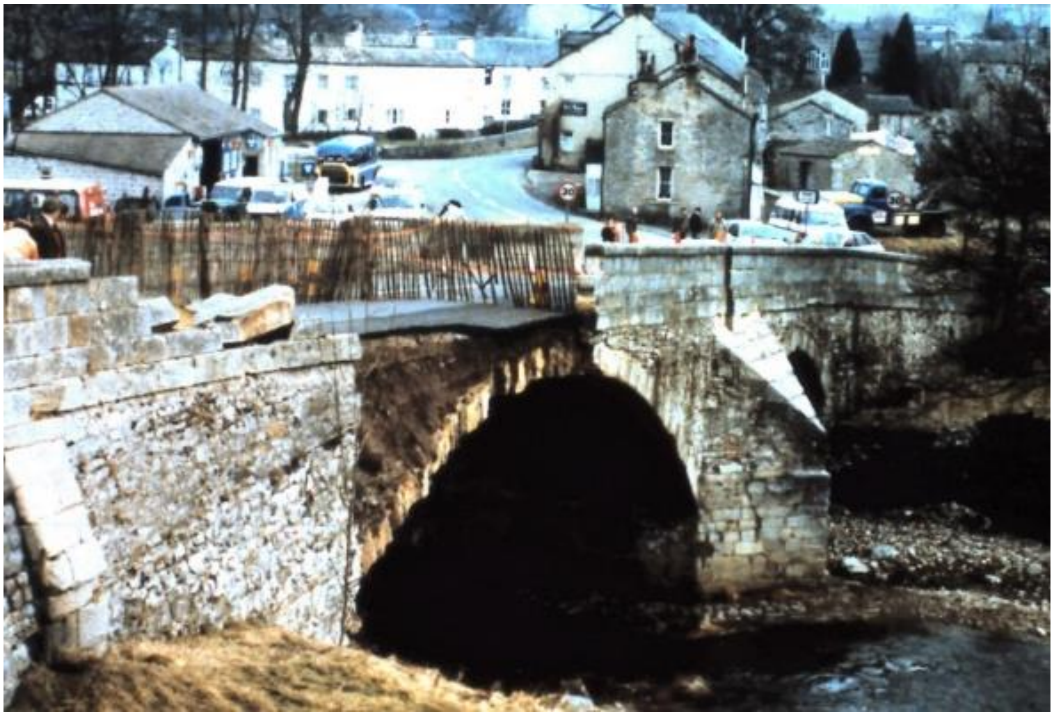

Figure 9. Failure of spandrel wall, Kettlewell New Bridge, 1984.

Figure 10. Construction of geogrid reinforced infill to spandrel walls, Kettlewell New Bridge, 1984.

LEAMINGTON GUT BRIDGE, NEWCASTLE UPON TYNE, UK

The first use of geogrid reinforced fill to form the spandrel walls of a new masonry arch bridge was at Leamington Gut Bridge, constructed in 2000, over a small tributary of the Tyne River west of Newcastle upon Tyne, seen in Figure 11. The bridge is a dual span structure, constructed using precast concrete arch elements providing two 26 m arches. The spandrel walls were constructed using reinforced soil with a masonry block facing (i.e., using the Hybrid Method of construction).

The design of the spandrel walls, which have a maximum height of 8 m at the springing of the arches, was undertaken in accordance with United Kingdom Memorandum BD 70/97 (Highways Agency, 1997). The same design was used to construct the extensive wing walls which flank the bridge.

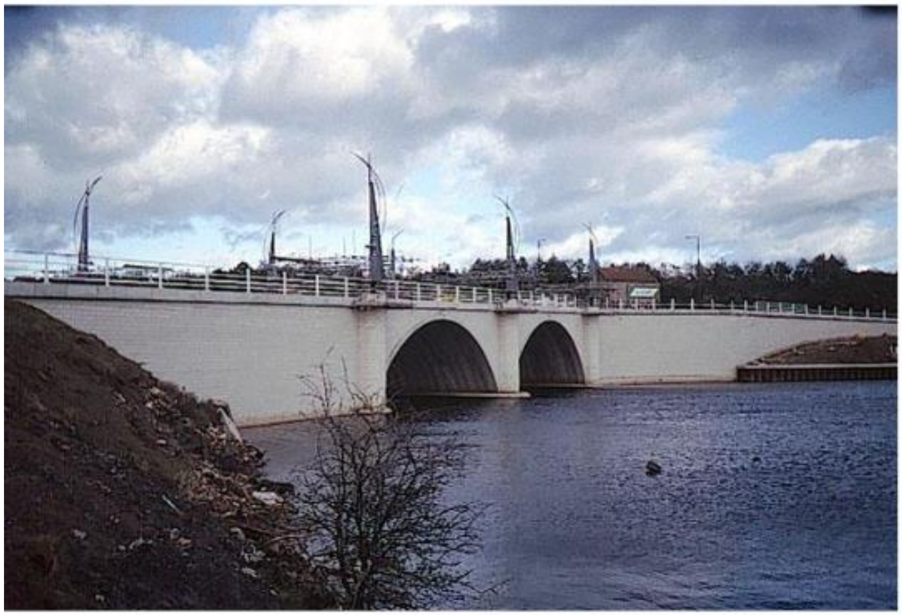

Figure 11. Leamington Gut Bridge, River Tyne, UK, 2000.

The facing of the spandrel walls was constructed using unreinforced concrete masonry blocks (400 mm long; 220 mm wide; 150 mm high). The reinforcement used was the Tensar geogrid. Geogrids with tensile strengths of 50, 80, and 120 kN/m were used so that the vertical spacing of the reinforcement could be kept constant at 450 mm (i.e., three blocks high), as shown in Figures 12 and 14. The connection between the reinforcement and the masonry block facing used a propriety system whereby the geogrid is held in place between the blocks using a polymeric comb, seen in Figure 13. The reinforcement was tensioned before the placement of the fill. The fill used to form the spandrel walls and adjacent retaining walls was DoT Type 6I with Type 8H drainage stone, and compaction of the fill was in accordance with DoT BD 70/97 (Highways Agency, 1997). The rate of construction was influenced by the need to accommodate the rise and fall of the Tyne River, which is tidal. The average construction rate was 40 m^2 of wall face/day.

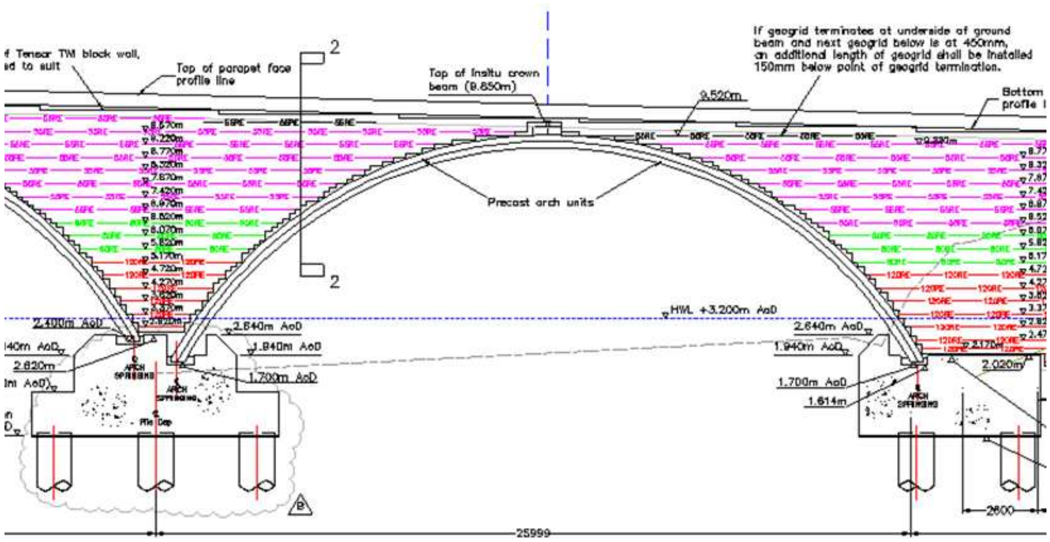

Figure 12. The location of geogrid reinforcement, highest strength at the springing of the arch.

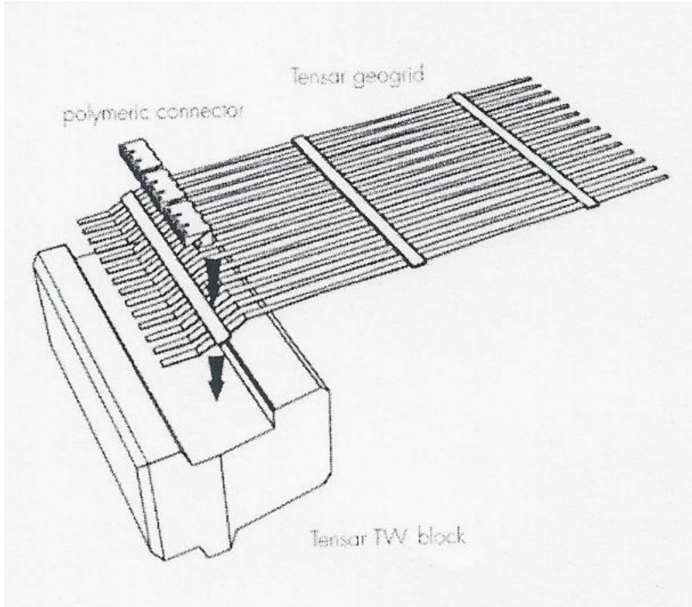

Figure 13. Details of the connection between the reinforcement and modular block facing.

Figure 14. Construction of the soil reinforced masonry spandrel walls.

CONCLUSION

The use of reinforced soil as the infill material of masonry arch bridges resolves a long-standing design and maintenance problem associated with the lateral loading of free-standing spandrel walls generated within the fill, leading to loss of integrity. This solution has been made possible by the development of polymeric geogrid reinforcement, which can be used with a wide range of infill materials. Reinforced soil infill is now an established method of repair of old masonry bridges having failing or failed spandrel walls. To date, two other old masonry arch bridges within 50 kilometers of Kettlewell New Bridge have been repaired using the technique.

Masonry arch bridges have been shown to be durable with low maintenance costs, and are a preferred form of construction in several situations. As reinforced soil structures are often the most economical form of construction of highway structures, the use of reinforced soil spandrel walls in the construction of new arch bridges is an economic and logical development fully compatible with modern design codes of practice.

ACKNOWLEDGEMENTS

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