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# Modelling backfill in masonry arch bridges: A DEM approach

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**Abstract.** In this paper, a novel modelling approach based on the discrete element method for the simulation of backfill material in masonry arch bridges has been proposed. According to the method, bricks in the barrel vault are represented as an assembly of distinct blocks separated by zero thickness interfaces at each mortar joint while backfill is represented as an assemblage of densely packed discrete irregular deformable particles. A series of computational models were developed and their results are compared against full scale experimental test results. A good agreement between the experimental and the numerical results was obtained which demonstrates the huge potential of this novel modelling approach proposed. One of the major advantages of this approach is the potential to simulate the initiation and propagation of cracking in the backfill and arch ring as a result of the application of the external load.

**Keywords:** Masonry Arch Bridges, Backfill, Numerical Modelling, DEM.

## 1 Introduction

### 1.1 The problem

Masonry arch bridges form an integral part of the European railway and highway bridge stock. Although most of the masonry arch bridges were constructed back in the 19th century, such structures are still standing and carrying today's traffic loads. Weathering, demands of increasing load intensity and axle loads, as well as factors such as increased frequency of flood events brought about by climate change have introduced a poorly constrained uncertainty on the long term performance of such infrastructure assets. The cost of replacing masonry infrastructure in the UK alone would run into tens of billions of pounds, and their aesthetic and heritage value is significant (e.g. the Grade II-listed Hungerford Canal Bridge, in Berkshire, England). Moreover, failure of such infrastructure could lead to significant direct and indirect costs to the economy and society and could hamper rescue and recovery efforts. Therefore, there is a pressing need to accurately assess the performance of ageing masonry infrastructure and provide detailed and accurate data that will better inform maintenance schemes and asset management decisions. Without a strategic approach to caring for our ageing masonry infrastructure, we run the risk of over-investing in some areas while neglecting others that are in need of our attention, or indeed risk failing to address economic and societal need.

Over the last thirty years, a significant amount of experimental work has been carried out in order to understand the effect of backfill into the serviceability and ultimate load bearing capacity of masonry arch bridges [1]. Discrete element method has been found to provide a useful approach for estimating the serviceability and ultimate load carrying capacity of masonry arch bridges [2]. However, most models based on the discrete element method of analysis, only consider the masonry elements (e.g. arches and piers) while the backfill material is simulated using a simplified manner [1, 3]. Given the importance of the soil backfill when estimating the mechanical behavior of masonry arch bridges, this can lead to significant inaccuracies of their mechanical behavior.

This paper presents a novel modelling approach, based on the discrete element method, for the simulation of backfill material in masonry arch bridges. According to the method, bricks in the barrel vault are simulated as an assembly of distinct blocks separated by zero thickness interfaces at each mortar joint. Backfill is represented as an assemblage of densely packed discrete irregular deformable particles, here called "inner-backfill particles". A series of computational models were developed and their results are compared against full-scale experimental test results.

## 2 Proposed DEM approach for the analysis of masonry arch bridges and representation of backfill material

### 2.1 Representation of masonry units and mortar

Within the proposed approach, masonry units are represented by rectangular blocks. Mortar joints are represented by a zero-thickness interface. In this way, the dimensions of the bricks have to be slightly increased to maintain the geometry of the brickwork. Masonry units can be represented as an assemblage of rigid or deformable district blocks that may take any arbitrary geometry. Rigid blocks do not change their geometry with the application of load. Deformable blocks are internally discretized into finite difference triangular zones. Each zone of the blocks responds according to a prescribed linear or non-linear stress-strain law [4].

### 2.2 Representation of backfill material

According to the proposed approach backfill can be represented as a series of irregular in shape particles of polygonal or Voronoi shape. Such fictitious irregular particles, here named "inner-backfill particles" are shown in Figure 1. Inner-backfill particles are subdivided into simple triangular finite elements (designated as zones), which give a detailed approximation of the strain field, rather than an assumption of a uniform strain in the inner-backfill particle.

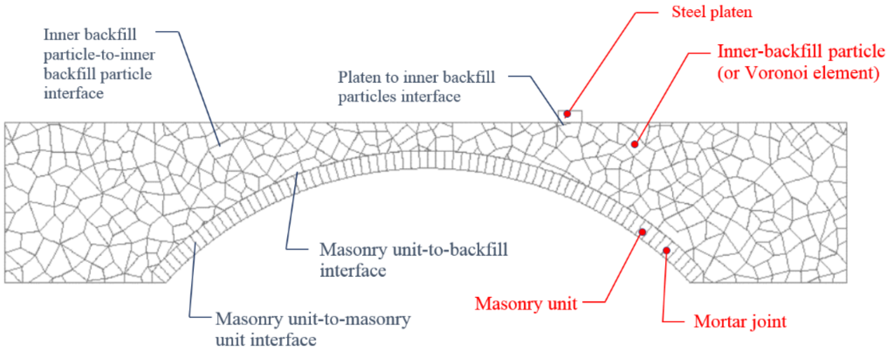



**Fig. 1.** Representation of backfill material within the proposed DEM approach.

# 3 Development of the computational model for soil-structure interaction

## 3.1 Experimental full scale masonry arch bridge testing

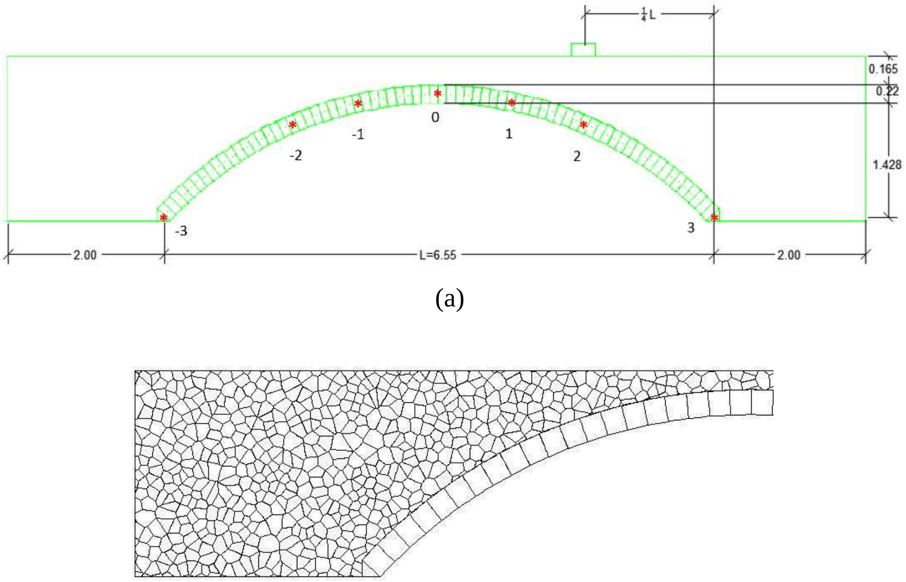
To demonstrate the effectiveness of the proposed computational modelling approach, this section presents the development and validation of the computational models used to investigate three different approaches to represent backfill and investigate soil-structure interaction phenomena in masonry arch bridges. The suitability of each of the computational modelling approaches were compared to full-scale experimental tests carried out on the Prestwood Bridge, located in Staffordshire, UK [5]. Prestwood Bridge has a span of 6.550 m and a rise of 1.428 m. The vault barrel, which is a single ring of bricks laid as headers, has a thickness of 0.220 m. The width of the bridge is 3.8 m. A line load was applied at quarter span across the width of the bridge using a 300 mm wide loading element. This was to avoid the effect of a concentrated load and premature failure of the fill. Hydraulic jacks were used to apply the load at increments until the bridge was not able to carry further load and ultimately collapsed. At each loading increment, displacements were measured remotely using total stations. The maximum load applied to the bridge before collapse was 228 kN, with the first visible evidence of damage appearing at a load of 173 kN. Failure was due to the formation of a four-hinge mechanism as shown in Figure 2.

**Fig. 2.** Failure mechanism of the Prestwood Bridge.

## 3.2 Development of the computational model

### 3.2.1 Geometric model development

Geometric models to represent the geometry of the Prestwood Bridge were created in the computational model. The geometrical characteristics of Prestwood Bridge were taken from [28] and can be seen in Figure 3a. In addition, Figure 3b shows the "inner-soil" particles as considered for the development of the present model. The size of the "inner-soil" particles has been assumed to be 10 cm.




(a)

(b)

**Fig. 3.** Model developed of the Prestwood Bridge: (a) geometrical model; and (b) part of the bridge showing the inner-soil particles to represent the backfill (size 10 cm) in the discrete element model.

### 3.2.2 Material properties

Mortar joints between bricks represented as zero thickness interface elements behaving according to the Mohr-Coulomb failure criterion which limits shear stresses along joints. In the numerical model the cohesion and tension was set to a low value and equal to 7 kPa. Material properties of the mortar interface, taken from [6]. In addition, material properties assigned to the voussoirs of the arch ring were obtained from [3]. Moreover, the joint cohesive, tensile strength and frictional resistance between the soil and platen was set high (e.g. 10 MPa) to make ensure that no slippage between the platen and the soil will occur. In particular the density of the masonry units taken as 2,000 $kg/m^3$, the Young's Modulus of the units as 4.14 GPa and the Poisson's ratio as 0.3. For the mortar joints, the normal and shear stiffness taken as 35 and 7 GPa/m accordingly. Also the friction angle was 37 degrees.

### 3.2.3 Boundary conditions

The base of the masonry arch bridge, as well as the left- and right-hand sides of the backfill was fixed in all directions. Self-weight effects were assigned as gravitational load. Gravitational forces give rise to compressive forces within the voussoirs of the arch and results in its stabilization. Initially, the model was brought into equilibrium under its own self-weight by ensuring that the maximum out-of-balance force was less than 0.001% of the total weight of the structure. Then a constant vertical velocity equal to 0.0005 m/s applied to the load spreader plate which was located on the top of the bridge at quarter span of the arch. The velocity applied to the loading element had to be closely examined and selected in order to maintain the analysis in a static manner and avoid the structure to have a dynamic response. A FISH sub routine was written that was able to record the reaction forces from the fixed velocity grid-points acting on the spreader plate at each time stem. Such conditions selected to replicate the real conditions of the experimental loading test carried out by TRRL. Histories of displacements at the intrados of the arch have been recorded at all times (See Figure 5 - colored in red and mark as -3…0…3).

## 4 Results and Discussion

Within the model, plastic deformation can occur within the voronoi cells. The stiffness of the model is significantly affected on the properties of the voronoi cells and of the properties of their interfaces. Figure 4 shows a comparison of the experimental against the numerical predictions of the load carrying capacity of the bridge. The load bearing capacity of this model was approximately 10% lower compared to the experimental results. Figure 5 shows the failure mechanism as predicted using the DEM model. The masonry arch bridge fails by a four hinge mechanism. The location of hinges matches with that of the experiment. From Figure 2 and 5, the biggest tensile crack was developed almost vertically above the right abutment. Smaller tensile cracks appeared below the loading element, above the crown. There were some slipped Voronoi elements in the vicinity of the passive earth pressure.

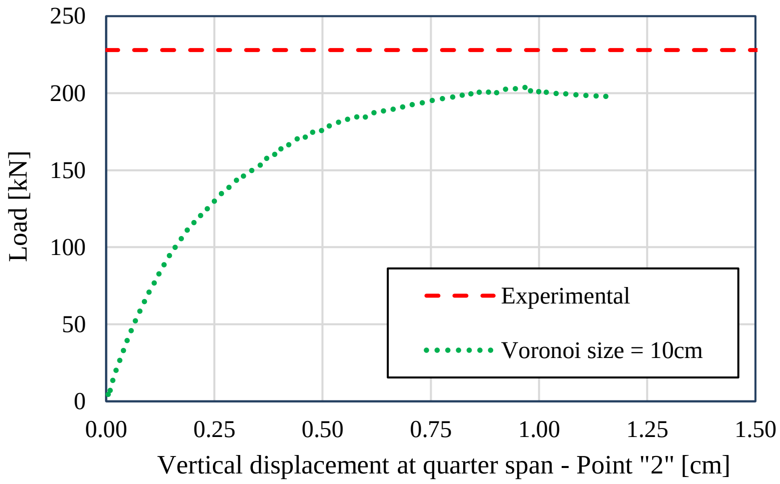
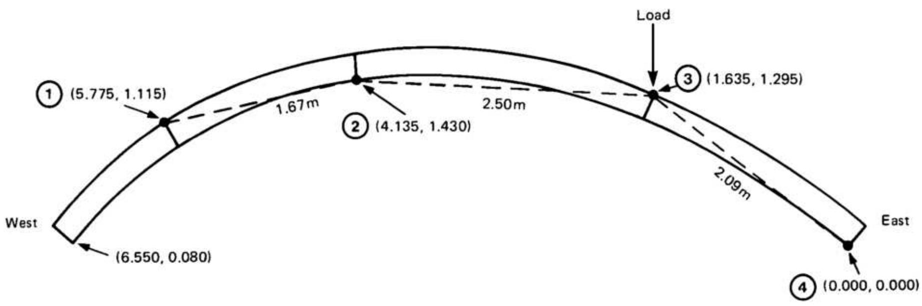
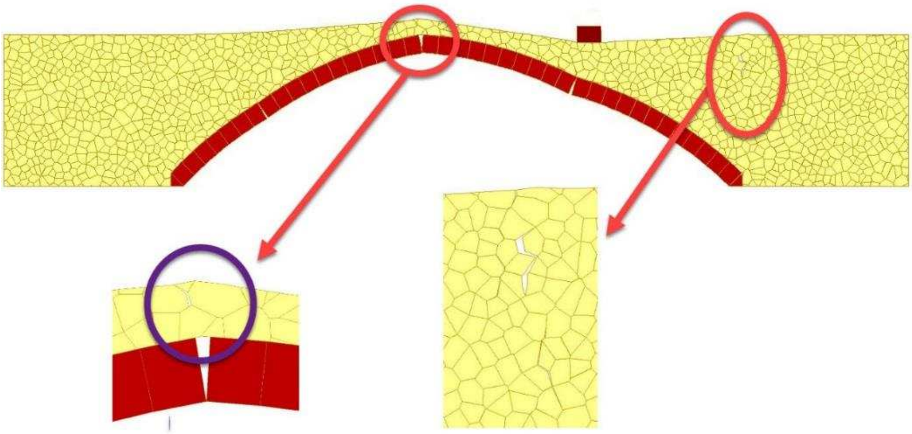



**Fig. 4.** Load against displacement curves for elasto-plastic voronoi or inner-soil particles.




(a)



(b)

**Fig. 5.** Model developed of the Prestwood Bridge: (a) Failure condition as obtained from the experiment; and (b) Failure mode of the bridge as obtained from the numerical model

## 5 Conclusions

Masonry arch bridges form a significant portion of the European transport infrastructure network. Many of these bridges are relatively old but still in service in their original configuration. Increasing vehicle loads and speeds have highlighted the need for reliable estimates of their service condition. Past research demonstrated that load-carrying capacity of a masonry arch bridge is significantly affected not only by the backfill material but also by the backfill to arch ring interaction. Today, the approaches used for the simulation of soil in masonry arch bridges is over-simplistic and most of them do not take into account the soil-structure interaction phenomena.

A novel modelling approach for the simulation of backfill in masonry arch bridges has been proposed. The approach is based on the discrete element method. Bricks in the barrel vault are represented as an assembly of distinct blocks separated by zero thickness interfaces at each mortar joint while backfill is represented as an assemblage of densely packed discrete irregular deformable particles. The mechanical behaviour of the backfill is influenced by the size and properties of the irregular soil particles and contacts. A series of computational models were developed and their results are compared against full-scale experimental results. A good agreement between the experimental and the numerical results was obtained demonstrating the huge potential of this novel modelling approach proposed.

One of the major advantages of the proposed approach is its ability to simulate the initiation and propagation of cracking in the backfill and arch ring with the application of the external load. It is envisaged that the current modelling approach can be used by bridge assessment engineers for understanding soil pressures and load distribution on the backfill and arch ring and thus develop serviceability criteria for masonry arch bridges of their care.

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**Keywords:** Masonry Arch Bridges, Backfill, Numerical Modelling, DEM.

## 1 The challenge

Masonry arch bridges form a significant portion of the European transport infrastructure network. Many of these bridges are relatively old but still in service in their original configuration. Increasing vehicle loads and speeds have highlighted the need for reliable estimates of their service condition. Past research demonstrated that load-carrying capacity of a masonry arch bridge is significantly affected not only by the backfill material but also by the backfill to arch ring interaction. Today, the approaches used for the simulation of soil in masonry arch bridges is over-simplistic and most of them do not take into account the soil-structure interaction phenomena [1].

## 2 The proposed approach for modelling backfill in masonry arch bridges

A novel modelling approach for the simulation of backfill in masonry arch bridges has been proposed. The approach is based on the discrete element method [2]. Bricks in the barrel vault are represented as an assembly of distinct blocks separated by zero thickness interfaces at each mortar joint while backfill is represented as an assemblage of densely packed discrete irregular deformable particles. The mechanical behaviour of the backfill is influenced by the size and properties of the irregular soil particles and contacts. A series of computational models were developed and their results are compared against full-scale experimental results. A good agreement between the experimental and the numerical results was obtained demonstrating the huge potential of this novel modelling approach proposed. A representation of the failure mode of the bridge model developed in the computational model is shown in Figure 1.

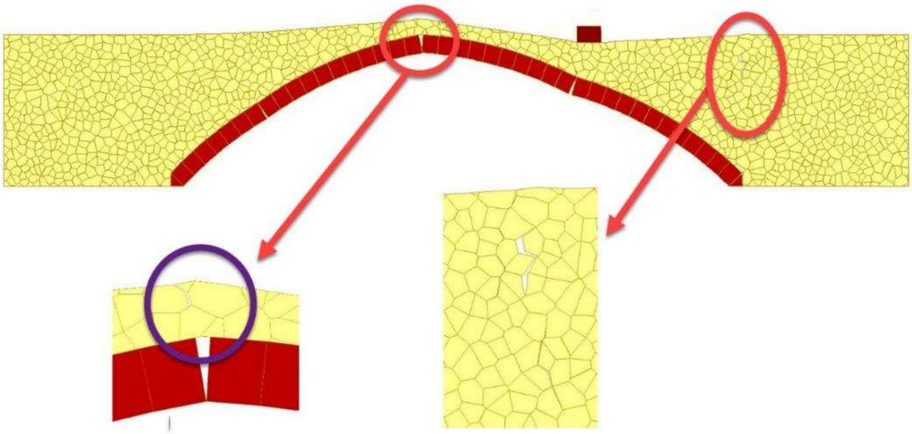

**Fig. 1.** Failure mode of the Prestwood bridge as obtained from the computational model; according to the approach initiation and propagation of cracking in the mortar joints and backfill can be obtained.

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