MODELLING SOIL-STRUCTURE INTERACTION IN MASONRY ARCH BRIDGES

Matthew Gilbert*, Colin C. Smith*, Samuel J. Hawksbee*, Gareth M. Swift+ & Clive Melbourne+

* University of Sheffield – Dept. Civil & Structural Engineering
m.gilbert@sheffield.ac.uk, c.c.smith@sheffield.ac.uk & s.hawksbee@sheffield.ac.uk

+ University of Salford – School of Computing, Science & Engineering
g.m.swift@salford.ac.uk & c.melbourne@salford.ac.uk

Keywords: Numerical modelling, limit analysis, masonry arch bridges.

Abstract: *It is well known that the backfill which is present in most masonry arch bridges contributes significantly to load carrying capacity. In this contribution various 'direct' analysis methods, which model the collapse state directly, without the need for iteration, are discussed. The direct methods considered include the 'rigid block' analysis method, finite element limit analysis (FELA) and the 'discontinuity layout optimisation' (DLO) method, a recently developed procedure which allows both the masonry and backfill to be explicitly included in the model. The latter method is then applied to various small-scale laboratory tests and also to a field bridge. Finally, outcomes are briefly discussed in the context of current masonry arch bridge assessment methods.*

1 INTRODUCTION

Although it has been known for at least a century that the backfill which surrounds the arch barrels of most masonry arch bridges on our transport networks has a fundamental influence on their mode of response [1], this importance is not reflected in the methods routinely used in their assessment. In fact these methods are often over-simplistic, making the task of identifying whether a given structure is capable of carrying additional loads difficult. For example, the still widely used ‘MEXE method’ of assessment, which dates back to the 1940s, takes no account of the nature of the backfill surrounding the arch barrel. In other widely used analysis models the backfill is not modelled explicitly, and instead only its anticipated effects are modelled. The current situation appears to stem from two issues: (i) the backfill is normally hidden from view, and it is thus potentially time-consuming and expensive to undertake the intrusive investigations required to properly characterise the fill material; (ii) the interactions between the backfill and the surrounding masonry are potentially complex, making realistic analysis difficult. In this paper the focus will be on (ii), considering in particular the effectiveness of relatively simple computational tools capable of directly modelling the structure at the point of collapse.

2 THE ROLE OF BACKFILL

As well providing a bridge with a level road or rail surface, the backfill:

1. applies dead loads to the arch barrel, providing pre-stress which makes the barrel more resistant to the effects of live loads;
2. distributes live loads, normally mitigating their destabilising effects;
3. restrains sway of the arch barrel by generating passive resistance pressures, protecting the bridge from the effects of very high destabilising live loads.

The net effect of these factors is significant, as indicated on Figure 1.

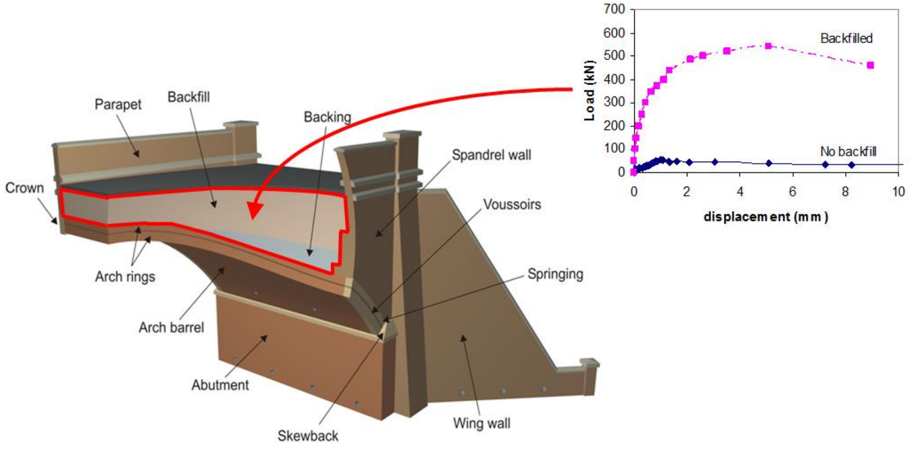


Figure 1: The importance of backfill in a masonry arch bridge (inset shows load vs. displacement plots of 3m span bridges with / without backfill, after [2])

In order to provide data to validate analysis models a variety of experimental studies have been undertaken, which will be considered briefly in the next section.

2.1 Previous experimental investigations

Perhaps the most high profile experiments on masonry arch bridges undertaken in recent years were those carried out on redundant field bridges in the UK in the 1980s and 1990s [3]. However, although these tests were very useful in highlighting hidden strengths in many bridges, their usefulness was limited by the fact that the opportunity to properly characterise the constituent materials - including the backfill materials - was not taken.
This was to some extent addressed in subsequent full-scale model bridge tests carried out, for example, in Bolton [4, 5]. However, results from soil pressure cells incorporated in the arch barrel and soil mass of each Bolton bridge proved quite difficult to interpret as the collapse state was approached, principally because soil movements could not be determined except at the free surface.
Laboratory tests performed at Edinburgh University went some way towards addressing this (e.g. [6]). In this case a clear sided tank was used to house test arches, and markers were introduced into sand fill to enable soil movements to be discerned. However, the model arches were rather small and the markers were relatively widely spaced, with the consequence that discontinuities in the soil movements could not always be easily identified (at that time digital imaging techniques were not readily available).
More recently, centrifuge tests were performed on model bridges at Cardiff University. Again markers were placed in the fill and initially low resolution digital images were collected. Although these tests proved useful, when investigating soil arch interaction the use of a finite size centrifuge box means that the size of the arch might need to be very small to ensure that boundary effects do not colour results. It can also be difficult to achieve representative masonry and soil properties. As far as soil-arch interaction is concerned, an outcome was a proposed refinement to traditional modified retaining wall theory [7], used to determine the passive restraint offered to the arch barrel by the surrounding soil.
However, more radical changes are required in order to obtain a generally applicable soil-arch interaction model. This in turn requires that a wider range of parameter sets are investigated experimentally. Thus, a large (8m long × 2.4m high) test chamber was recently commissioned at Salford University to house masonry arch bridges [8]. A key feature of the test chamber is the provision of extremely stiff and essentially frictionless side walls which give effectively plane strain conditions. Furthermore, one side wall is transparent to permit Particle Image Velocimetry (PIV) techniques to be used to capture soil movements. This latter development is proving revolutionary in that it permits a significantly more detailed view of the mode of response of the soil than has hitherto been possible. Further details of the current experimental test programme are provided elsewhere in the conference proceedings.

2.2 Soil-arch interaction modelling

A variety of indirect, incremental, analysis tools have been applied to masonry arch bridges. For example, Thavalingam et al. [9] compared finite element, discontinuous deformation analysis and discrete element (particle flow code) approaches. However, these tools rely on many parameters and arguably remain too cumbersome for routine use at the present time. A further problem has been the paucity of experimental data, and many workers have validated their models against previous field bridge tests for which many parameters are poorly defined. The sheer number of masonry arch bridges in the world (estimated to be over a million arch spans) means that a detailed incremental analysis of each is unlikely to be feasible for the foreseeable future; for this reason simpler 'direct' analysis methods are considered here. In such methods the collapse state can be analysed directly, without the need for iteration.

3 DIRECT ANALYSIS METHODS

3.1 The mechanism method

The so-called mechanism method, described in the 1930s by Pippard et al. [10] but popularised following the work of Heyman [11], typically involves postulating a collapse mechanism and refining this to directly compute the load required to cause collapse. Workers such as Harvey [12] and Crisfield and Packham [13] subsequently modified the procedure to include passive soil pressures, derived from classical retaining wall theory.

3.2 Rigid block analysis

A drawback of traditional mechanism methods is that ad-hoc procedures are normally required to find the geometry of the critical collapse mechanism. A more general method which involves the use of mathematical optimisation to rigorously find the critical collapse mechanism, whatever its form, was put forward by Livesley [14]. Gilbert [15] subsequently presented an extended formulation incorporating 'backfill elements' to ensure that soil pressures are always mobilised in the correct sense. This approach was used in the RING software, now developed by LimitState [16].

3.3 Finite element limit analysis

A drawback of the above approaches is that it they model the anticipated effects of soil backfill, rather than the backfill itself. To address this Cavicchi & Gambarotta [17] developed direct analysis models for treating soil-arch interaction. However, they found that the gap between upper and lower bound estimates of the collapse load was quite wide, and chose not to validate their output against high quality laboratory data. These issues were subsequently addressed by Gilbert et al. [18] who applied finite elements with quadratic shape functions to close the gap between upper and lower bounds and the resulting model was compared with laboratory test data. A key finding was that it is necessary to use *mobilised* rather than peak strengths in the analysis in order to accurately replicate laboratory test results.

3.4 Discontinuity layout optimisation (DLO)

One issue with finite element limit analysis is that it is necessary to discretise the soil using a mesh, the form of which can affect the results. In contrast with DLO the soil is discretised using nodes, which form the endpoints of potential discontinuities. The critical layout of the discontinuities is then found using optimisation. DLO can be considered as a natural extension to (and generalisation of) the rigid block analysis method, enabling both discrete blocks and continua to be treated, and also applied to masonry arch bridge problems. In [19] DLO was applied to full-scale laboratory tests, but here the focus will be on applying it to small-scale laboratory tests and to bridges in the field, to illustrate its range of applicability.

4 CASE STUDIES

4.1 Application of DLO to small-scale laboratory tests

Callaway et al. [20] described a novel laboratory test programme designed to verify how much load carrying capacity can be attributed to passive restraint effects (generated as parts of the arch barrel remote from the load sway into the fill) and how much is a result of dispersion of the live load through the fill. In the tests the various effects could be switched 'on' and 'off'; full details of the tests are available in [22]. In Figure 2 experimental and DLO results are compared. (The numerical results presented are taken from [20] but most of the DLO mechanisms have not been presented before.)

Note that to obtain the DLO results given in Figure 2 mobilised rather than peak soil strengths were used except directly under the load (i.e. in the areas coloured green in Figure 2. This was achieved by multiplying the frictional strength, tanϕ, of the sand backfill used by 0.33). This is analogous to using scaled-down rather than full passive pressures in conventional mechanism or rigid block analyses, as has been standard practice for decades. This is justifiable because large mobilised soil strengths - and hence large passive pressures - require large soil strains, which are in practice generally not encountered prior to collapse.

4.2 Application of DLO to a field bridge

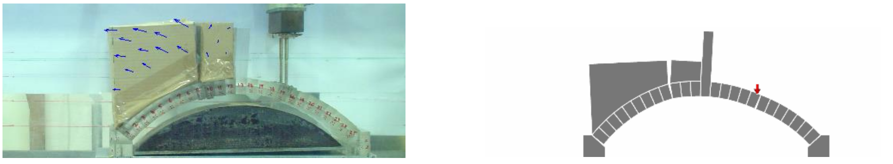
A key driver for the present research is to develop tools which are practically useful. Figure 3 shows a bridge in the field which contains elements which are difficult to model when using simpler tools, but which can be modelled using DLO (cylindrical openings and reinforced concrete near-surface slab), highlighting its potential range of applicability.

5 DISCUSSION

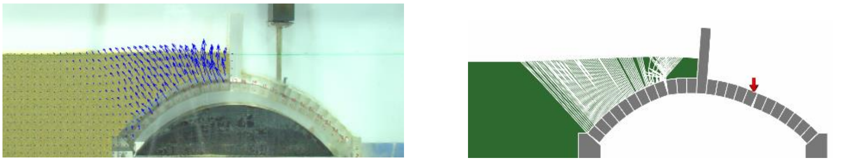
In the previous section it has been demonstrated that good predictions of ultimate load carrying capacity can be obtained when using a comparatively simple 'direct' analysis model, provided mobilised rather than peak soil strengths are used in appropriate regions of the backfill. However, several issues arise:

i. In the case of the laboratory bridges considered here, failure always involved quarter span loading and a four hinge failure mechanism. This meant that it was relatively easy to identify in advance in which regions mobilised rather than peak soil strengths should be used. However, this may not always be the case.
ii. The direct analysis models presented assume negligible structural deformation of the bridge at the point of failure. In reality some structural deformation will take place, but quantifying this, and also the precise soil strength mobilised at the point of collapse is not straightforward. A 'mobilisable strength design' approach could be used (e.g. [21]), but this would need to be calibrated for arch bridge specific problems.
iii. Alternatively, given that bridge owners are typically most interested in the performance of bridges under service rather than ultimate loads, there is a strong argument for

instead focusing on determining the soil strength that can be expected to be mobilised prior to significant structural deformations. This state might also correspond to the Permissible Limit State (PLS), i.e. to the maximum loading that will not (of itself) cause deterioration of the bridge. This is an area of current research; see also [22].

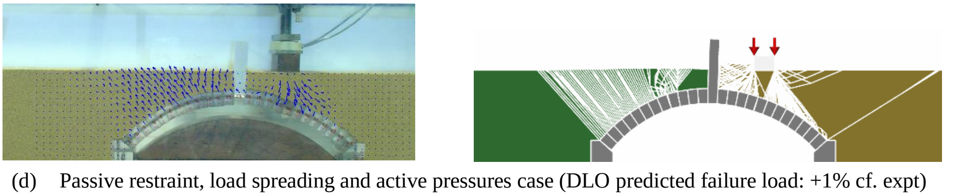


(a) Fill dead weight only case (DLO predicted failure load: -2% cf. experiment)

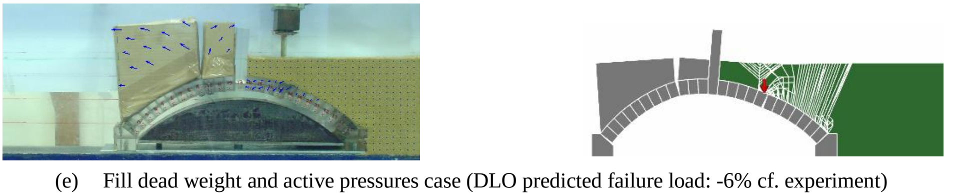


(b) Passive restraint case (DLO predicted failure load: +3% cf. experiment)

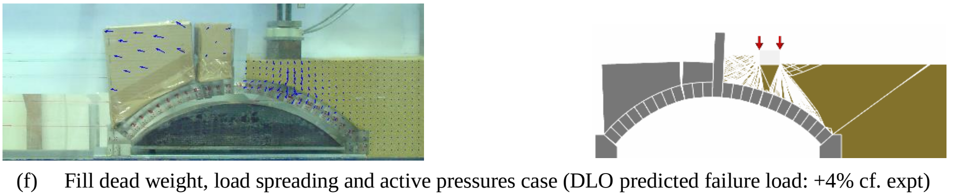
(c) Passive restraint and active pressures case (DLO predicted failure load: -1% cf. experiment)



(d) Passive restraint, load spreading and active pressures case (DLO predicted failure load: +1% cf. expt)



(e) Fill dead weight and active pressures case (DLO predicted failure load: -6% cf. experiment)



(f) Fill dead weight, load spreading and active pressures case (DLO predicted failure load: +4% cf. expt)

Figure 2: Callaway et al. tests [20]: experimental and DLO predicted failure mechanisms

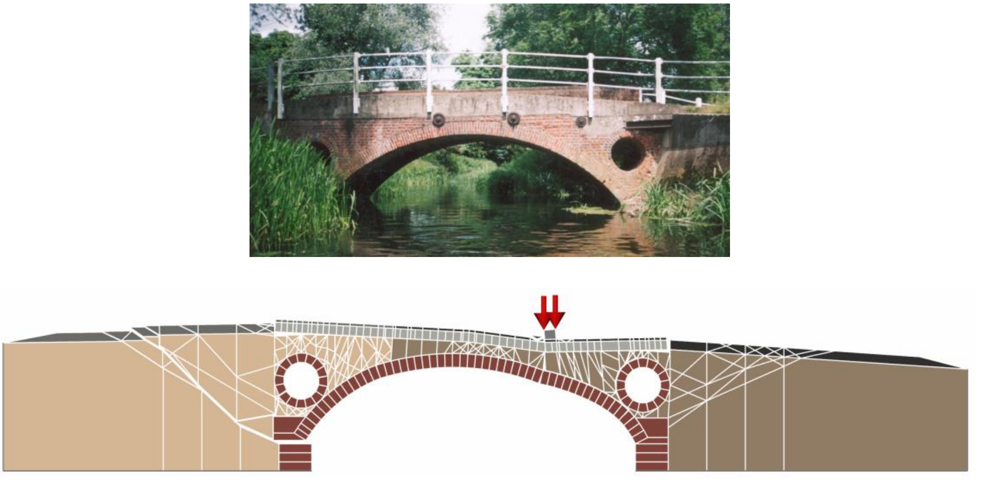


Figure 3: Application of DLO to a field bridge

6 CONCLUSIONS

- Although masonry arch bridge researchers have traditionally focused on the masonry elements of such bridges, soil backfill, when present, plays an important role in overall bridge behaviour.
- 'Direct' methods of analysis, which model the collapse state directly, can be useful for modelling the soil-arch interactions which occur in masonry arch bridges. As these interactions become more complex, recourse to techniques capable of modelling both masonry and soil elements explicitly becomes necessary. One such technique is discontinuity layout optimisation (DLO).
- DLO modelling of small-scale laboratory test bridges has confirmed that mobilised rather than peak soil strengths should be used in a 'direct' analysis to represent regions of the backfill where strains are low.
- Research to establish the extent to which 'direct' methods of analysis can be used to model masonry arch bridges at states prior to collapse is currently underway.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the UK Engineering and Physical Sciences Research Council (EPSRC), under grant references EP/I014357/1 and EP/I014489/1.

REFERENCES

[1] Alexander, T. & Thomson, A. W. 1900. The Scientific Design of Masonry Arches, with Numerous Examples. Dublin University Press.

[2] Smith, C.C., Gilbert, M. & Callaway, P.A. 2004. Geotechnical issues in the analysis of masonry arch bridges. Proc. 4th Int. Arch Bridges Conf., Barcelona. pp. 343-352.

[3] Page, J. 1993. Masonry Arch Bridges State of the Art Review'. HMSO UK.
[4] Melbourne, C. & Walker, P.J. 1989. Load test to collapse on a full scale model, six metre span, brick arch bridge. Transport and Road Research Laboratory Contractors' Report 18.
[5] Melbourne, C. & Gilbert, M. 1995. The behaviour of multi-ring brickwork arch bridges. *The Structural Engineer* 73(3): 39-47.
[6] Fairfield, C.A. & Ponniah, D.A. 1994. Model tests to determine the affect of fill on buried arches. *Proc. Inst. Civ. Engrs: Structures & Buildings* 104:471-482.
[7] Burroughs, P., Hughes, T.G., Hee, S. & Davies, M.C.R. 2002. Passive pressure development in masonry arch bridges. *Proc. Inst. Civ. Engrs: Structures & Buildings* 152:331-339.
[8] Gilbert, M., Smith, C.C., Wang, J., Callaway, P. & Melbourne, C. 2007. Small and large-scale experimental studies of soil-arch interaction in masonry bridges. Proc. 5th Int. Arch Bridges Conf., Madeira, pp381-388.
[9] Thavalingam A., Bicanic N., Robinson J.I. & Ponniah D.A. 2001. Computational framework for discontinuous modelling of masonry arch bridges. *Computers and Structures* 79 (19):1821-1830.
[10] Pippard A.J.S., Tranter E. & Chitty L.C. 1936. The mechanics of the voussoir arch. *J. Inst. Civ. Engrs* 4:281-306.
[11] Heyman, J. 1982. The masonry arch, Ellis Horwood.
[12] Harvey, W.J. 1988. The application of the mechanism method to masonry arch bridges. *The Structural Engineer* 66(5): 77-84.
[13] Crisfield, M. A., & A. J. Packham. A mechanism program for computing the strength of masonry arch bridges. No. RR 124. 1987.
[14] Livesley, R.K. 1978. Limit analysis of structures formed from rigid blocks. *Int. J. Numer. Meth. Eng.* 12:1853-1871.
[15] Gilbert, M. 2001. RING: a 2D rigid-block analysis program for masonry arch bridges. Proc. 3rd Int. Arch Bridges Conf., Paris. pp. 459-464.
[16] LimitState. 2011. LimitState:RING Manual, Version 3.0. LimitState Ltd, Sheffield. http://www.limitstate.com/ring.
[17] Cavicchi, A. and Gambarotta, L. 2007. Load carrying capacity of masonry bridges: numerical evaluation of the influence of fill and spandrels, Proc. 5th Int. Arch Bridges Conf., Madeira. pp. 609-616.
[18] Gilbert, M., Nguyen, D., and Smith, C.C. 2007. Computational limit analysis of soil-arch interaction in masonry arch bridges. Proc. 5th Int. Arch Bridges Conf., Madeira. pp. 633-640.
[19] Gilbert, M., Smith, C.C., and Pritchard, T.J. 2010. Masonry arch analysis using discontinuity layout optimisation. *Proc. Inst. Civ. Engrs: Engineering and Computational Mechanics* 163:155-166.
[20] Callaway, P., Gilbert, M. and Smith, C.C. 2012. Influence of backfill on the capacity of masonry arch bridges. *Proc. Inst. Civ. Engrs*: *Bridge Engineering* 165:147-157.
[21] Bolton, M. D. & Powrie, W. 1988. Behaviour of diaphragm walls in clay prior to collapse. Géotechnique 38(2):167.
[22] Melbourne, C., Cole, C., Gilbert, M., Swift, G.M. & Smith, C.C. 2013. A road-map for the assessment of masonry arch bridges. Proc. 7th Int. Arch Bridges Conf., Split.