USE OF A PHYSICS ENGINE TO MODEL SOIL FILLED MASONRY ARCH BRIDGES

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SUMMARY

In this paper soil filled masonry arch bridges are modelled using a physics engine, of the sort widely used in the entertainment industries. The presented modelling method can be seen as an alternative to the traditional discrete element method approach providing potentially much faster simulations and a contact model that does not require extensive tuning. In the paper the arch barrel is idealized as an assemblage of rigid bodies, allowing most common failure modes to be captured, including the formation of plastic hinges and sliding. Frictional soil backfill material is also modelled as an assembly of rigid bodies, with macro-scale deformation properties simulated by inter-particle sliding and rolling. When masonry and soil elements are combined in a masonry arch bridge model it is shown that the overall behaviour of the bridge is modelled remarkably realistically, with the phenomena of passive and active soil pressure mobilization both modelled faithfully.

Keywords: *Masonry arch bridges, physics engines, DEM*

1. INTRODUCTION

Most masonry arch bridges comprise an arch barrel which is surrounded by soil backfill material. As well as providing a level traffic surface, the backfill material distributes the applied load and pre-stresses and provides passive restraint to the arch barrel, which together very significantly enhance load carrying capacity. However, traditional analysis tools for masonry arch bridges model the effects of backfill in a highly simplified manner. For example, most limit analysis methods model the anticipated effects of the backfill, rather than the backfill material itself (see e.g. [1]). This means that semi-empirical factors need to be employed to ensure good agreement with experimental test results. Alternatively non-linear finite elements can be employed, but when modelling both masonry and soil elements this generally necessitates the use of complex constitutive equations, with many input parameters, some of which can be difficult to quantify.

In this paper soil filled masonry arch bridges are instead modelled using a physics engine, of the sort widely used in the entertainment industries (e.g. the film and computer games industries). The physics engine employed, Box2D, provides similar functionality to the established discrete element method (DEM) software. However, Box2D uses a more intuitive contact model which does not require extensive tuning and can also potentially obtain solutions far more rapidly.

Here the arch barrel is idealized as an assemblage of rigid bodies, allowing most common failure modes to be captured, including the formation of plastic hinges and sliding. Frictional soil backfill material is also modelled as an assembly of rigid bodies, with macro-scale deformation properties simulated by inter-particle sliding and rolling. When masonry and soil elements are combined in a masonry arch bridge model it is shown that the overall behaviour of the bridge can be modelled remarkably realistically.

In the paper the discrete modelling approach adopted is briefly described and is then applied first to masonry arch ribs and then to masonry arch bridges. Application of the physics engine model described to soil bodies is described elsewhere [2].

2. PHYSICS ENGINE MODELLING APPROACH

2.1. Overview

Masonry arches are frequently modelled as assemblages of discrete blocks, either using limit analysis methods (e.g. [3]) or using the discrete element method (DEM). In the latter case the soil surrounding a masonry arch can be modelled as an assemblage of particles (e.g. [4]).

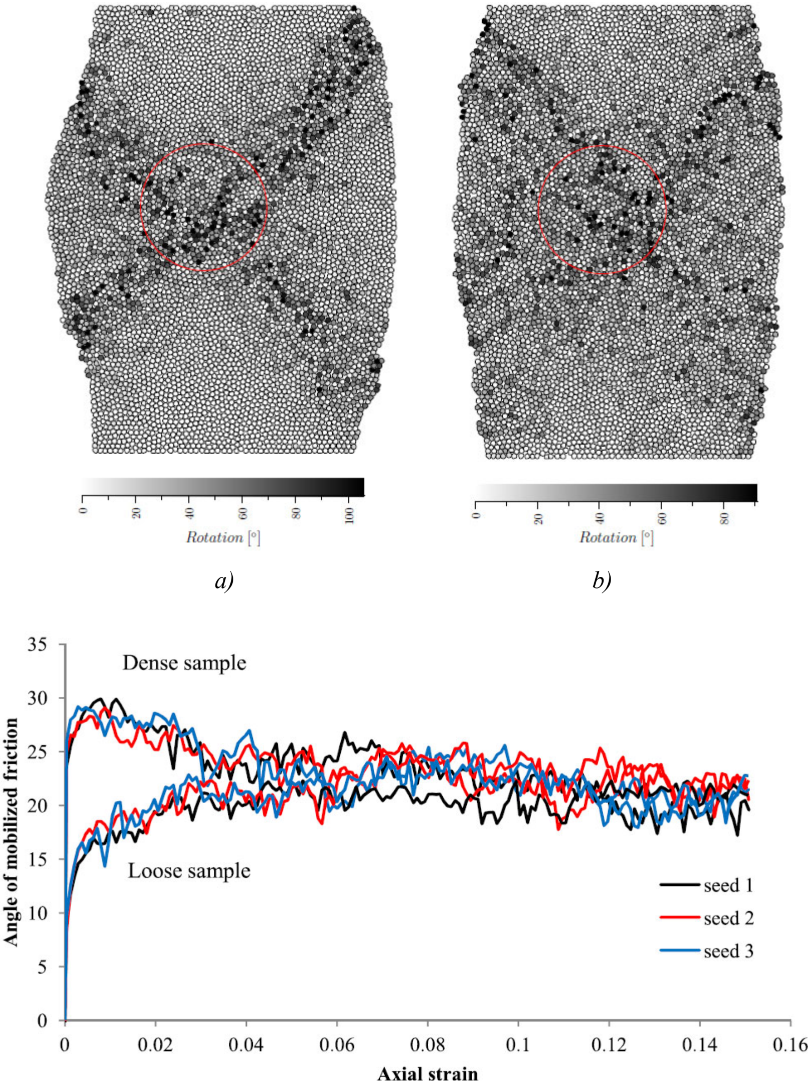
However, another option exists: physics engines are designed to simulate physics in real-time, taking advantage of advanced features of modern computer hardware, and are capable of modelling problems involving numerous arbitrarily shaped elements in a highly efficient manner. This means that large-scale problems, represented using large numbers of blocks and/or soil particles, can be analysed relatively rapidly. In this paper a widely used 2D rigid body physics engine, Box2D is employed [5]. The engine uses the semi-implicit Euler scheme to simulate the evolving behaviour of assemblages of individual particles, each modelled as a rigid body. Particle interaction is, in principle, modelled in a similar way to the ‘contact dynamics’ approach considered by Jean [6]. Particles interact via instantaneous collisions which are resolved using a constraint based contact model. Collision detection, resolution of multiple collisions and the approximations necessary when dealing with custom shape particles determine the efficiency and accuracy of the method. Further details are provided by Pytlos [2].

2.2. Modelling soil

Pytlos et al. [7] demonstrate the capability of a physics engine to capture the essential features of a granular soil; Fig. 1 shows sample results for dense and loose soil samples subject to compression loading. It is evident that shear bands can successfully be captured, and that, in line with observed behaviour, the angles of friction of the samples coalesce when strains are large.

2.3. Modelling masonry structures

For the purposes of the feasibility study described, masonry structures are idealised as assemblages of rigid bodies. Each masonry unit is modelled as a separate geometrically expanded entity, with masonry joints assumed to have zero thickness. The joints are assumed to be capable of sustaining infinite stresses in compression, but zero stresses in tension. In the context of a masonry arch structure, the idealised model used here allows most common failure modes to be captured, including the formation of plastic hinges and sliding. (Crushing of the masonry is, however, not captured.)



a) *b)*

c)

Fig. 1. *Modelled response of biaxial compression specimen: a) dense sample, b) loose sample; c) mobilization of friction vs. strain for three random particle packings (after [7]).*

3. MODELLING A MASONRY ARCH RIB

Before attempting to model comparatively complex soil-filled masonry arch bridge problems, various bare arch rib models were set up and solved. These models comprised an arch rib with span 20m, ring thickness 1.2m, and comprising voussoirs of unit weight 20kN/m^3; other parameters were varied as indicated in Table 1.

Gravity was applied slowly over a period of 100 seconds to avoid dynamic load effects. A vertical load was then applied to a single voussoir. In order to avoid dynamic effects a limiting condition was set on the velocity of the loaded voussoirs and the test was stopped when the total displacement of the loaded voussoir exceeded the ring thickness.

The desired accuracy of the simulations could be controlled by adjusting the time step size, Δt, and the maximum number of velocity iterations per time step available to the constraint solver, N_i. In general the smaller the value of Δt and the higher the value of N_i the greater the accuracy, though the higher the runtime. Methods of obtaining answers of sufficient accuracy in a reasonable timescale were devised by Pytlos [2].

To verify the accuracy of the solutions obtained, results were compared with those obtained using the widely used masonry arch limit analysis software LimitState:RING [8]; results are shown in Table 1 and Fig. 2. It is evident that a range of failure modes could be simulated, and that excellent agreement with LimitState:RING was obtained in all cases.

***Table 1**. Bare arch tests: parameters varied and failure loads.*

Test	Span to rise ratio	No. of units	Coefficient of friction	Load position (span)	Failure load Box2D	Failure load LimitState: RING	Diff (%)
a)	4	11	0.6	0.25	518.8	517	0.35
b)	4	24	0.6	0.25	412.8	412	0.19
c)	4	51	0.6	0.25	401.7	402	0.07
d)	3	25	0.6	0.25	263.6	263	0.25
e)	5	25	0.6	0.25	580.5	580	0.09
f)	4	25	0.3	0.25	352.6	352	0.16
g)	4	25	0.2	0.25	189.7	190	0.18
h)	4	25	0.6	0.5	2284.1	2280	0.18

4. MODELLING MASONRY ARCH BRIDGES

Now that it has been shown that soil and masonry elements can both be faithfully modelled using the Box2D physics engine, masonry arch bridge models will be considered. Here a dense soil will be used, and the results obtained will be compared with those obtained using the LimitState:GEO limit analysis software [9], which has in the past been successfully applied to masonry arch bridge problems [10].

For this initial study the models again include an arch of span 20m and ring thickness 1.2m, and formed from voussoirs of unit weight 20kN/m^3. Also a span to rise ratio of 4 was employed, with the arch formed using 24 voussoirs, and with the joints possessing a coefficient of friction of 0.6. The backfill height was set at 8.0m and a dense soil with unit weight of 21 kN/m^3 (including voids) and initial angle of friction of approx. 26 degrees was selected. These properties were achieved by adjusting the particle shapes and inter-particle friction (see Pytlos [2] for details). The gross-displacement response of the soil employed is shown in Fig. 3 (averaged from tests on three biaxial compression samples).

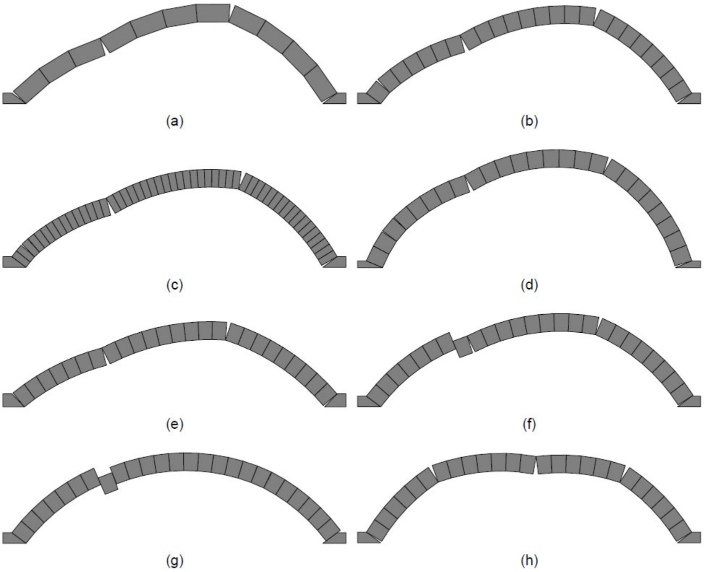


Fig. 2. *Bare arch test failure modes for tests a) - h).*

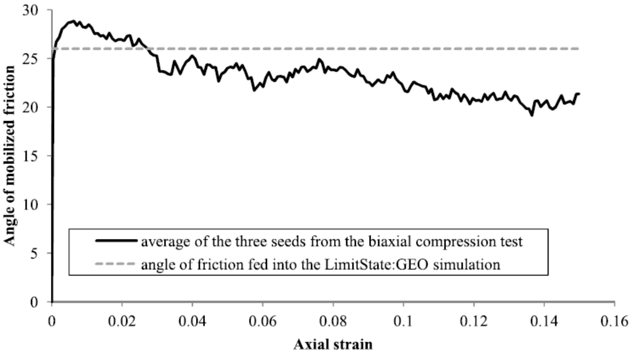
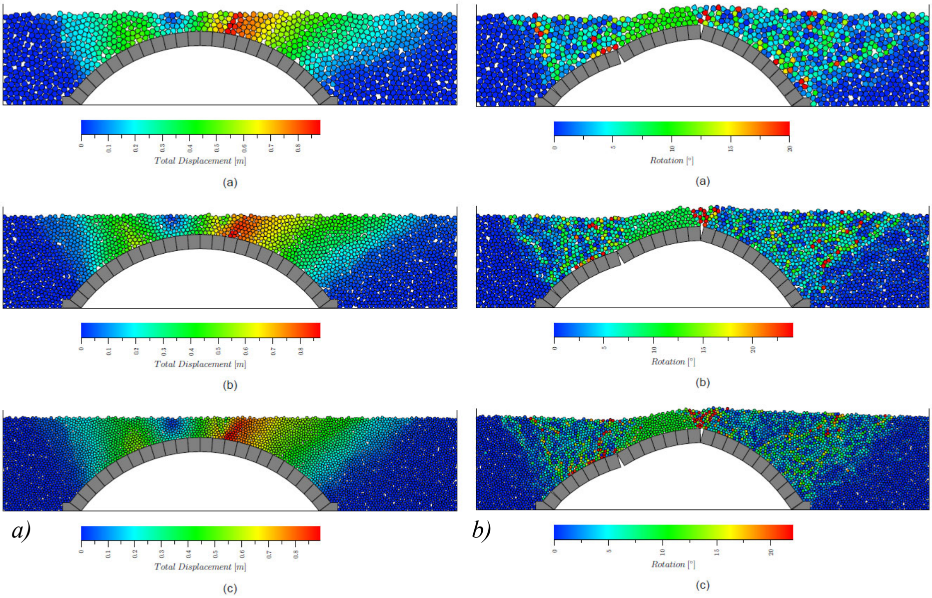


Fig. 3. *Mean angle of friction vs. axial strain response for dense soil sample shown in Fig. 1c.*

To avoid the potential for local soil failure, the voussoir located at the quarter span point was loaded in the initial study. Also, the influence of the number of particles used to discretise the backfill was varied; results are shown in Figs. 4a and 4b, and in Table 2.

***Table 2**. Arch bridge tests: Box2D and limit analysis failure loads.*

Approx. no. of particles	**Box2D (mean)**	**Failure load LimitState: GEO**	**Diff (%)**
1000	1895	1941	2.4
2000	1979		2.0
4000	1921		1.0



***Figs. 4** a) Influence of particle size on mode of response, showing displacements fringes, with approx. number of particles: (a) 1000, (b) 2000, (c) 4000.*
b) Influence of particle size on mode of response, showing deformed shape and accumulated particle rotation fringes, with approx. number of particles: (a) 1000, (b) 2000, (c) 4000.

To validate the results a limit analysis model was also prepared using LimitState:GEO, employing the same geometrical and material properties as outlined previously. Note that the dense soil used in this case mobilized shear strength rapidly (Fig. 3); this obviated the need to use reduced 'mobilized' soil strengths in the limit analysis model, as employed previously [10].

The mechanism of failure in the limit analysis model is shown in Fig.55; the corresponding failure load is included in Table 2. The latter is clearly very close to Box2D physics engine results.

Finally, a further Box2D model was set up but this time employing a more standard surface load; graphical output at different loading stages are shown in Fig.6.

It is evident from Fig.6 that two distinct modes of response are being captured: firstly a bearing failure mode; secondly a global bridge failure mode. When the same basic model was subsequently set up in the LimitState:GEO limit analysis software, using the defined material properties, only the first stage could be captured. This illustrates a key benefit of the proposed physics engine modelling approach, which can more faithfully capture the various soil-structure interactions involved.

5. CONCLUDING REMARKS

It has been demonstrated that a physics engine, of the sort widely used in the entertainment industries, has the potential to be used to model the behaviour of soil-filled masonry arch bridges. Although outside the scope of the present contribution, physics engines are well developed and can be deployed on modern computer architecture (e.g. GPUs) to ensure solutions are obtained extremely rapidly.

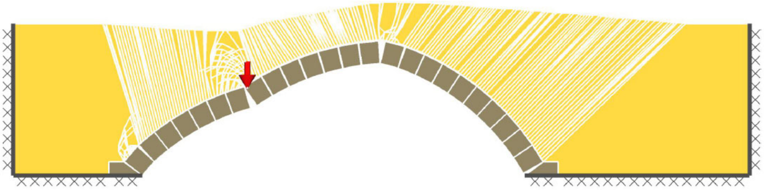


Fig.5. *Limit analysis model of soil-filled arch bridge (LimitState:GEO).*

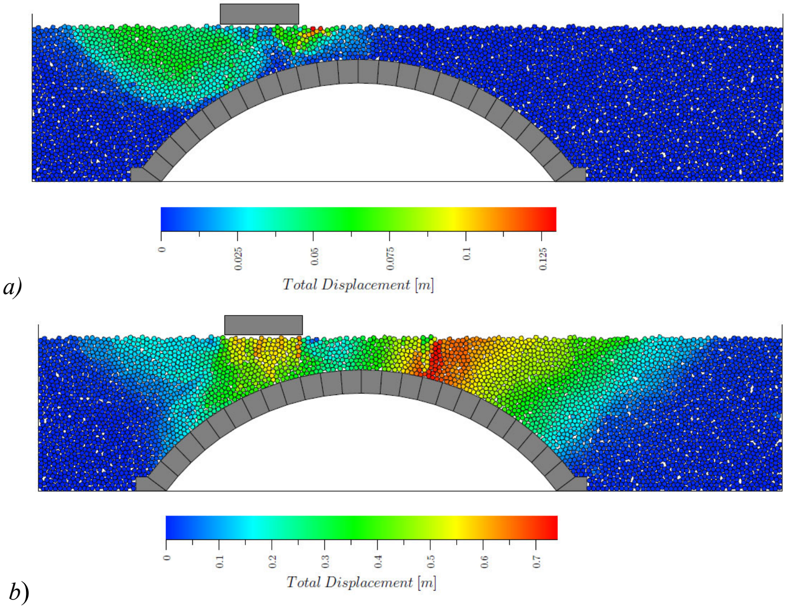


Fig. 6. *Surface loaded bridge showing displacement fringes at loading beam displacements of: a) 0.1 m, b) 0.6 m*

6. ACKNOWLEDGEMENTS

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