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Comparison of thrust line analysis, limit state analysis and distinct element modeling to predict the collapse load and collapse mechanism of a rammed earth arch

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ABSTRACT

This paper assesses the suitability of two analytical and one numerical analysis techniques to determine the collapse load and the collapse mechanism of a rammed earth arch. The first method, based on thrust line analysis, is a graphic statics based approach that can predict collapse relying only on material properties of density and compressive strength, assuming that rammed earth has no tensile strength. The second method, limit state analysis, is based on a virtual work formulation to predict the collapse assuming the same set of material properties. Both analytical methods have been adapted from masonry analysis to take into account the limited compressive strength of rammed earth to better predict the rammed earth arch's behavior and can be generalized to any material without tensile strength. The third method is based on a distinct element modeling technique. It is shown through a comparison with a load testing experiment of a 2 m span rammed earth arch that thrust line analysis is an excellent tool to predict the collapse load, but that it cannot provide decisive information regarding collapse mechanisms. Limit state analysis, in contrast, is very suitable to determine the collapse mechanism but may underestimate the ultimate load capacity if the location where cracks can form is not known in advance. Distinct element modeling can provide accurate information on both collapse mechanism and collapse load, but is more computationally demanding and requires a comprehensive characterization of material properties. The application of these techniques to rammed earth is motivated by the rise of the design of new arched and curved rammed earth structures, while appropriate analysis tools are lacking.

1. Introduction

Rammed earth has seen a surge in attention over the past two decades for its low environmental impact. As earth can typically be amassed on site, often without material and transportation costs or energy-consuming manufacturing, it is an excellent sustainable construction material [1–3]. As this potential has been repeatedly recognized during the past decennium, research into the structural behavior of rammed earth has been steadily increasing. Studies have mainly addressed the behavior of linear wall elements thus far [4–9], while arches, vaults and shells made from rammed earth or even more general earthen materials have barely been discussed in literature [10]. However, a limited set of vaulted rammed earth structures have been designed and built in recent years (for example, those designed and constructed by Rowland Keable in the UK [11], Martin Rauch at ETH Zurich and Tasha Aitkin at CAT in Wales [12]). Within this context, the question arises what methods are suitable to assess the load bearing capacity and collapse mechanisms of curved rammed earth structures.

In this paper two analytical and one numerical techniques are presented and compared for the prediction of the collapse load of a 2 m span rammed earth arch which was subsequently tested until collapse. The first analytical technique examined is a thrust line analysis, which is a graphic statics-based technique which gives a lower boundary estimate for the arch's collapse load. A second estimate is provided by a kinematic limit state analysis based on virtual work computations, and finally a numerical approach is presented in the form of distinct element analysis which captures the collapse mechanism through a displacement-based time-stepping scheme. Finite element modeling (FEM) is not used because it typically assumes small displacements and it relies heavily on the elastic properties of the material which might not be practical for rammed earth. This approach is discussed in detail in Section 2.2.

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2. Materials and methods

2.1. Rammed earth arch experiment

To assess the performance of the methods and enable their comparison, the methods were all applied to the same rammed earth arch which was tested to failure. Therefore, the material testing, construction and load testing of this arch are detailed first.

2.1.1. Material testing

The arch studied in this paper was constructed out of unstabilized and unreinforced rammed earth made from soil from a site in Princeton (NJ, USA). The soil's composition was determined according to ASTM D 422 – 63 [13] and was found to consist of 15% clay, 24% silt and 61% of combined sand and gravel. This composition falls within the acceptable range for rammed earth construction [1,4]. The soil was compacted at the optimum water content of about 10% by mass. This optimum water content for the rammed earth compaction had been determined through the testing of a set of 9 cylinders using the procedure detailed in [4]. The unconfined compressive strength of the material was obtained through the testing of 16 cylindrical samples of approximately 10 cm in diameter and 18.5 cm in height. Tests were conducted using an Instron 600 DX machine at a displacement controlled loading rate of 2 mm/min. Testing was performed after a drying period of 52 days at which point the mass of the cylinders had been constant for more than 28 days. The average compressive strength was found to be 1.3 MPa with a standard deviation of 0.21 MPa, which corresponds to the value of rammed earth compressive strength (also 1.3 MPa) reported by Bui [9]. The average bulk density of these samples was 1959 kg/m^3 with a standard deviation of 63 kg/m^3. Despite the rather low compressive strength (due in part to the high silt content), no soil improvements were carried out. Soil improvement could have been performed by impacting the soil composition (adding more non-expansive clay for example), or by adding stabilizers like lime or Portland cement. Research has pointed out, however, that the environmental impact of rammed earth increases linearly with the amount of stabilizer added [14,15]. Therefore, it was decided to perform the study using unmodified soil to demonstrate that the applied methods work even for lower-strength soils.

2.1.2. Arch construction

The soil used for the construction of the rammed earth arch was sieved through a 2 cm mesh to remove large particles and was then mixed with water (10% by mass) in a concrete mixer on-site. The soil was then dumped into a rigid plywood formwork (depth 30 cm, length 3 m, height 1.25 m) and compacted using manual tampers. The opening for the arch was created by inserting a curved wooden formwork (part of a circle) that remained in place during drying. Compaction was carried out continuously while filling the formwork for the arch in order to create a homogeneous arch without horizontal layers (working in horizontal lifts could make the arch more prone to shear failure between horizontal layers due to the horizontal thrust of the arch). The span of the arch was 2 m, with a rise of 49 cm and thus a rise-to-span ratio of about ¼. On the left side, the arch was supported by a buttressing perpendicular wall. On the right side, the wall curved into a semicircle after a straight zone of approximately 43 cm (see Fig. 1). Initial cracking occurred after removal of the formwork supporting the arch, as the rammed earth had slightly settled during drying (see Fig. 1 for the location of the cracks). The arch was left to dry for 58 days (during August and September 2015) and was protected by a tarp from rain damage during this period.

2.1.3. Load test

The load test was carried out by gradually stacking concrete masonry units over the middle section of the arch creating a total load of 2354 (±50) N. Additional loading at the center was then gradually added to determine the collapse load. The arch collapsed when an additional point load of 3140 (±50) N was applied at the center of the arch (see Fig. 2). The collapse of the arch was recorded through a set of slow-motion videos shown in Fig. 3, which allowed for the identification of the collapse mechanism. The recording captured in Fig. 4 clearly shows a four-hinge failure mechanism involving crushing at the location of the hinges (material crushing by itself is not considered as global failure as long as the arch remains standing). Two hinges formed at the intrados of the arch, one at each springing (A and D) as well as one hinge at the extrados in the middle of the arch (B). The fourth hinge (C), which caused collapse, was formed at the intrados between the middle (B) and the right hinge (D). The three initial cracks occurring at locations A, B and D did not run all the way from extrados to intrados before the final collapse load, but did continue all the way through the depth (30 cm) of the arch.

The collapse occurred after an extension of these initial cracks over the entire thickness of the arch happened and hinges A, B and D formed. This collapse also activated part of the mass of the buttresses on each side of the arch. The initial cracks due to shrinkage and settling thus significantly affected the collapse behavior. Hinge C only formed during the load test, as can be observed in Fig. 4, which shows the collapse sequence. It is important to note that the crack associated with hinge C did not run vertically, but diagonally towards the middle of the arch. This has a significant effect on the results obtained from the limit state analysis as will be discussed in Section 4.2. Right before the collapse, material crushing was observed around hinges A, and D. The arch thus failed by the formation of three blocks by a hinge at the left springing at the intrados (A), by a hinge at the top in the middle of the arch (B), a hinge at the right springing (D) and finally a hinge at the intrados (C) between B and D. The horizontal distance between hinge A and B was 1 m, the horizontal distance between C and D was 0.5 m. The block defined by A and B contained material from the arch and the left buttress. The middle block was much smaller than the other two blocks and was defined by hinges B (a vertical crack) and hinge C (a diagonal one). The zone between B and C was also affected by material crushing due to the applied load. Finally, the third block was defined by the diagonal crack associated with C, and the crack running from the springing D diagonally into the right buttress. The crack associated with hinge C ran diagonally due to a local crushing phenomenon. The central load was exerted onto one cinder block and thus a stress concentration arose at the intersection of this block and the extrados of the rammed earth arch. This stress concentration triggered the compressive failure and crack which then ran diagonally to hinge C at the intrados.

Based on the uncertainties on the geometric data (about 1% error), density (3%), compressive strength (2%), distributed load (2%) and failure load (2%), a total error of up to 10% on the predicted collapse failure load can be expected.

2.2. Methods

Rammed earth can be considered a homogenous and isotropic material that can crack at any given location where tensile stresses arise due to the material's extremely low tensile strength. A wide array of analytical and numerical modeling techniques can be employed to predict this structural behavior of rammed earth structures under external loading. One technique is finite element modeling (FEM) [5,8,16]. FEM assumes small displacements and relies heavily on the elastic properties of the material. This can be complicated for a material as rammed earth that is brittle: