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# INFLUENCE OF THE BACKFILL PARAMETERS IN DISTINCT ELEMENT MODELING (DEM) OF A BACKFILL MASONRY ARCH BRIDGE THROUGH THE PFC2D SOFTWARE

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**ABSTRACT**

This paper presents an investigation on how to model a backfill masonry arch bridge using the discrete element method (DEM). The calculations that geotechnical engineers use the most today are elastic calculations, which use an elastic modulus "E", or plastic analysis that check the equilibrium limit, through a cohesion "c" and a friction angle "Φ". There is an important problem here in determining these parameters. Soils are not homogeneous materials, but have a great variability. The micromechanics of particles arises here to solve these difficulties

PFC2D software is used for this purpose. A certain backfill masonry arch bridge is modelled, with different types of fill, mortar and voussoir materials. Contact bonds and parallel bonds are installed to create the arch at a first stage, positioning balls by their center and radius. Secondly the fill is introduced in several layers and finally the arch is loaded until its collapse in three different load cases. A biaxial test has been programmed using 'FISH' code to obtain the micro-parameters used in the model so that they match the macro-parameters obtained from a real biaxial test. Also, a macro within a spreadsheet has been created to simplify the process of introducing the geometry of the arch.

Further discussion on the influence of the DEM backfill parameters is presented as well as a sensitivity analysis for the arch bridge, specially with backfill parameters and load position. Advantages, disadvantages and limitations of this method of analysis are identified in relation to other frequently used methods.

**KEYWORDS**: Discrete Element Method; Backfill Masonry Bridge; PFC2D; Geomechanical modelling; Soil-structure interaction.

## 1. INTRODUCTION

Masonry constructions are an essential part of the historical architecture of our towns and cities. Being part of the skeleton of our churches, palaces or castles as well as arch bridges, they represent not only a legacy to preserve, but a fundamental cultural, identity and tourist element.

Masonry bridges base their resistant scheme in their arch shape through the concept of antifunicularity [1], [2], [3]. The basic idea of the arch bridge is the arrangement of stone elements called voussoirs with an arch geometry that leads to internal compression forces, exerted on a voussoir against a voussoir, perpendicular to the joints and compressing them uniformly, bringing the loads to the foundation. If the internal pressure line caused by a given state of charge passes through the traced arch, we are facing a stable arch. Further explanation of this phenomena can be found in the works of J. Heyman [3] and Sejourné [4].

The stone materials resist mainly the compression efforts and little or nothing the tractions and the shear forces. In this way, the structural typology of the arch matches perfectly with the working form of the stone. Masonry bridges with backfill also have the collaboration of the so-called backfill. First of all, it is necessary to clarify what the term backfill refers to, since it is not entirely clear, within the group of the masonry arch bridges. Under this term we want to refer everything located between the factory vaults and the running surface.

Following [5] and [6], fills are classified from the structural point of view into two groups. On the one hand, rigid or cemented fill materials and on the other loose ones. Rigid filling is usually located in the area near the beginning of the vaults, while the loose one is in the area near the key of the vault. The structural meaning of the fillings is very important within the overall behavior of the vaults. The loose filling serves to receive the loads that act on the running surface and distributes them along the filling to the back of the vault. Thus, local effects of application of the overloads are reduced, spreading the efforts on a much larger surface. It also helps to center the line of pressures on the thickness of the vault by increasing the weight of the structure itself. The rigid filling has mechanical properties similar to the factory of the vaults, piles and abutments. The effective thickness of the arch, as well as its carrying capacity, are increased thanks to this filling.

Several methods for the analysis of the bearing capacity of the backfill masonry arch bridges are available. Among them we can mention simple conservative methods (MEXE, see UIC Code 778-3R, 1994) [7] and other more recent methods aided by the development of computer calculation methods such as the FEM (finite element method) [8], [9], [10] or the DEM (discrete element method) [11].

Following [12] and [13], we can assert that the calculations, that geotechnical engineers use the most today are elastic calculations, which use an elastic modulus “E”, or plastic analysis that check the equilibrium limit, through a cohesion “c” and a friction angle “Φ”. There is an important problem here in determining these parameters. Soils are not homogeneous materials, but have a great variability. The orientation, the type of soil, the tensional range as well as dilated effects over time, such as consolidation, play a very important role. The micromechanics of particles arises here to solve these difficulties. However, it is important to emphasize that the micromechanics of particles does not arise to replace these elastic and plastic methods, but as a complement to them, to understand the mechanical phenomena that occurs in soils on a smaller scale.

## 2. DEVELOPMENT

### 2.1. Discrete Element Modeling

In this paper, the methodology of analysis will be based on DEM, to enhance the study of the interaction between the filling and the masonry. The role that micro-mechanics plays in the behavior of the filling is really important for the whole bridge. The calculation environment used is PFC2d (Particle Flow Code) version 4.0, developed by the Itasca Consulting Group Inc [14].

This method models the movement and interaction between particles, allowing them moving independently and only interacting in the contacts between adjacent particles, based on the Newton's second law. Contact forces are defined in the normal and shear directions in each calculation cycle, considering the relative displacements between particles and the rigidity of the contact in the corresponding directions. In this way, contact forces are updated according to the force-displacement law in each calculation cycle.

The contacts between particles can be modeled through two types of contacts. 'Contact bonds' can be envisioned as a pair of elastic springs (or a point of glue) with constant normal and shear stiffness' acting at the contact point. 'Parallel bonds' provide the force-displacement behavior of a finite-sized piece of cementatious material deposited between two balls. These contact models are used in this paper to create both the filling and the masonry arch.

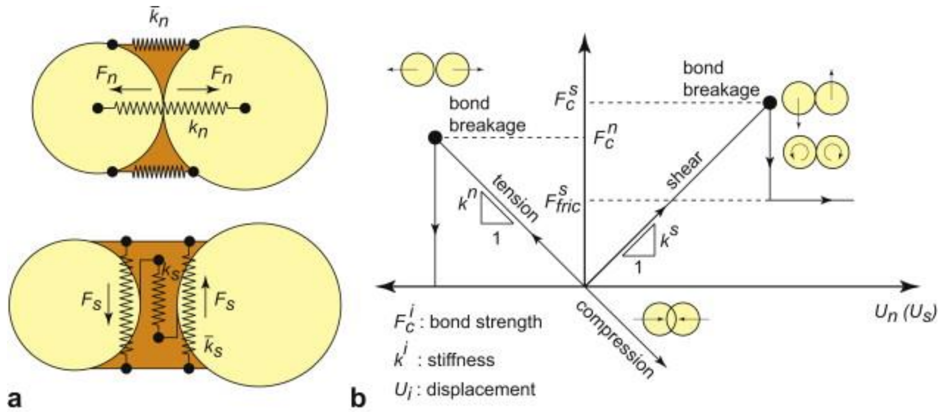


Fig. 1. The parallel bond model implemented in PFC. (a) Normal and shear stiffnesses between particles. (b) Constitutive behavior in shear and tension. Figures redrawn after Potyondy and Cundall (2004) [15].

## 2.2. Case Study

The case analyzed in this paper tries to determine the influence of the filling on the back of an arch bridge in the general behavior of the structure itself. The geometry of the bridge, as well as the load cases considered are shown in Fig 2. The inner radius of the bridge used is 3 meters, and the outer radius is 4 meters, with an arch thickness of 1 meter.

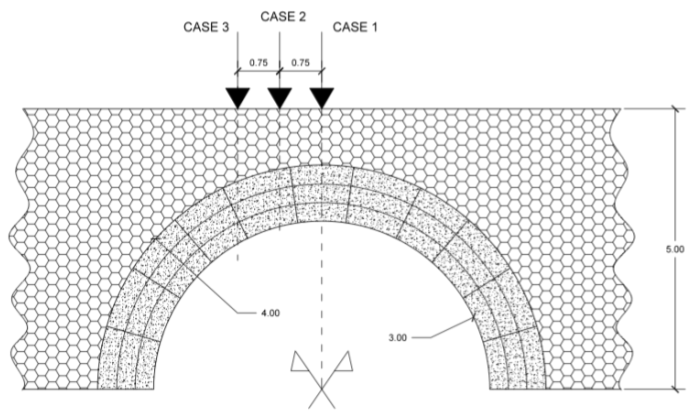


Fig. 2. Case study. The arch is divided into 11 equal segments. The inner radius is 3 meters and the outer radius is 4 meters. The filling height considered is 5 meters. The 3 load cases analyzed are shown.

The main phase of the model is the construction of the arch. A worksheet has been created for this goal, as the introduction of an arch in PFC2D is at least laborious. It has been decided to use three layers of particles to form the thickness of the arch. It could be done with more or less balls if desired. The final results do not depend on this, as these particles will be bonded together with high values of parallel bonds, to simulate the voussoirs of the arch, behaving like a solid rigid. Thanks to the worksheet created, given a certain arch geometry, it is possible to iterate with different particle radii to achieve a perfect arch geometry. In this way, the thickness of the arch is divided into three concentric sectors, as shown in Fig. 3. The balls of each sector have the same radius between them.

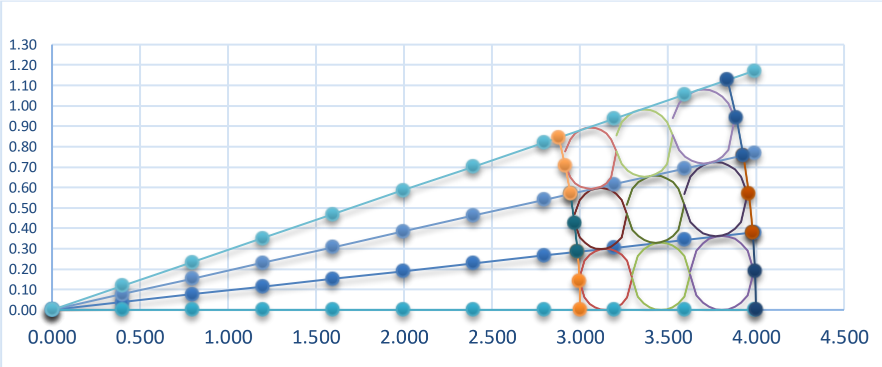


Fig.3. Scheme of division of the vault edge.

In order to ease the introduction of geometry in future cases, a ‘macro’ within the spreadsheet has been created. Coordinates X and Y of the center of all the particles, as well as their radius are obtained from this sheet, and this ‘macro’ allows to export these values to a .dat format that can be executed in PFC2D. In this way, no code is written directly into the program (something extremely cumbersome), obtaining a file of the complete geometry of the arch in a substantially less time than facing the PFC2D environment directly.

The supports of the arches, as well as the lateral limits of the analyzed bridge, are created with 'wall' elements. These walls serve as limits of the created model, to support the arch and retain the filling. It should be noted that up to this point, that mortar infill joints between voussoirs have not been created yet, but that the arch acts as a set with particles strongly bonded by 'parallel bonds'.

In the process of building an arch of this type, the arch is first created, with the different voussoirs, and once it reaches its equilibrium, the structural fill in the backfill begins to be placed.

Once the arch geometry is created, the fill is introduced. To achieve this, and to control the porosity of the structural filling, its particles are introduced in several layers, allowing each layer to settle under the action of gravity as shown in Fig. 4. In this case, a loop has been programmed in which the different filling layers are introduced until the geometry of the model is completed. Finally, the joints between voussoirs are created, with their particular properties.

The joint planes can be defined in PFC2D to represent surfaces where slip and separation between joined groups of particles is possible. These properties are such that they allow one segment to slide over another as long as the friction force between them is overcome. This frictional force is a parameter that is introduced into the program.

Subsequently, the arch is left again to adjust to its new equilibrium position, working together with the filling. Thus, the calculation model is complete, ready to be analyzed under the action of different actions. In Fig.5. the modeling of the bridge obtained is displayed. It shows the different voussoirs obtained after placing the joints. The compressive forces between the particles that form the structural arch are also drawn in black.

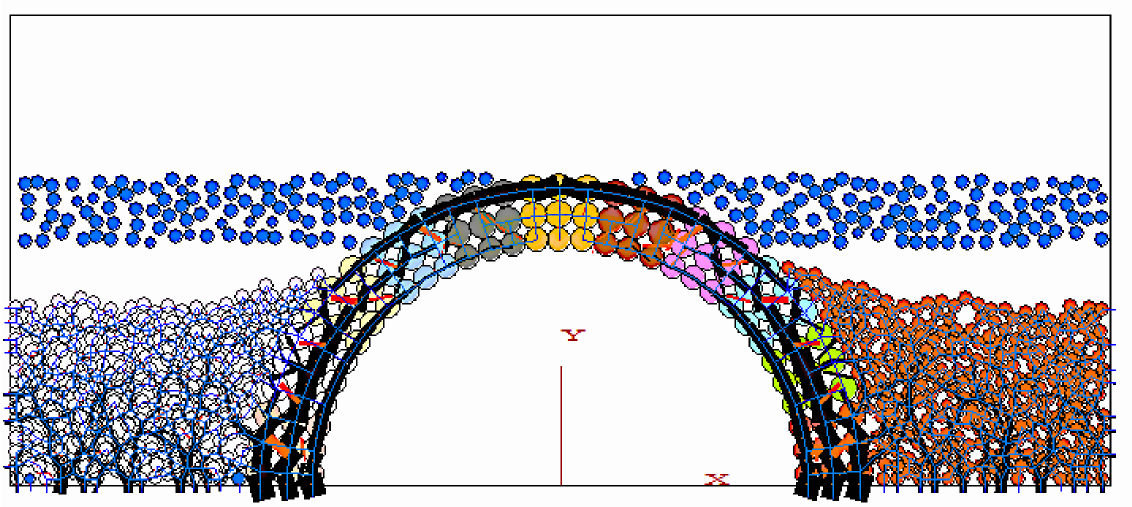


Fig.4. Introduction of the fill by several layers, allowing each one to be settled under the action of gravity. Compression forces between particles are painted in black. It is clear that compression forces pass through the arch.

Tables 1 and 2 show the properties of the two fillings used in this paper, masonry voussoirs and walls used in the simulation. Parameters "kn" and "ks" correspond to the normal and transversal stiffness's. "Density" indicates the specific weight. Parameters "n_bond" and "s_bond" indicate the normal and shear strengths at the "contact bond" contact. "pb_kn" and "pb_ks" indicate the normal and shear stiffness in the "parallel bond" contact. Units are indicated in the table.

The calibration of these properties depends on laboratory tests realized. While in continuous codes these values are usually introduced directly, in PFC2D it is mandatory to get to the most basic level of behavior, which synthesizes the behavior of the material from the micro-components or equivalent grains that make up the material. The process used to reach these properties is iterative. First, properties from real biaxial tests of the materials are obtained. Then, certain values for micro properties are assumed. A biaxial test has been programmed in FISH language in which the material with the same properties that will be used later in the complete model is evaluated.

The biaxial test simulated consists of a sample generated by radius expansion, with a certain particles size range and porosity. The sample is confined by four walls that intersect one another. After initial compaction, the lateral walls are given stiffness's that are one-tenth of the particles stiffness, in order to simulate a soft confinement. Throughout the process, the confining stress is kept constant by adjusting the lateral wall velocities using a numerical servomechanism implemented by the FISH functions servo and get_gain. This mechanism is also used to control the velocity of the loading wall for the bridge. Then, the elastic properties of the sample can be determined by performing a loading/unloading test under elastic conditions (high bond strength and friction. Thus, this test can be used to evaluate Young's modulus, and then further comparison with the real value of E obtained from the real biaxial test can be done. Properties must be changed in each biaxial test simulated, in order to finally get an appropriate relationship between the micro and macro properties of the material.

The bearing capacity of the bridge is analyzed through a 'loading wall' applied in three different positions: in the center of the bridge (Case 1), 75 cm to its left (Case 2) and to another 75 cm to the left (Case 3). This 'loading wall' is given a fixed speed in the vertical direction. The collapse load is obtained by monitoring the resulting force in the 'loading wall'.

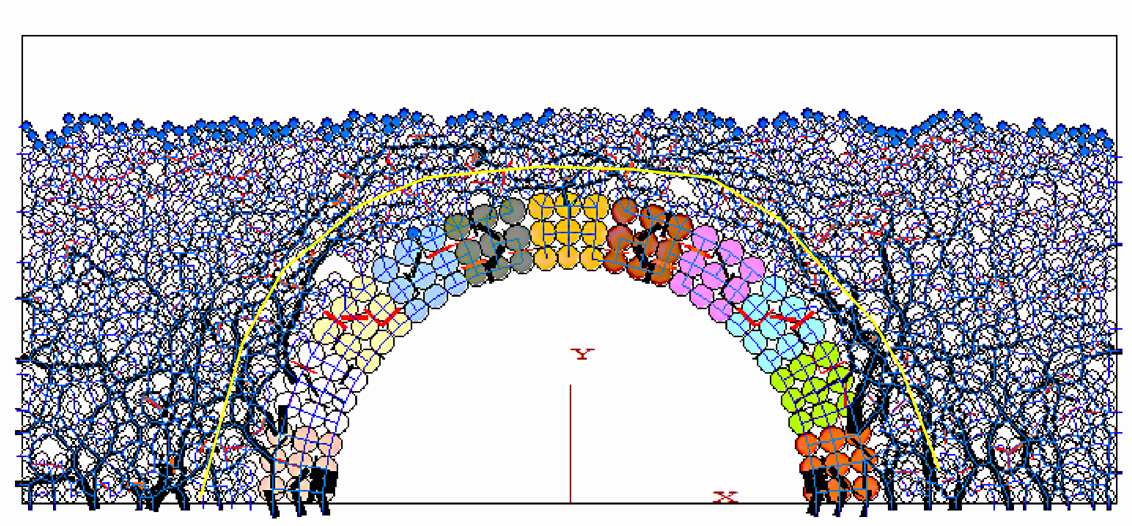


Fig.5. Complete modeling of the bridge. The voussoirs of the arch are appreciated in different colors. In black the compression forces between particles creating a discharge arch through the filling, remarked with the yellow line.

Table 1. DEM properties for a medium soil.

| | | | | CONTACT BONDS | PARALLEL BONDS | REAL PROPERTIES |
|---|---|---|---|---|---|---|
| | kn & ks (N/m) | density (kg/m3) | Friction coeff | n_bond & s_bond (N/m) | pb_kn & pb_ks (N/m3) | E (MPa) Young's modulus |
| Filling | 1e8 | 2000 | 0.6 | 1e8 | - | 52 |
| Masonry | 1e10 | 2200 | 0.6 | 1e10 | 1e20 | - |
| Walls | 1e20 | - | 0.3 | - | - | - |

Table 2. DEM properties for a soft soil.

| | | | | CONTACT BONDS | PARALLEL BONDS | REAL PROPERTIES |
|---|---|---|---|---|---|---|
| | kn & ks (N/m) | density (kg/m3) | Friction coeff | n_bond & s_bond (N/m) | pb_kn & pb_ks (N/m3) | E (MPa) Young's modulus |
| Filling | 1e5 | 1800 | 0.4 | - | - | 20 |
| Masonry | 1e10 | 2200 | 0.6 | 1e10 | 1e20 | - |
| Walls | 1e20 | - | 0.3 | - | - | - |

## 3. RESULTS

The failure load obtained is 420 kN in Case 3 and medium soil, which is the worst case within the cases analyzed. Four hinges are formed according to ultimate loads. Once Load Case 3 and medium soil is stablished as the worst load case, several simulations have been carried out in other to get more understanding on the backfill parameters and how they influence the loading capacity of the whole bridge. The results match the conclusions drawn in [16]. These following conclusions can be drawn with respect to the influence of the type of filling on the general behavior of the backfill masonry arch bridge, as well as other sensitivity studies:

*DEM PARAMETERS SENSITIVITY*

- On the one hand, the perpendicular force in the n-bond contact is the determining parameter when obtaining the breaking load. The s-bond transverse force has very little influence since the predominant type of fracture is a mechanism in which no slippage occurs. However, the value of "s_bond" cannot be below a minimum since this parameter prevents a shear break mechanism from occurring, and is needed to give the initial stability to the arch.

- In order to analyze the influence of different types of soils and materials, the friction angle of the mortar varied from values from 30º to 40º, as well as the friction angle of the fill, which varied from 35º to 45º. The results suggest that the collapse load is not significantly influenced by the change in this parameter. The friction coefficient "k" is related to the friction angle by $ø=\tan_{-1} k$.

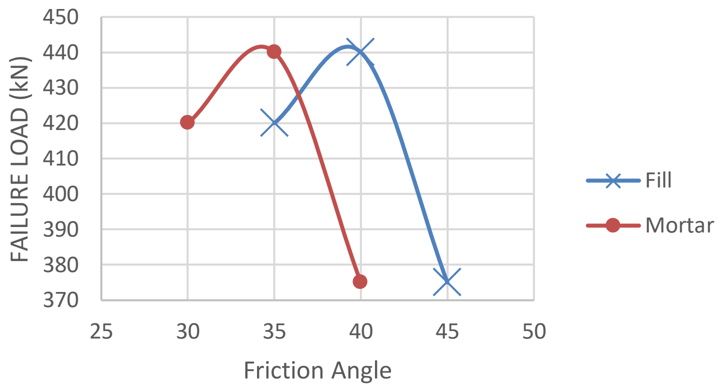


Fig 6. Friction Angle vs Failure Load.

*BACKFILL PARAMETERS*

- The use of medium sand as a filling causes smaller deflections than in the case where loose sand is used. Therefore, the rigidity of the filling has a significant importance in the displacements, causing larger ones in cases where there are less rigid fillings.

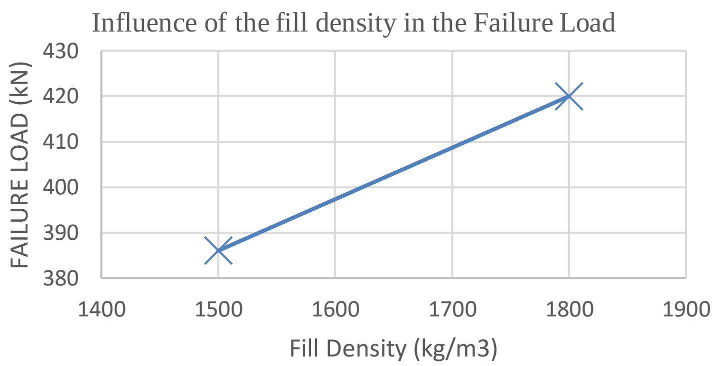


Fig 7. Fill Density vs Failure Load.

- The distribution of forces in the filling is substantially different. The medium sand (more rigid) distributes the load in a wider region, with which the tensions produced in the arch are smaller. Again, the importance of the stiffness of the filling is fundamental for the overall behavior of the bridge.

- A compact filling, with high elastic limit value reduces tensions in the vault. The tensions in the filling increase but not enough to exceed its stress limit.

- The fill height also influences the collapse load. The results show clearly that the failure load increases as the fill height does.

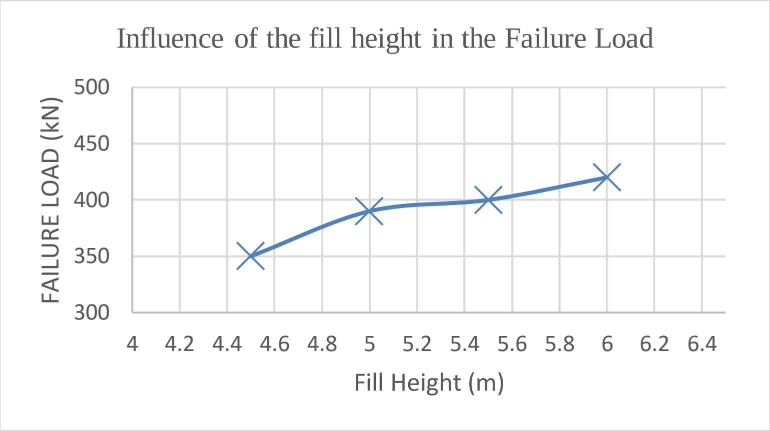


Fig 8. Fill Height vs Failure Load.

## 4. CONCLUSIONS

As final considerations with respect to the DEM method to analyze masonry bridges with backfill fillings, it can be established that the DEM and FEM analysis techniques involve a substantially greater modeling effort with respect to the approximate techniques such as the MEXE or limit analysis as the method of the mechanism.

However, if the analyzed case requires a more sophisticated analysis due to variations in the use of the bridge, or there are important pathologies, or simply do not reach an acceptable failure mode with the existing simplified methods, the use of DEM analysis has full force.

The really interesting thing would be to use several types of analysis. A first basic study could be done when we are facing structures that are in good condition, with normal geometries and under stress. This first level of analysis could be carried out with the aforementioned simplified methods (MEXE, limit analysis). However, in the case where we are facing a singular structure, DEM analysis should be used. This type of studies requires, as it has been seen, field work, sample collection and laboratory analysis, since the choice of the mechanical properties of the materials conditions the correct response of the calculation model used.

Future research in this field should be aimed at the systematization of this type of calculation and the implementation of the DEM method in simpler and more accessible calculation programs. In this way, precision in the analysis of this type of important structures would be gained, correctly predicting the mechanisms of failure and the interaction between the filling and the structure of the arch.

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