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Three-dimensional mesoscale modelling of multi-span masonry arch bridges subjected to scour

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A B S T R A C T

Many masonry arch bridges cross waterways and are built on shallow foundations which are often submerged and exposed to the scouring action of the stream. The limited resistance of masonry arch bridges to foundation settlements makes them very vulnerable to scour and calls for the development of advanced tools for evaluating and improving the capacity against this flood-induced effect. This paper describes a novel three-dimensional modelling strategy for describing the behaviour of multi-span masonry arch bridges subjected to scour at the base of the pier shallow foundations. A mesoscale description is employed for representing the heterogeneous behaviour of masonry units, mortar joints and brick-mortar interfaces, whereas a domain partitioning approach allowing for parallel computation is used to achieve computational efficiency. The scouring process is described via a time-history analysis in which the elements representing the soil are progressively removed from the model according to a specific scour evolution. The proposed modelling approach is first employed to simulate available experimental tests on a dry masonry wall subjected to the settlement of the bearing system and on a reduced scale brick-masonry bridge specimen subjected to scour-induced pier settlements. Subsequently, a numerical example consisting of a multi-span arch bridge subjected to the scouring action is presented to illustrate the potential of the proposed modelling approach and its capabilities for evaluating the vulnerability and risk of masonry arch bridges under flood scenarios.

1. Introduction

Masonry arch bridges are durable, sustainable, and aesthetically appealing structures forming a significant portion of the bridge stock of Europe [1,2]. Many masonry arch bridges span rivers and have their substructures, either piers or abutments or both, founded in the river bed. This exposes them to different flood-induced actions, including hydrodynamic pressure on the submerged surfaces, buoyant forces reducing the effective unit weights of submerged components, impact of lumps/debris [3]. More importantly, water flow results in scour at the footings of piers and abutments, which is the most common cause of collapse due to the high vulnerability of arches to foundation settlements [4,5]. Given the high number of masonry-arch bridges and their socio-economic and cultural heritage value, the accurate prediction of their capacity against scour is a task of paramount importance.

In the last decades, intensive research has been carried out to develop models capable of simulating the complex behaviour and interaction of the components of masonry arch bridges, including the arch barrel, the backfill, the lateral walls, and the piers and abutments. In particular, various numerical models of different degree of complexity have been proposed for the collapse analysis of arch bridges under combined permanent and traffic loads (see Zhang et al. [6] and Sarhosis et al. [7] for a state of the art review). Despite the numerous experimental and numerical studies carried out to date, there are still several open issues in the analysis of masonry arch bridges. First of all, most of previous experimental and numerical studies have focused on single span masonry arches whereas many bridges consist of multiple spans. Thus, the presence of the substructures with their foundations and their interaction with the superstructure has yet to be fully explored. Moreover, numerical models have seldom considered the three-dimensional (3D) nature of the problem, which is important even in the case of vertical patch loading [8–10]. Finally, no modelling strategies have been proposed thus far for describing the vulnerability of masonry arch bridges to scour. In this respect, it should be observed that arch bridges are often built on shallow footings, and that many procedures for scour risk assessment [11,12] assume that the bridge collapses when the maximum scour depth reaches the level of the foundation base. However, given the complexity of the problem, the non-symmetric shape of

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the scour hole, and the bridge redundancy, a 3D structural analysis of the soil-foundation-bridge domain is required to evaluate fully the effects of scour. To date, only a few works have investigated the effect of scour on bridges by performing a full analysis of the soil-foundation-bridge domain (e.g. [13–15]). However, these studies address bridges with pile foundations. Thus, there is a significant need for numerical models that allow the investigation of masonry arch bridges with shallow foundations.

Previous work at Imperial College proposed a mesoscale approach [16] for evaluating the behaviour of masonry arches [10] and single-span masonry arch bridges [17], under vertical loading. This advanced modelling strategy, implemented in ADAPTIC [18] and validated against experimental results, allows for an accurate bridge response prediction, as it takes into account the 3D nature of the problem and important features of masonry arches such as the masonry bond, the spandrel walls contribution, and the arch-backfill interaction. Moreover, although the proposed modelling strategy is computationally expensive, significant reduction of the computational cost can be gained in the numerical simulations by coupling the proposed modelling strategy with the hierarchic partitioning approach allowing for parallel computation developed previously at Imperial College [19–21].

This paper illustrates the extension of this modelling strategy to the analysis of multi-span bridges under different types of flood-induced loadings which require the consideration of the 3D nature of the problem and the interaction between the superstructure, the piers and the bridge foundations. Firstly, the capability of the proposed modelling approach to describe the collapse mechanism induced by settlements is investigated by simulating an experimental test carried out on a simple masonry wall with dry bricks [22]. Subsequently, the results of the test on a 1/2 scale model of a two-span bridge conducted at Polytechnic University of Turin [23] are considered and simulated by developing a numerical model of the bridge. In the test, the bridge was subjected to translational plus rotational settlements at the base of the pier foundations to represent the undermining of the foundation due to scour.

In the second part of the paper a realistic model of a two span bridge similar to Copley Bridge in Yorkshire, which recently collapsed because of pier scour, is developed together with the foundations and the soil domain represented by using the Winkler approach. The effect of scour is described by performing a time-history analysis where the elements defining the soil are progressively degraded, which allows the combined modelling of both the loss of support and the settlements due to scour. The proposed modelling approach enables the representation of the complex 3D mechanism which often characterises the failure of masonry arch bridges subjected to pier scour and can be conveniently employed in more general frameworks and procedures for flood risk assessment and mitigation [24].

2. Modelling strategy for multi-span brick-masonry arch bridges subjected to scour

This section describes the finite element (FE) modelling approach and analysis procedure for describing the 3D behaviour of masonry arch bridges subjected to foundation scour. The proposed approach extends and advances the models originally developed at Imperial College for the analysis of large-scale unreinforced masonry walls [16,25], and for the evaluation of arches [10] and single-span masonry arch bridges [17] subjected to vertical loadings. In particular, the previous single-span bridge models are extended here to consider multi-span bridges, accounting further for the behaviour of the substructures and the foundations, as well as the interaction between the soil and the foundation, which is essential for simulating the effects of scour (Fig. 1).

The next sub-sections describe in detail the modelling approach for the bridge components, the hierarchic partitioning strategy for speeding up the bridge analysis, and the strategy for describing the effects of scour.

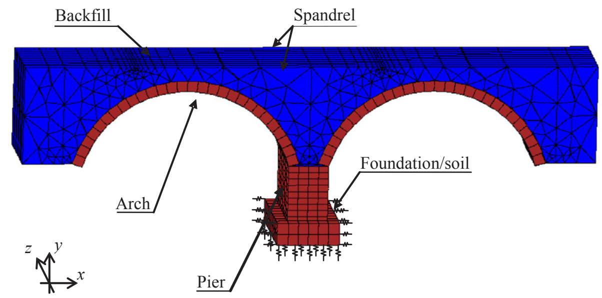

Fig. 1. Bridge-foundation-soil model and Winkler-type interfaces.

2.1. 3D model of the bridge

Masonry is a heterogeneous and strongly nonlinear material whose behaviour depends on the orientation of the loading direction with respect to the masonry bond, where mortar joints represent preferential fracture planes [26]. In this respect, a detailed mechanical model for the masonry arch and piers should take into account not only the mechanical characteristics of units and mortar but also the actual 3D masonry texture. Unlike continuous approaches which assume masonry a homogeneous material [9,27], a discrete modelling strategy is employed to represent the actual masonry bond and model the development of cracks in real brick/stone-masonry arches and piers. This numerical strategy allows for an accurate description of the 3D domain of any masonry arch/pier, as the actual 3D masonry bond is represented using two or more elastic solid elements for each brick and 2D nonlinear interface elements for mortar joints. In particular, 20-noded elastic solid elements formulated according to standard FE procedures are used together with specific 2D zero-thickness nonlinear interface elements with 16 nodes accounting for material and geometric nonlinearity. In this way, the typical fracture surfaces which characterise the nonlinear response up to collapse of masonry arches can be represented. These correspond to radial cracks, circumferential cracks leading to ring separation in multi-ring arches and longitudinal cracks caused by transverse bending. While the first two types of crack generally take place in the mortar joints, longitudinal cracks may pass also through the masonry units. Thus nonlinear interface elements are placed also in the middle of each brick to capture the potential development of cracks. This renders the FE mesh for brick-masonry arches relatively simple, as it is made up of identical solid elements connected to each other by nonlinear brick-brick and mortar interface elements as shown in Fig. 2. Material nonlinearity is taken into account by employing for the interface elements a cohesive model, which enables an effective representation of damage, cracks and plastic separations [16]. In particular, the latest refinement of the interface model, based on the concept of coupled plasticity and damage and described in detail in

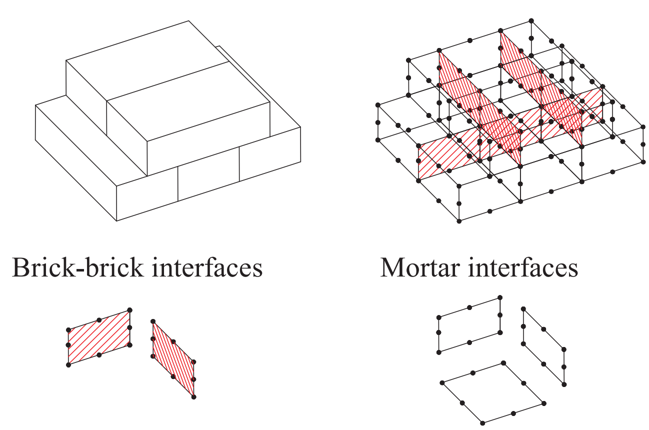

Fig. 2. Portion of a brick wall with flemish bond and relevant FE modelling.