Numerical analysis of stone masonry historical monuments

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Abstract. This paper presents the results of numerical investigations of the behavior of the model of Protiron, an ancient dry-stone masonry structure located in Split, Croatia, under seismic excitation, in comparison with experimental tests. The numerical analysis was performed by 3D finite-discrete element model, which was enhanced with the additional elements, clamps and dowels, which connect the stone blocks and may deform, yield and pull out from the stone during the seismic excitation. The most significant results of the measured displacement versus time have been numerically reproduced by presented numerical model.

Keywords: historical monument; numerical analysis; seismic load; finite-discrete element method (FDEM)

1. Introduction

Analysis of seismic resistance of historical ancient monuments made of stone blocks with dry joints has been a subject of investigation in numerous studies which are aimed at preserving and protecting cultural heritage. Numerical modelling of discontinuous nature of these structures is very challenging due to finite rotations and finite displacements which can occur between stone blocks. A comprehensive approach to the analysis of such structures include advanced numerical models based on discrete or combined finite and discrete element approaches, accompanied with the knowledge of contact interaction and transition from continuum to discontinuum mechanism.

In this paper, we present the results of numerical investigations of seismic behavior of the model of Protiron (Nikolić *et al*. 2019a), an ancient dry-stone masonry structure located in Split, Croatia, in order to identify the main factors affecting the stability, and to understand the mechanisms for preventing the structural collapse due to strong earthquakes.

For that purpose 3D finite-discrete element model (Smoljanović *et al*. 2018) developed for dry-stone masonry structures, was enhanced with the additional elements, clamps and dowels, which connect the stone blocks and may deform, yield and pull out from the stone during the seismic excitation. The behavior of the structure obtained in numerical testing was compared with experiment (Nikolić *et al*. 2019a).

2. Experimental program

Experimental investigation of the seismic behavior of a physical model of the structure with geometric scale of 1:4 (Nikolić *et al*. 2019a), was performed on the shaking table of the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS)

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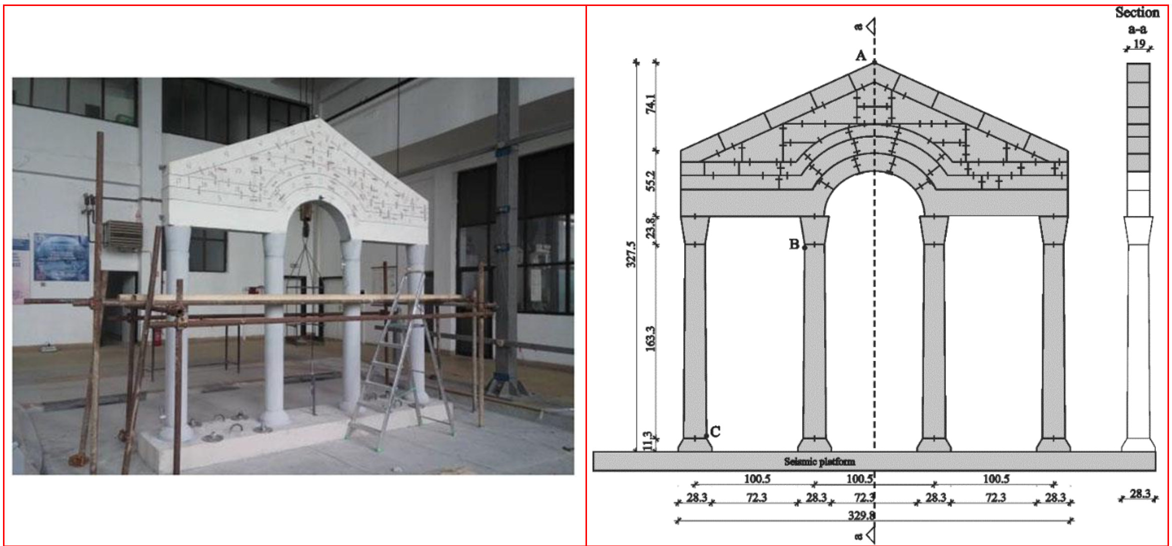
in Skopje. Figures 1(a)-(b) shows the geometric characteristics of the model together with arrangements of the blocks and positions of clamps and dowels respectively.



(a) Physical model | (b) Geometrical characteristic

Fig. 1 Model of the Protiron structure

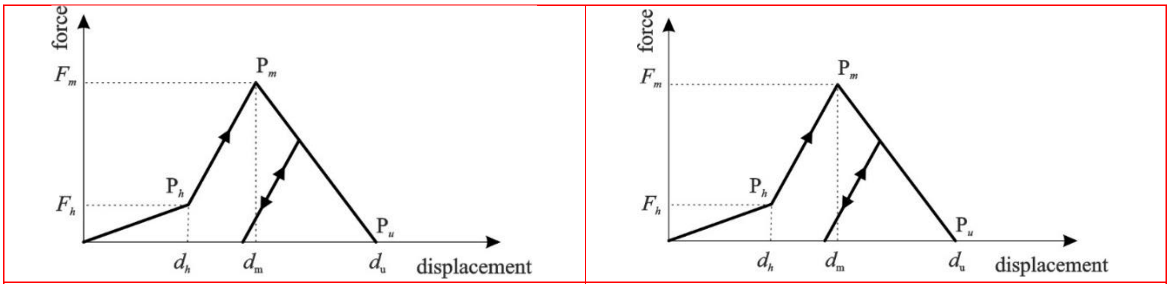
Blocks were made of micro-concrete whose density, modulus of elasticity and compression strength were equal 2190 kg/m^3, 19000 MPa and 20 MPa respectively. All clamps and dowels were made of copper with average tensile strength of 224.7 MPa, while the holes in which the clamps and the dowels were inserted were filled with lead.

Seismic testing of model was carried out by Petrovac earthquake N-S component, recorded on April 15th, 1979 in Dubrovnik on rock soil during an earthquake whose epicenter was in Petrovac, Montenegro (Nikolić *et al*. 2019a). The original record was scaled in time domain with scale factor of 0.5, according to rules for the true replica model, and shown in Fig. 2. Only the horizontal in-plane component was applied to the model. Seismic testing was organised through 15 seismic tests, with gradual increase in intensity, ranging from 0.017 *g* to 1.9 *g*, until the collapse of the model.

3. Numerical analysis

Numerical analysis of the Protiron model was performed by 3D finite-discrete element model (Smoljanović et al. 2018) for dry-stone masonry structures, developed in the framework of open source Y-3D numerical code (Munjiza 2004).

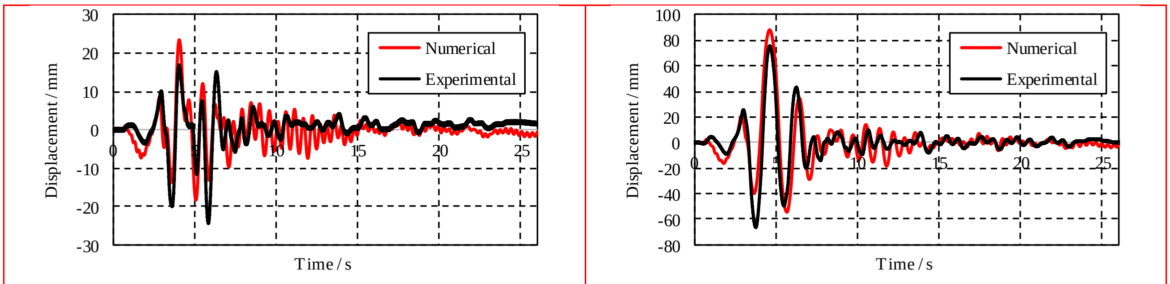
The model was further enhanced with connectors (clamps and dowels), which connect the stone blocks and may deform, yield and pull out from the stone during the seismic excitation. The basis for modelling of the connectors in 3D finite-discrete elements was recently described in the reference (Nikolić et al. 2019b). The main parameters which influence on the behaviour of the clamps and the dowels are material properties of stone and connectors, width and depth of the hole, infill material characteristics, geometry of connectors and interaction between the stone and infill, as well as infill and connector. In this paper, the effect of strengthening was modelled through the integrated force-displacement relation, representing the material properties, the geometrical properties and the effects of the connectors and infill on the stone block (Figure 3).



(a) Clamp | (b) Dowel

Fig. 3 Integrated force-displacement relation

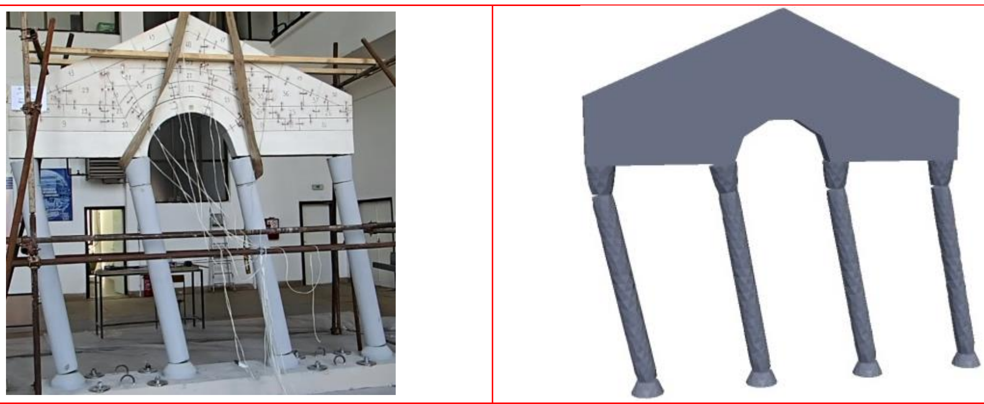
Figures 4(a)-(b) shows the comparison of experimental and numerical results of horizontal displacement of point A for ground acceleration of a_g=0.47 *g* and a_g=1.1 *g*, respectively. It can be seen that the numerical response very closely follows the experimental once, for both intensity of seismic excitation, in terms of amplitude and frequency.



(a) Ground acceleration a_g=0.47 *g* | (b) Ground acceleration a_g=1.1 *g*

Fig. 4 Response history for horizontal displacement of point A

The collapse of the structure in experimental analysis occurred at the intensity of the seismic excitation of 1.9 *g*. This acceleration also caused the collapse in numerical analysis. Figure 5 shows the experimental and numerical failure mechanism where quite good agreement of the results was achieved. The collapse occurred due to the reaching critical opening of the contacts at the ends of the columns and rotation of the columns where the entire upper part of the structure above the capitals behaved as a rigid body and moved to one side causing complete loss of connections with the columns. The result is losses of geometrical stability by in-plane overturning of the structure.



(a) Experimental (b) Numerical

Fig. 5 Failure mechanism of the model for a_g=1.9 g

5. Conclusions

The numerical and experimental investigations of the Protiron model subjected to seismic loading, have shown remarkable seismic resistance of the model of strengthened dry-stone masonry structure. The numerical response, obtained by 3D finite-discrete element model, very closely follows the global behaviour of the structure in experiment, in terms of collapse acceleration and frequency. It was also showed that the mechanism which led to the collapse of the model is the same in both analyses, numerical and experimental.

Acknowledgments

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