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Dynamics of a gravity stonewall

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ABSTRACT

Treated is the dynamics of a gravity stonewall. The wall is excited by a transient damped periodic oscillation simulating an earthquake. The model adopts a stick-slip friction constitutive law. Sensitivity of energy dissipation to parameters such as number of blocks, friction coefficient, sticktion and slipping stiffness and excitation amplitude and frequency is determined. A 2-D model of the monolithic wall is also analyzed to compare displacement and shear stress of the two constructions.

1. Introduction

In the archeological site of Delphi, Greece, it was observed that a specific stonewall had an unusual but carefully laid close-packed pattern of blocks depicted in the photograph of Fig. 1(a). During ancient times, shaping the blocks was labor intensive since artisans relied on archaic tools. Due to the size of each block, it is reasonable to assume that the effort had to be synchronized among several workmen, as this was necessary to fit the different blocks so perfectly as seen in Fig. 1(b). The fact that standard methods of laying parallelepiped blocks existed during this time, raises questions on the choice of this unusual pattern (Fig. 1(a)). It is speculated that the reason behind this seemingly unconventional and complicated pattern is its inherent property to withstand strong earthquakes by maximizing friction energy dissipation. Simulating the dynamics of the gravity stonewall and demonstrating the merits of this unusual configuration forms the basis of this investigation.

The wall is constructed by stacking stone blocks shaped so as to adhere to adjacent blocks forming a close-packed configuration. At the interface of blocks, normal force results from reaction to weight, and shear force results from interface friction from relative block motion. The bottom block is supported by soil while friction force acts along its interfaces with the next adjacent block and with the soil. The later transmits transverse motion from earthquake to the wall.

The static problem and stability of masonry walls has been treated extensively in the literature. Giambanco et al. (2001) derived a formulation implemented by a finite element method of an interface model simulating mortar joints in masonry structures. The interface laws are based on elasto-plasticity simulating the softening response from de-cohesion. Nguyen et al. (2009) simulated the mechanical behavior of masonry without mortar adopting mechanical homogenization parameterized by the opening and closure mechanism of joints. Sulem and Muhlhaus (1997) used discrete formulation and considered joints as elastic interfaces to derive the macroscopic properties of the equivalent Cosserat material. Zhang et al. (2004) use the FEM method to model dry stone masonry. The difficulty was to determine stiffness parameters experimentally. Villemus et al. (2007) developed a model for calculating the stability of dry stone retaining walls. The model considers internal failure accounting for geometric irregularity of stones and their arrangement using experimentally determined parameters. Nimbalkar and Choudhury (2007) determined the design weight of a wall using pseudo-dynamic seismic forces acting on soil and wall.

For seismic excitation of masonry structures, Casolo (2000) modeled the out-of-plane behavior of walls by rigid elements. Casolo and Pena (2007) adopted a rigid element model for the in-plane dynamics of masonry walls considering hysteretic behavior and damage. Casolo and Sanjust (2009) analyzed the seismic behavior and strengthening design of a masonry monument by a rigid body spring model. Papandonopoulos et al. (2002) predicted numerically response from earthquake of classical columns using the distinct element method. Psycharis et al. (2003) studied numerically the behavior of a part of the Parthenon Pronaos. Prieto et al. (2004) treated the impulse Dirac-delta forces in the rocking motion. De Lorenzis et al. (2007) analyzed the failure of arches under impulse base motion. Pena et al. (2007) analyzed the dynamics of rocking motion of single rigid block structures.

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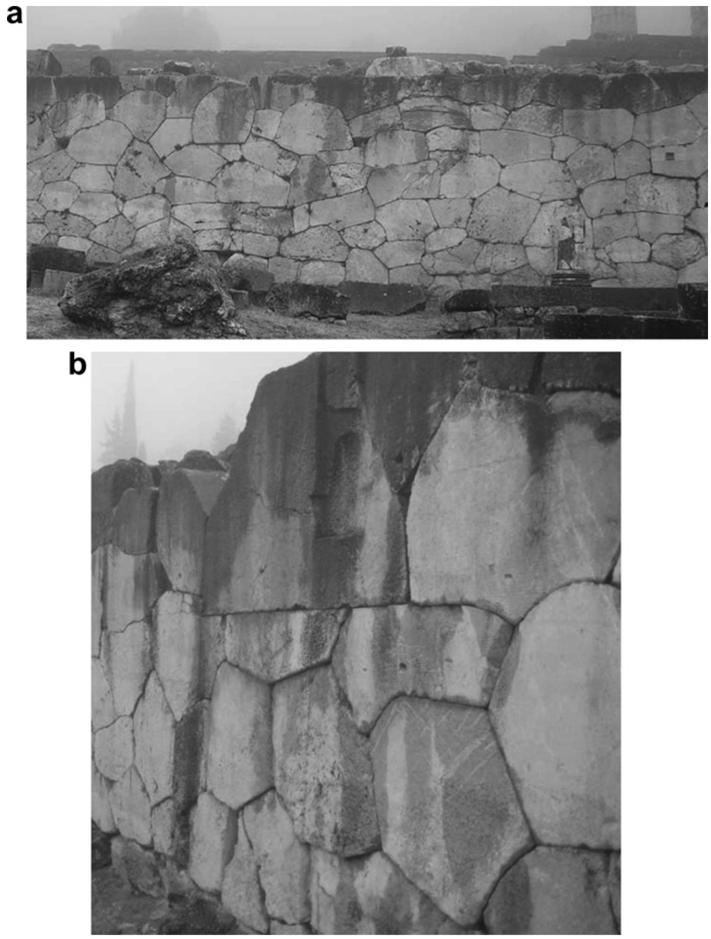

Fig. 1. (a) Ancient stonewall in Delphi, Greece and (b) Details of carefully close-packed stone blocks.

None of the references above treated the dynamics of gravity stonewalls. And except for masonry bricks bonded by mortar, these references did not consider friction-held large close-packed blocks.

An important aspect of the problem is friction mechanics. One of the earliest models of friction is Coulonmb's law, where friction force F_f is proportional to interface reaction factored by friction coefficient. The sign of F_f follows the sign of velocity V. A change in V's sign produces a jump in force with magnitude $2|F_f|$. Dahl (1968) suggested a model named the "bristle model" where prior to slipping, applied force rises linearly with infinitesimal motion alongi a steep stiffness line with slope K_1 (see Fig. 2(a2)) until sticktion is overcome allowing slipping along a gradual stiffness line with slope K_2 (see Fig. 2(a2)). Dahl's model smoothes the transition from sticktion to slipping compared to Coulomb's model where $K_1 = \infty$ and $K_2 = 0$. A simple demonstration of Dahl's model is that of a brush on a friction surface. Applying force along the surface to the brush at rest first deforms its bristles elastically while bristle tips are in contact with the surface. A critical force is reached that exceeds sticktion of the bristle tips allowing them to slip. Bliman (1992) relied with Dahl's idea and cast it in rigorous mathematical formalism. Later, Bliman and Sorine (1993) generalized the formulation by introducing hysteresis operators. An extensive survey on analysis tools and control compensation methods can be found in Armstrong-Helouvry et al. (1994).

In this study, the coupled dynamic equilibrium equations of the stacked blocks forced by soil time dependent motion are derived. Interface forces from friction satisfy the bi-linear hysteretic stick-slip friction constitutive law. Number of blocks, friction coefficient, sticktion stiffness K_1, slipping stiffness K_2, and amplitude of prescribed motion characterize friction energy dissipation from relative block motion. Optimum values are determined of those parameters causing appreciable rise in energy dissipation.

Although the opening and rocking modes are neglected in the formulation (Prieto et al. (2004) and Pena et al. (2007)), these effects are investigated separately and shown to be small for this configuration thus justifying the purely translational kinematics adopted throughout this work.

Dynamics of a cantilever monolith having the same geometric, material properties, and forcing function as those of the gravity block wall is also analyzed to compare displacement and shear stress from the two constructions. Since the monolith model emphasizes on the drastic rise in internal forces from flexure compared to those from friction, the monolith calculation lacks the practical aspect of the inverse pendulum effect well established in earthquake engineering (see Housner (1963)). However, the generality of the flexural model could allow for this effect by inserting a dynamic rotational impedance at the monolith's cantilevered end. This was deemed unnecessary since parameters of the impedance derive from soil mechanical properties, an aspect that is beyond the scope of this work.

2. Stacked gravity stonewall

Consider a wall of stacked blocks with cross-section shown in Fig. 2(a1) and total height h_w. The ith block with height h_i, depth d_b, width w_b, density ρ and mass $m_i = \rho h_i w_b d_b$, is acted upon by friction force $F_i(u_{rel(i)})$ on its bottom face, and $F_{i+1}(u_{rel(i+1)})$ on its