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Centrifuge modelling for evaluation of seismic behaviour of stone masonry structure ☆

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ABSTRACT

Many surviving ancient monuments are freestanding stone masonry structures, which appear to be vulnerable to horizontal dynamic loads such as earthquakes. However, such structures have stood for thousands of years despite numerous historic earthquakes. This study proposes a scaled-down dynamic centrifuge modelling test to study how these masonry structures resist seismic loading. The test is proposed for seismic risk assessments to evaluate risk of damage from a future seismic event. The seismic behaviour of a 3-storey, freestanding stone block structure has been modelled and tested within a centrifuge. Models were made at 3 different scales and dynamic tests were conducted using different centrifugal acceleration fields so that the behaviours could be transformed to an equivalent full-scale prototype and compared. Data from 2 earthquakes and a sweeping signal were used to simulate the effects of earthquake ground motion within the centrifuge. The acceleration and frequency responses at each storey height of the model were recorded in different centrifugal acceleration fields. Similar behaviours appeared when the results of the small-scale models were transformed to a full-size prototype scale. This confirms that the seismic behaviour of stone masonry structures can be predicted using scaled-down models.

1. Introduction

Heritage monuments constructed using stone masonry appear to be vulnerable to horizontal dynamic loads such as earthquakes. Culturally significant stone structures, such as freestanding columns, however, have stood for over a thousand years despite numerous historic earthquakes. This fact leads to 2 questions: how are these structures able to survive multiple earthquakes, and how safe are they for future seismic events? There have been many studies on the dynamic behaviour and seismic vulnerability of stone masonry structures. However, analytical approaches and numerical modelling are difficult and the results are often inconclusive. A full-scale shake table test yields the best data, but such a test is costly. Because friction governs the behaviour of stone masonry structures, reduced-scale centrifuge modelling can be an effective alternative.

The stress conditions of a scaled model in a centrifuge test are known to be the same as in a full-scale prototype. Thus, this equivalent stress condition makes it possible to simulate real seismic behaviour using a reduced-scale model. This study proposes a dynamic centrifuge test for structural analysis and seismic risk assessment as a means to evaluate its safety for future earthquakes.

In this study, the scaling factors are examined through a 'modelling of models' procedure, which is used to evaluate the effects due to scaling. Scaled testing is particularly useful when no full-scale test data is available [1]. Models of 3 different scales were made, representing a 3-storey rectangular parallelepiped stone structure. The dynamic response of each block was recorded using accelerometers installed at the middle of each block. Acceleration data was collected at different centrifugal acceleration fields (*g*-levels). Two real earthquakes, Hachinohe and Ofunato, and a sine-sweeping signal were used as input accelerations in the centrifuge. The tests were conducted at different *g*-levels so that the recorded behaviours of one model scale at different *g*-levels could be transformed to simulate an imaginary full-scale test and compared.

2. Dynamic behaviour of stone masonry structure

The cyclic or dynamic behaviours of block structures, such as ancient stone monuments freestanding on their foundations, have been subject to numerous studies. Cyclic displacements due to the elastic response of the soil–foundation system under vibration loading have been the primary focus. Theoretical solutions for rocking and sliding motions of rigid rectangular foundations have

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been proposed [2–6]. Since the pioneering research of Housner, various studies have been conducted on the dynamic behaviour of single block structures in rectangular shapes. Housner produced a basic understanding of the rocking behaviour of a block and derived a useful mathematical model [7]. Ishiyama [8] classified the behaviours of single blocks into 6 categories and established governing equations for each category, through which he studied the natural characteristics and mode conversion standards of each category. Spanos and Koh [9] have studied the steady state modes of a rigid body by analysing its behaviour in harmonic motion. Also, Tso and Wong [10] approached these modes experimentally.

In the case of multi-block systems, determining the governing equations and mode conversion of the entire system becomes analytically difficult because of the complicated boundary conditions between blocks. Psycharis [11] proposed a governing equation, assuming that rocking takes place only in 2 slender block structures. Makris and Zhang [12] examined the transient rocking response of anchored blocks subjected to horizontal pulse-type motion. Spanos et al. [13] systematically reviewed various analytical, probabilistic, and experimental assessment studies of dynamic behaviour of block structures, including the above-mentioned studies. Makris and Konstantinidis [14] examined the distinct characteristics of the rocking spectrum for a slender rigid block. Since this study, the dynamic behaviours of 2 rigid block structures caused by ground motion have been organised analytically according to patterns and numerically compared.

Today, complex numerical analysis of multi-block systems is possible. And shake table tests and seismic risk assessments are routinely conducted for significant historic stone monuments. Psycharis et al. [15,16] and Konstantinidis and Makris [17] presented a numerical investigation on the seismic response for multi-drum classical columns of ancient monuments. Kim and Ryu [18] produced a full-scale model of a stone pagoda in Sang-Gye-Sa Temple that had been damaged by an earthquake in 1936. They conducted a 1*g* shake table test to predict the accelerations in the monument caused by the earthquake. D'Ayala et al. [19] analysed a series of shake table tests on 3 1/10-scale 3D dry masonry models. Peña et al. [20] described the dynamical behaviour of various freestanding block structures under seismic loading using 1*g* shake table tests. Konstantinidis and Makris [21] also investigated the seismic response of 1/4-scale models of freestanding laboratory equipment subjected to strong earthquake shaking through experimental and analytical studies. Kounadis et al. [22] discussed the dynamic stability rocking response of such a rigid block, 2-DOF systems subjected to horizontal harmonic ground motion using a closed form solution and numerical study. D'Ayala and Ansal [23] authored the guidelines ‘Risk assessment of cultural heritage buildings’ to address the vulnerability of cultural assets, specifically buildings with international cultural value.

The dynamic behaviour of a stone monument during a seismic event includes complex behaviours combined by sliding and rocking motions. In the case of multi-block systems, there are many analytical and numerical difficulties when trying to predict and understand the various mode characteristics of the materials and the interaction between units. Currently, a full-scale 1*g* shake table test is the most useful method for acquiring useful data on structural behaviour, but such a test is time and resource intensive.

This study proposes a dynamic centrifuge test to evaluate the seismic behaviours of stone structures for seismic risk assessment of heritage monuments. For multi-block systems, the friction characteristics between stone units have a significant effect on the behaviour of the structure. The centrifuge test described in this paper simulates the N times gravity accelerations for a $1/N$ scaled model. If an appropriate scaling law is used and the model material has the same density as that of the real structure, the seismic behaviour can be observed under the same stress conditions as those of reality. Therefore, this method is a useful alternative to numerical analysis and full-scale shake table tests. With this said, there exists a limitation in this method in that it is difficult to reproduce the same surface roughness between modelled stone structure and a full-scale prototype.

Table 1
Scaling laws for dynamic centrifuge test and 1g shake table test.

Quantities	Scaling factors (prototype/model)	
	Dynamic centrifuge test	1*g* shake table test
Displacement, length	N	N
Acceleration, gravity	N^{-1}	1
Mass	N^3	N^3
Density	1	1
Stress	1	N
Strain	1	1
Time (dynamic)	N	$N^{0.5}$

Scaling laws are the main factors in testing a full-size prototype as well as a small-scale model. The laws used for the centrifuge test are listed in the second column of Table 1 [1]. In the case of a 1*g* shake table test for the reduced model, a scaling law has been established by Iai et al. [24]. When the density and shear wave velocity of the prototype and model are same, Iai's scaling factors are summarised as in the third column of Table 1. When comparing the scaling laws of a dynamic centrifuge test and 1*g* shake table test for a $1/N$ scaled model, the biggest difference is the stress condition. For the centrifuge test, the stress condition is the same as in the full-size prototype in terms of gravity direction and horizontal direction. This equivalent stress condition supports the possibility of accurately simulating the seismic behaviour of historic stone monuments in a dynamic centrifuge test on a reduced-scale model.

3. Experiment setup for modelling of models

This study was conducted at a recently established centrifuge facility at the KOCED Geotechnical Centrifuge Center at KAIST [25,26]. The centrifuge is able to simulate seismic motion by spinning at a desired centrifugal acceleration. The KOCED earthquake simulator used in this research is of an electro-hydraulic-servo type with rotation radius of 5.0 m and maximum capacity of 240*g*. This earthquake simulator provides 40 g shaking acceleration for no payload and 20*g* shaking acceleration for up to 700 kg of payload. A 40*g* centrifuge acceleration is equivalent to a peak ground acceleration (PGA) of 0.5*g*. Korean seismic design has a maximum seismic design acceleration (for rock outcrop) of 0.22*g*.

The ‘modelling of models’ technique was performed on a 3-storey rectangular parallelepiped stone structure. Each storey level consisted of one block;each block has identical size, mass, and contact surface properties. Models were made at 3 different scales so that the tests could be performed at different *g*-levels, behaviours transformed to full-scale, and compared in order to simulate the behaviour of one full-scale prototype. Tests were conducted using 3 sets of differently scaled models in separate test sets. For example, the dynamic motions of models 1, 2, and 3 were recorded at centrifuge accelerations of 10*g*, 15*g*, and 20*g*, respectively. These 3 test results, all at the same model scale, were aggregated as prototype 1. This was labelled as Test Set 1. Table 2 summarises the entire experiment setup.

The stone used in the experiment is Hwang-deung stone, a type of homogenous granite. All the contact surfaces were cut using a water jet. The density of the stone specimen is 2.67 t/m^3 and the