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THE DYNAMIC RESPONSE OF A MOCK-UP OF THE RESTORED ANCIENT NORTH WALL SCHEME FOR THE MACEDONIAN PALACE AT VERGINA - GREECE.

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Abstract. *This paper presents summary results from a numerical study that examined the dynamic behaviour of a mock-up of the proposed retaining wall scheme aimed at supporting the North ancient wall of the Macedonian Palace at Vergina, Greece. Part of this retaining wall scheme represents the ruined ancient wall that will be restored. This wall will have at its base those monoliths of the ancient that survive in good condition so that can be used again. For the rest of the wall new monoliths will be used which will be constructed in-situ for this purpose. The restored wall will be partly supported by an additional wall to be built at its back which will also support the ruins of the Macedonian palace. The restored ancient defense wall will be connected at its back with special ties to the rest of the retaining wall scheme. The stability of the restored ancient wall is examined through a mock-up that simulates the geometric non-linearities from the sliding and rocking of the monoliths as well as those from the special ties. The friction characteristics between the new prototype monoliths were investigated experimentally at the laboratory.*

1 INTRODUCTION

Ancient Greek and Roman walls are usually composed of large heavy members (monoliths) that simply lie on top of each other in an almost perfect-fit construction without the use of connecting mortar (figures 1 and 2). In this way they are distinctly different from other types of fortifications that use connecting mortar and different type of masonry construction. This type of dry stone masonry is also used as part of the typical structural form of ancient Greek or Roman temples of the peripteral form. The columns and the dry stone masonry are connected at the top with the epistyle (entablature), also composed of monolithic orthogonal marble blocks, spanning the distance the columns and the stone masonry wall (figure 3). The earthquake response of free standing columns has been researched by the first author ([5 to 18]) in the past as well as by other researchers ([1 to 4] and [19 to 27]). This paper focuses on the response of square monoliths that lie on top of each other without connecting mortar at their contact horizontal surfaces, as it is typical in the mentioned before dry stone masonry construction.

Figure 1. Greek ancient walls at the ancient Palace of Tyrins, Greece.

Figure 2a. Mycenae, Greece, Outer wall

Figure 2b. Part of the Hadrian wall, North of England

Figure 3. The Erectheum, at the Acropolis of Athens.

The seismic response mechanisms that develop on this solid block structural system during strong ground motions can include sliding and rocking of the various monoliths, thus dissipating the seismic energy in a different way from that of other forms of masonry. This paper presents results and conclusions from an experimental study that examines the dynamic response of such prismatic stone formations. Towards this objective the dynamic response of a simple dry stone masonry assembly that is composed by five (5) stones is studied. This stone dry-masonry assembly is simply supported on the bottom of the first block (figure 4). It is then subjected to various types of horizontal base motions (including sinusoidal as well as earthquake base motions), reproduced by the Earthquake Simulator Facility of Aristotle University, as will be described in section 3.

This study is partially linked with the North ancient walls of the Macedonian Palace of Vergina, Greece. At present, these walls are in a state of ruin; however, the restoration of these walls in their original formation is planned together with similar repair and restoration works for the Macedonian Palace itself. The restoration of the walls will utilize only those original monoliths that are in sound condition (figure 4). However, because such ancient monoliths are in small numbers the construction of new monoliths, having the same dimensions as the ancient ones is planned.

a) View along the base of the North wall at the Vergina Macedonian Palace with the few remaining monoliths

Figure 4. The remains of the stone monoliths of the ancient North wall of the Macedonian Palace at Vergina Greece.

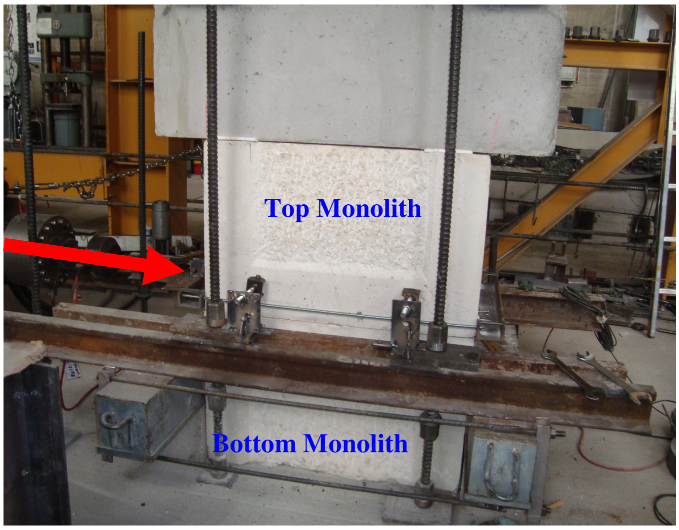
Figure 5a. Detail of the horizontal contact surface of the new monoliths

Figure 5b. Arranging two monoliths on top of each other at the laboratory of Strength of Materials and Structure at Aristotle University

Such monoliths are shown in figures 5a and 5b as part of an experimental investigation that was conducted at the laboratory of Strength of Materials and structures of Aristotle University having as an objective to determine the coefficient of friction between these monoliths, as is reported in the next section. These monoliths were constructed in-situ at the archaeological site of Vergina-Greece and were transported at the premises of the laboratory at Aristotle University. Prior to this, an experimental investigation was also conducted in order to determine the compressive strength of the ancient monoliths as well as the new monoliths in comparison. However, these results are not reported here.

2 STUDY OF FRICTION BETWEEN THE NEW MONOLITHS

In this section summary results are presented as obtained from the study that was performed in order to determine the coefficient of friction between the new monoliths that will be part of the restored ancient North wall of the Macedonian Palace at Vergina, Greece.



a) Friction-sliding testing arrangement

b) Added dead load on top of the tested monoliths

Figure 6. Friction of the new monoliths at the laboratory

The loading arrangement for these tests is shown in figure 6. One monolith (bottom monolith, figure 6a) is attached on the strong reaction floor of the testing rig in a way that it cannot slide whereas the other monolith (top monolith, figure 6a) is simply supported on the bottom monolith in a way that it can slide on this contact surface when a horizontal force is applied very close to this contact surface. In order to permit the sliding displacement between the two monoliths only in the direction of the applied horizontal force and prohibit any other rigid motion between the monoliths a set of two roller sliders were placed at either side of the top monolith as shown in figure 6b. Moreover, in order to study the influence of the amplitude of the dead load acting at a normal direction to the horizontal contact surface a number of concrete and steel blocks were placed above the top monolith for this purpose, as shown in figure 6b. Instrumentation was provided to measure the applied horizontal force as well as the horizontal displacement that would develop at the contact interface between these two monoliths. Two displacement transducers were placed at either side of the monoliths in order to measure the sliding displacement at the interface. Moreover, apart from the load cell measuring the horizontal displacement the normal stress acting on the contact interface was obtained by dividing the weight of all the objects (top monolith as well as the concrete and steel blocks) placed above the top monolith by the area of the contact surface. This weight was varied in such a manner that it results in normal to the contact surface stress amplitudes varying in the following way:

$\boldsymbol{\sigma}_n$ = 0.0126MPa, 0.0265MPa, 0.047MPa, 0.0686MPa and 0.0831Mpa

The sliding displacement was imposed gradually in the following way, shown in figure 7. For a given dead weight (in this case 35.32KN) the horizontal force was applied gradually that initially caused no sliding displacement. Next the horizontal force was increased and a sliding displacement of small amplitude was observed. The load/displacement was imposed in a cyclic seismic-type manner, as shown in figure 7 with a frequency of 0.10Hz. Next, the imposed sliding displacement was further increased in amplitude.

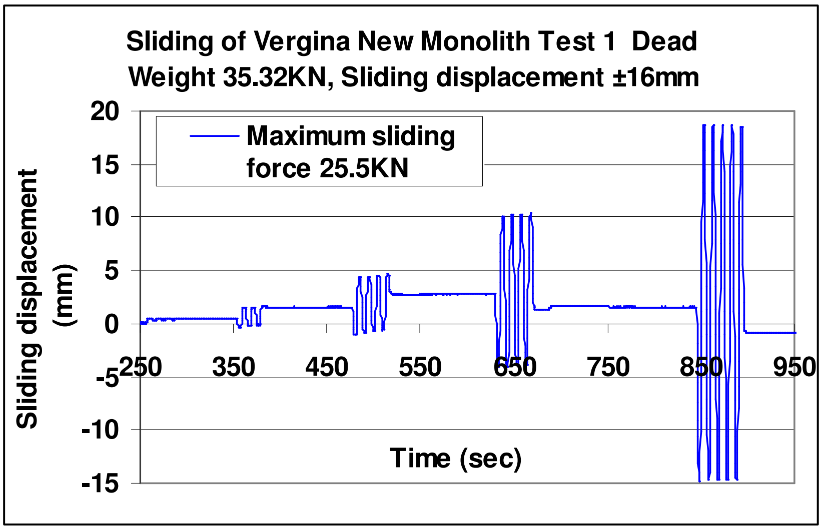


Figure 7. Time history of imposed load/sliding displacement

The last group of imposed load/displacement cycles reached an average maximum sliding displacement amplitude of ±16mm, as shown in figure 7. The obtained sliding response in terms of imposed horizontal load and resulting sliding displacement is depicted in figure 8.

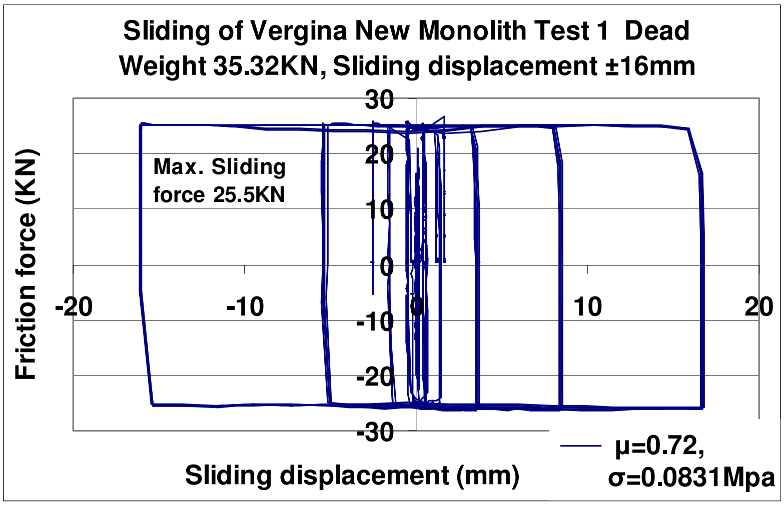


Figure 8. Cyclic friction load / sliding displacement cyclic response obtained for the Vergina new monoliths.

As can be seen in figure 8, the cyclic sliding response of the two monoliths is stable resulting in a dynamic coefficient of friction equal to μ= 0.72. This value of the friction coefficient remained almost constant for all the range of normal stress amplitudes that were tried during this experimental sequence, as already mentioned before.

3 PERFORMANCE OF THE STONE DRY-MASONRY ASSEMBLY UNDER HORIZONTAL BASE MOTIONS

In what follows, summary results from the dynamic performance of the dry-masonry five-stone assembly, mentioned in the introduction, will be presented. Two basic configurations are examined here; the first is that these stones are free to rock and slide till they become geometrically unstable and collapse. In the second configuration a practically non-deformable structure (steel beam) is built at the back of the stone formation that extends to the same height as the stone assembly. Whereas in the first structural formation the stone assembly and the steel beam are not connected in the second structural formation the upper three stones are connected with the steel beam with a system of flexible ties that can develop tensile and compressive forces of certain limited amplitude.

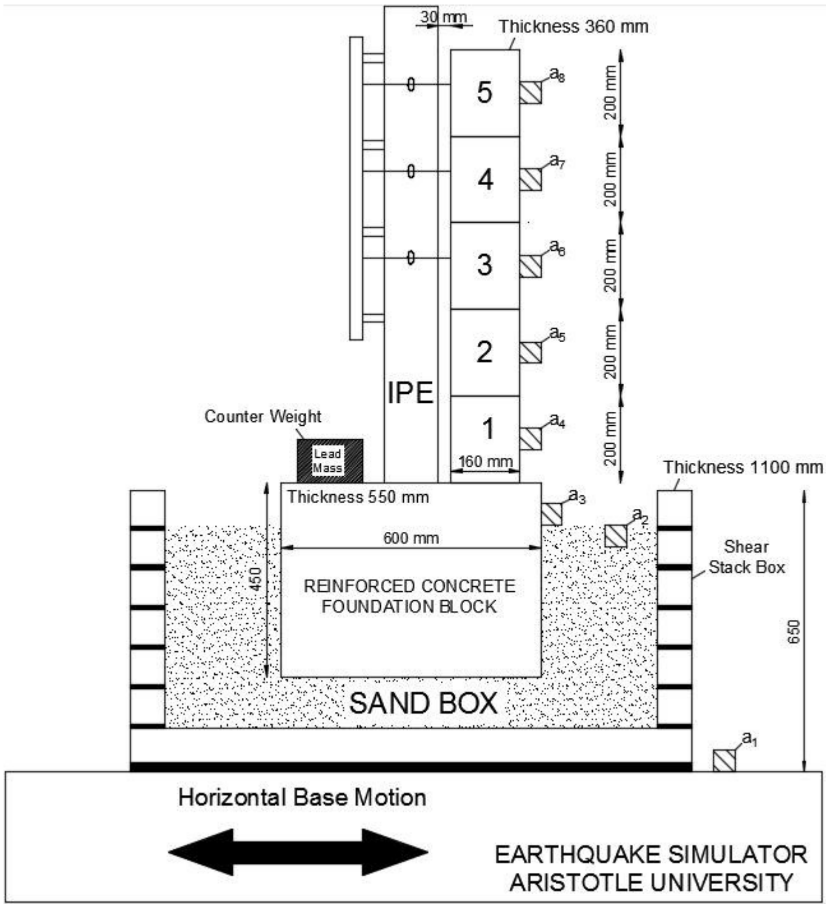


Figure 9. Testing arrangement of the five stone dry-masonry assembly

The used testing arrangement is depicted in figure 9. A shear stack aluminum box filled with dry sand was rigidly secured on top of the earthquake simulator steel platform (shaking table). This box was hosted the foundation block of the five-stone dry masonry assembly as shown in figure 9. This foundation block was partially embedded within the sand and also carried, apart from the five-stone assembly, a counter weight lead mass rigidly fixed on the foundation block as well as a steel beam to be used to partially support the five-stone assembly with horizontal links, as indicated in this figure. This is also shown in figure 10. This testing arrangement was utilized in order to portray up to a point foundation conditions for the five-stone assembly that could be claimed to represent more realistically the in-situ soil-foundation conditions of the ancient wall monoliths. A number of acceleration sensors were rigidly attached on each of the five stones as well as on the foundation block. Moreover, additional acceleration sensors were also placed near the surface of the sand box as well as on the steel platform of the shaking table. These sensors are indicated in figure 9 from a1 to a8 and are also depicted in figure 10.

Figure 10. Testing arrangement of the five stone dry-masonry assembly

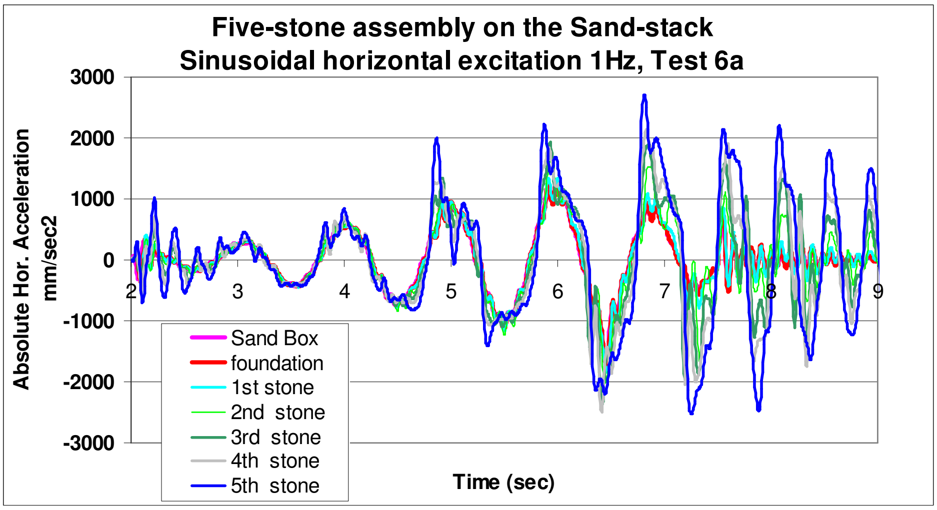


Figure 11. Acceleration response along the height of the unattached five-stone assembly 0.165g, Test 6a.

3.1 Obtained results from sinusoidal tests with the unattached five-stone assembly

In what follows, summary results will be presented from the dynamic tests of the five-stone assembly when it was excited with sinusoidal horizontal base motions being unattached from the steel beam. A number of such dynamic tests were carried out keeping the frequency of the excitation constant (1.0Hz) and gradually increasing the amplitude of the base motion from test to test. Results from two tests will be shown here. Small rocking could be measured when the maximum horizontal base acceleration reached during a test the value of 0.15g, where g the acceleration of gravity. During the next test (Test 6a), despite the observed relative large amplitude of the base motion, the five-stone assembly did not develop any form of large rocking or sliding displacements leading to instability. The acceleration response along the height of the five-stone assembly is depicted in figure 11. As can be seen in this figure, for a peak base acceleration equal to 0.165g the fifth (top) stone develops a peak acceleration of approximately 0.27g

During the next test (Test 7a) with larger base excitation than Test 6a (0.173g), the five-stone assembly developed large rocking displacement response as shown in figure 12. In addition, sliding between the various stones at their contact interface became also noticeable as depicted in figure 13.

Figure 12. Large rocking displacement response of the unattached five stone dry-masonry assembly, being unattached from the steel beam

Figure 13. Sliding between stone-blocks at the contact interface of the unattached five-stone assembly

The acceleration response along the height of the five-stone assembly for Test 7a is depicted in figure 14. As can be seen in this figure, for a peak base acceleration equal to 0.173g the fifth (top) stone develops a peak acceleration of approximately 0.68g. It was observed in the past during the experimental sequences with columns having drums that for a given frequency of excitation there is a boundary between the stable rocking response and the overturning. This boundary has relatively high values of non-dimensional excitation amplitude for high frequency values and relatively low values of non-dimensional excitation amplitude for low frequency values.

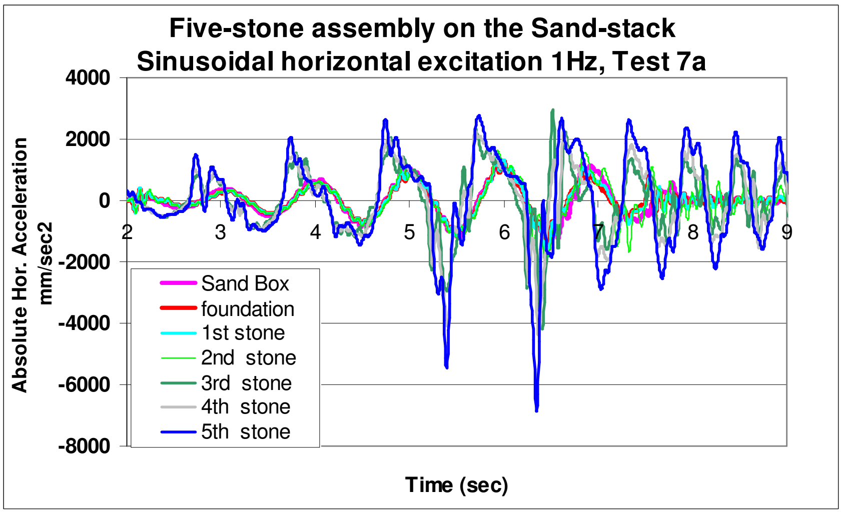


Figure 14. Acceleration response along the height of the unattached five-stone assembly (peak base horizontal acceleration 0.173g, Test 7a)

3.2 Obtained results from sinusoidal tests with the attached five-stone assembly

Again, summary results will be presented from the dynamic tests of the five-stone assembly when it was excited with sinusoidal horizontal base motions. However, the vive-stone assembly is being now attached from the steel beam with relatively weak steel wires. A number of such dynamic tests were carried out keeping again the frequency of the excitation constant (equal to 2.0Hz) and gradually increasing the amplitude of the base motion from test to test. Results from two tests will be shown here. Small rocking could be measured when the maximum horizontal base acceleration reached during a test the value of 0.2g, where g the acceleration of gravity.

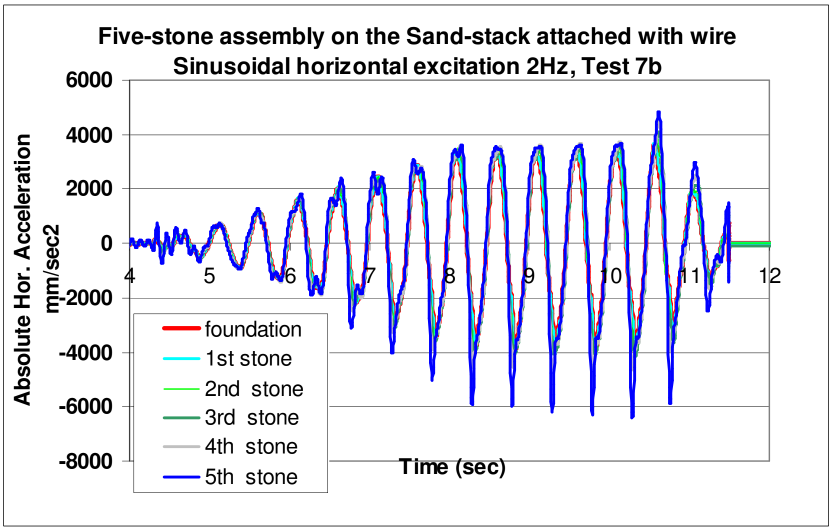


Figure 15. Acceleration response along the height of the attached five-stone assembly (peak base horizontal acceleration 0.4g, Test 7b)

During the next tests, despite the observed relative large amplitude of the base motion, the five-stone assembly did not develop any form of unstable rocking or excessive sliding displacements leading to instability. The acceleration response along the height of the five-stone assembly is depicted in figure 15 for test 7b. As can be seen in this figure, for a peak base acceleration equal to 0.4g the fifth (top) stone develops a peak acceleration of approximately 0.64g, responding in a stable rocking mode. However, during the next test (Test 8b) the five-stone assembly developed unstable rocking response that was accompanied with the fracture of the wire links as is depicted in figure 16. The maximum acceleration measured at the top stone was in excess of 0.7g, as can be seen in figure 17 where the acceleration response along the height of the five-stone assembly is depicted.

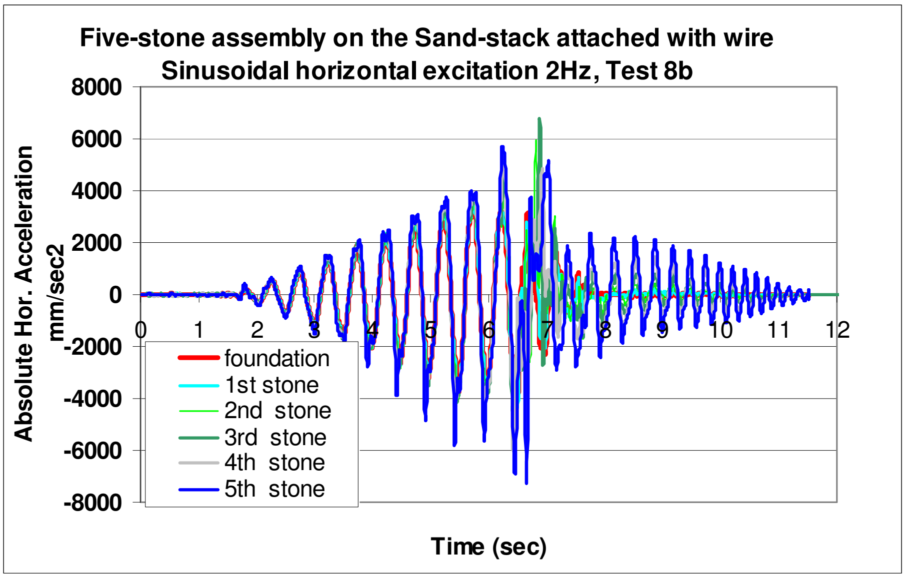


Figure 17. Acceleration response along the height of the attached five-stone assembly (peak base horizontal acceleration 0.4g, Test 8b)

As can be seen by comparing the measured acceleration response in figures 11 and 14 for the unattached mock-up five-stone assembly with the measured acceleration response of the same mock-up being this time attached with steel wire links with a supporting structure (figure 15 and 17), the stability of the rocking response was retained for much larger base acceleration amplitudes when the steel links were present.

4 CONCLUSIONS

- The value of 0.72 was found as friction coefficient for the new monoliths to be used for the restoration of the North wall of the Macedonian Palace at Vergina, Greece.
- The mock-up of a five stone dry masonry assembly developed stable rocking and unstable rocking dynamic response that was combined with sliding at the contact interfaces.
- This stable-unstable rocking response of the mock-up of a five stone dry masonry assembly resembles similar behaviour that was observed for the response of mock-ups of ancient free standing columns with drums.
- Steel wire links with limited tensile capacity can have, up to a point, beneficial influence on this stable-unstable rocking response of such type stone dry masonry. The stability of the rocking response was retained for much larger base acceleration amplitudes when the steel links were present than when the used mock-up of the five-stone assembly was unattached.
- In this case a supporting structure must also be properly designed to be used as support system for such links.

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REFERENCES

[1] Ambraseys, N. and Psycharis, I. N. (2011) "Earthquake stability of columns and statues", Journal of Earthquake Engineering, Vol. 15, pp. 685-710.

[2] Aslam , M.M., et.all. 1978. Rocking and Overturning response of rigid bodies to earthquake motions, Report No. LBL-7539, L. B. Lab. Univ. Of California, Berkeley.

[3] Demosthenous M, 1994. Experimental and numerical study of the dynamic response of solid or sliced rigid bodies, Ph. D. Thesis, Dep. Civil Eng., Aristotle University.

[4] Koh, A.S. and Mustafa G. 1990. Free rocking of cylindrical structures, J. of Eng. Mechanics, Vol. 116, N0 1, pp.35-54.

[5] Manos, G. C. and Demosthenous, M., 1990. The behavior of solid or sliced rigid bodies when subjected to horizontal base motion. Proc. 4th U.S. Nat. Confer. Earth. Eng, Vol. 3, pp. 41-50.

[6] Manos G.C. and Demosthenous M. " Study of the dynamic response of models of ancient columns or colonnades subjected to horizontal base motions", 11WCEE, Session 6.3.3. of Abstract Volume Analysis of Masonry Structures, Acapulco, Mexico, 1996.

[7] Manos G.C. and Demosthenous M. “Models of ancient columns or colonnades subjected to horizontal base motions - study of their dynamic and earthquake behavior”, STREMA97, pp. 289-298, San Sebastian Spain.

[8] Manos G.C., “The dynamic performance of models of ancient columns and colonnades with and without the insertion of wires made of shape memory alloy”, STREMAH 99, pp. 281-290, Dresden, Germany, 1999.

[9] Manos, G.C., Demosthenous M., Hatzigeorgiou A., Manou-Evison J., “Study of the dynamic and earthquake behavior of models of ancient columns and colonnades with and without the inclusion of wires with energy dissipation characteristics”, 12th WCEE, Auckland, New Zealand, 2000.

[10] Manos, G.C., Demosthenous M., Kourtides, V., Hatzigeorgiou A., “The Dynamic and Earthquake Behavior of Ancient Columns and Colonnades with and without Shape Memory Alloy Devices”, STREMAH 2001, Florence, Italy, 2001.

[11] Manos G.C. et.al “Study of the Dynamic and Earthquake Behavior of Rigid Bodies with or without the Inclusion of Shape Memory Alloy Devices” , 16SMIRT, Washington D.C. 2001.

[12] Manos, G.C., Demosthenous M., Kourtides V., Hatzigeorgiou A, “Study of the dynamic and earthquake behavior of models of ancient columns and colonnades with and without the inclusion of wires with energy dissipation characteristics”, 9th Canadian Conference on Masonry Structures, Univ. New Braunswick, Canada, 2001.

[13] Manos, G.C., Demosthenous M., Kourtides V., “The Response of Models of Ancient Columns and Colonnades under Horizontal Forces with or without SMAD’s” 2o Int. Conf. “Studies in Ancient Structures” Constantinoupol, Turkey, 2001.

[14] Manos, G.C., Demosthenous M., Kourtides V., “The Dynamic and Earthquake Response of Models of Ancient Columns and Colonnades with and without Energy Dissipation Devices”, 12th European Earthquake Engineering Conference, London, England, 2002.

[15] Manos G.C., Koidis, George and Demosthenous Milton, “Investigation of the Sliding Response of a Rigid Body System to Uni-Direction Horizontal Dynamic and Earthquake Excitations”, COMPDYN 2011, Corfu, Greece, 26–28 May 2011.

[16] Manos G. C, Koidis G., Demosthenous M., “The Sliding Response of a Rigid Body System Subjected to Uni-Directional Horizontal Dynamic and Earthquake Excitations” EURODYN 2011, Leuven, Belgium, 4-6 July, 2011.

[17] Manos G. C, Koidis G., Demosthenous M., “The response of a two-degree-of-freedom dynamic sliding system subjected to uni-direction horizontal dynamic and seismic excitations”, Int. J. of Computational Methods and Experimental Measurements, Vol. 1, No. 3, pp.221-237, 2013.

[18] Manos G.C., Petalas A., Demosthenous M. “Numerical and experimental study of the rocking response of unachored body to horizontal base excitation”, 4th ECOMASS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering – COMPDYN 2013, 12-14 June 2013, Kos Island, Greece.

[19] Mouzakis, H., Psycharis, I. N., Papastamatiou, D. Y., Carydis, P. G., Papantonopoulos, C. and Zambas, C. (2002) "Experimental investigation of the earthquake response of a

model of a marble classical column", Earthquake Engineering and Structural Dynamics, Vol. 31, pp. 1681-1698.

[20] Mouzakis, H., Psycharis, I. N., Papastamatiou, D. Y., Carydis, P. G., Papantonopoulos, C. and Zambas, C. (2002) "Experimental investigation of the earthquake response of a model of a marble classical column", Earthquake Engineering and Structural Dynamics, Vol. 31, pp. 1681-1698.

[21] Psycharis Ioannis N. (2007) A Probe into the Seismic History of Athens, Greece from the Current State of a Classical Monument. Earthquake Spectra: May 2007, Vol. 23, No. 2, pp. 393-415

[22] Papantonopulos, C., Psycharis, I. N., Papastamatiou, D. Y., Lemos, J. V. and Mouzakis, H. (2002) "Numerical Prediction of the Earthquake Response of Classical Columns Using the Distinct Element Method", Earthquake Engineering and Structural Dynamics, Vol. 31, pp. 1699-1717.

[23] Ambraseys Nicholas, Psycharis Ioannis N., "Assessment of the long-term seismicity of Athens from two classical columns" Bulletin of Earthquake Engineering, December 2012, Volume 10, Issue 6, pp 1635-1666, Date: 13 Oct 2012

[24] Psycharis I. N., "Dynamic Behaviour of Rocking Two-Block Assemblies" (1990) Earthquake Engineering and Structural Dynamics, Vol. 19, pp. 555-575.

[25] Psycharis, I. N., Papastamatiou, D. Y. and Alexandris, A. (2000) "Parametric Investigation of the Stability of Classical Columns under Harmonic and Earthquake Excitations", Earthquake Engineering and Structural Dynamics, Vol. 29, pp. 1093-1109.

[26] Psycharis, I. N., Lemos, J. V., Papastamatiou, D. Y., Zambas, C. and Papantonopoulos, C. (2003) "Numerical Study of the Seismic Behaviour of a Part of the Parthenon Pronaos", Earthquake Engineering and Structural Dynamics, Vol.32, pp. 2063-2084.

[27] Spanos, P.D. and Koh A.S., 1984. Rocking of rigid blocks due to harmonic shaking. J. of Engin. Mech., ASCE 110 (11), pp. 1627-1642.