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Dynamic Response of Models Subjected to Horizontal Motions

Comportement dynamique de modèles soumis à des forces horizontales

Dynamisches Verhalten von Modellen unter horizontaler Anregung

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SUMMARY

This paper presents predominant modes of response shown by ancient monuments in Greece that can lead to damage during strong earthquakes. Observations from an experimental and analytical investigation of the seismic behaviour of model ancient columns are also presented, utilising the Earthquake Simulator of Aristotle Univ. of Thessaloniki.

RÉSUMÉ

Cette étude présente les modes de réaction prédominants de monuments de la Grèce antique, face à des tremblements de terre de grande intensité, pouvant conduire à des dommages. Des observations provenant d'une étude expérimentale et analytique du comportement séismique de modèles de colonnes anciennes sont aussi présentées. Ces observations sont basées sur l'utilisation du simulateur de tremblements de terre de l'Université Aristote de Thessalonique.

ZUSAMMENFASSUNG

In der vorliegenden Arbeit werden die wichtigsten Verhaltenscharakteristiken antiker Monumente in Griechenland gezeigt, die nach starken Erdbebenbeanspruchungen zu erheblichen Tragfähigkeitsverlusten führen können. Weiterhin werden Ergebnisse experimenteller Untersuchungen an charakteristischen antiken Säulen gezeigt, die in der Erdbebensimulationsanlage der Aristoteles-Universität Thessaloniki gewonnen worden sind. Diese Ergebnisse werden mit denjenigen numerischer Untersuchungen verglichen.

1. EARTHQUAKE DAMAGE TO ANCIENT MONUMENTS.

Ancient Greek and Roman type structures composed of large heavy members that simply lie on top of each other in a perfect fit construction without the use of connecting mortar type materials are distinctly different from relatively flexible contemporary structures. The material used for the formation of ancient columns was usually limestone or marble of an average bulk density 2.7 t/m^3. For rough contact surfaces peak values of the angle of static friction are approximately 35^0 to 40^0. However, drums were caused to revolve around a central pivot until, by the addition of sand inserted for the purpose, they rested, with no overlap whatsoever, on the drum beneath in which case the angle of static friction would have been reduced to about 28^0 to 35^0.
For the monuments of Ancient Greek or Roman type, discussed in this paper, an earthquake may bring about the damage or collapse of the relatively rigid, freestanding columns in one (or a combination) of the following ways:

1) By causing the column to slide off its base or at joints higher up between drums (fig. 1).
2) By setting the column to large amplitude rocking response resulting in overturning (fig. 2).
3) By progressively inducing excessive permanent tilting of its foundation (fig. 3).
4) By causing drums of weak or damaged stone material to fail in compression.

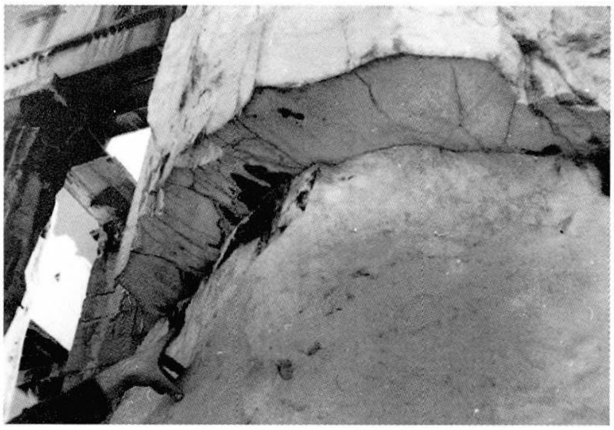


Fig. 1 Drums showing a sliding response.

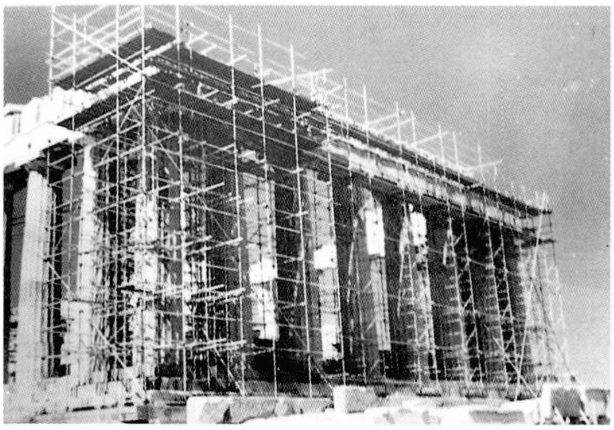


Fig. 3 The NE side of Parthenon after the EQ of 1981.

Fig. 2 Overturned monolithic column.

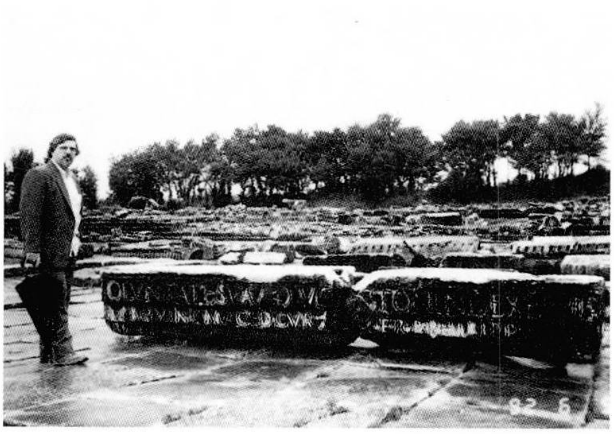


Fig. 4 The ancient city of Philippi, Macedonia - Greece.

Apart from the partial damage resulting from the earthquake response of the main supporting elements (columns or colonnades) listed above, the cumulative damage of such elements in large numbers led to the partial or total destruction of urban centers which had structural forms of this type. The destruction of cities, reported by ancient historians due to strong earthquake motions such as the ancient city of Sparti (464 B.C.), the city of Eliki (373 B.C.) , the city of Philippi at Macedonia in Greece (597 A.D.) (fig. 4) [1] can be seen as happening in the way described above.

The scientific and engineering achievements of this century have also been spreading slowly to the field of the seismic response of historical monuments due to the necessity of repair and preservation of these cultural landmarks for human civilization. The inherent structural complexity and the variability of building and foundation materials, makes each historical monument a unique case for study requiring special consideration. Because of this, rational proposals for the repair of such monuments need special attention and utilisation of the most advanced techniques in the field of engineering, and in depth knowledge of certain aspects of earthquake engineering in particular. The experimental investigation discussed in what follows, which employs advanced dynamic excitation techniques and measurement media, can be classified as one of the advanced tools available today in the engineering community. The results of such an investigation can be utilised in the repair effort of ancient monuments of the Greek and Roman type shown in the photographs of this paper.

2. AN EXPERIMENTAL INVESTIGATION INTO THE EARTHQUAKE RESPONSE OF MODELS OF ANCIENT COLUMNS.

The seismic response mechanisms that develop on this solid-block structural system during strong ground motions can include sliding and rocking, thus dissipating the seismic energy in a different way from that of conventional contemporary buildings. The seismic behaviour of this type of structure (ancient Greek and Roman monuments) or of their components can be investigated by studying the earthquake response of solid or sliced rigid bodies during simulated base motions.

The present study deals with the dynamic response of three different geometries of solid or sliced rigid - block type bodies (fig. 5). The solid and sliced specimens are either square prisms, cylinders or truncate cones and are assumed to represent models of prototype structures 20 times larger. Two basic categories of practically non-deformable bodies were studied. The first one deals with whole solid bodies of certain geometry whereas the second category includes non-deformable bodies of the same geometry but this time these bodies are formed with slices that lie on top of each other without any connecting material. The tests performed include sinusoidal sweep tests within a chosen range of frequencies and amplitude as well as earthquake simulated tests using the El Centro 1940 record as will be explained below.

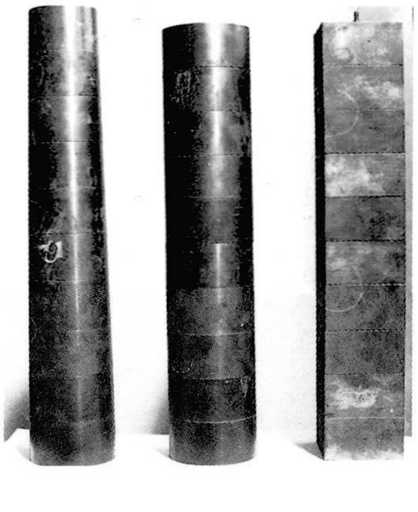
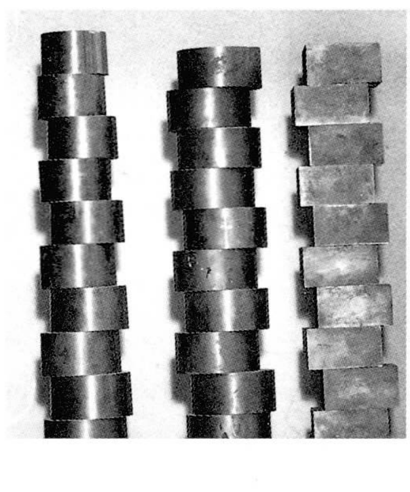


Fig. 5. Solid and sliced rigid bodies



The behaviour of solid-block structures supported on either rigid or flexible foundation, when subjected to earthquake ground motions, has been researched for quite sometime. Housner (1963) investigated the dynamics of a solid block on a rigid base, Aslam et.al. (1980) investigated the sliding and rocking response of solid rectangular concrete blocks on the earthquake simulator facility of the University of California at Berkeley, Priestley et.al. (1978) has dealt with the problem in a way that also included experiments with a shaking table. Yim et.al. (1984), Spanos et.al. (1984), Oppenheim et.al. (1986) and Koh et al. (1990) have also been investigating this problem treating it with various analytical approaches. Ishiyama has also studied this problem and among other things gives a comprehensive survey of the rigid-block research (1980).

2.1. Behaviour of solid bodies.

2.1.1 Preliminary free vibration test

Free vibration tests were performed for the solid specimens with the aim of assessing the coefficient of restitution of the test structures. Figures 6a, 6b and 6c depict with a solid line the rocking angle response for each specimen. Superimposed on each graph is a dashed line curve that corresponds to a predicted rocking response with a coefficient of restitution that gave the best fit to the experimental measurements.

The predicted rocking response was derived from the linearised equations of motion (Aslam et al. 1980). Whereas there is good correlation between predicted and observed rocking response for the prismatic specimen certain discrepancies are apparent at the initial large amplitude rocking stages for the cylindrical and conic specimens. As was also stated by Koh (1990) this must be attributed to 3-D rocking, since rocking in a perfect plane for a 3-D model requires exacting initial conditions and the slightest out of plane disturbance will cause rocking to be three dimensional.

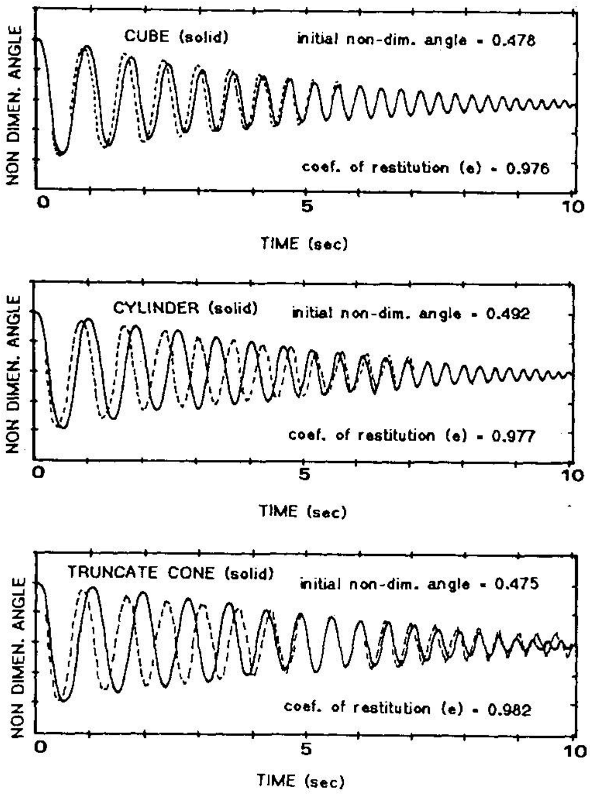


Fig. 6. Free vibration response

2.1.2 Sinusoidal tests for the solid specimens.

During these tests the frequency of motion was varied from 1Hz to 7Hz, in steps of 1Hz. This resulted in groups of tests with constant frequency for the horizontal sinusoidal motion for each test. In the various tests belonging to the same group of constant frequency, the amplitude of the excitation was varied progressively from test to test. The above stages are graphically portrayed in the plot of figure 7. The ordinates in this plot represent the non-dimensional amplitude of the base motion whereas the absiscae represent the non-dimensional frequency given by the following formulae :

$$A = x / (\theta * g), \quad \Omega = \omega / p, \quad p^2 = W\,Rc / Io \tag{1}$$

A = The non-dimensional base acceleration amplitude .
x = The actual horizontal peak acceleration of the sinusoidal motion.
θ = The critical angle that indicates overturning of the specimen (rads).
g = The gravitational acceleration
Ω = The non-dimensional frequency
ω = The actual sinusoidal frequency (Hz).
p = The natural rocking frequency of the specimen (Hz).
W = The weight of the Block
Rc = The distance of the center of gravity from the pole of rocking
Io = The mass moment of inertia of the block with respect to the pole of rocking

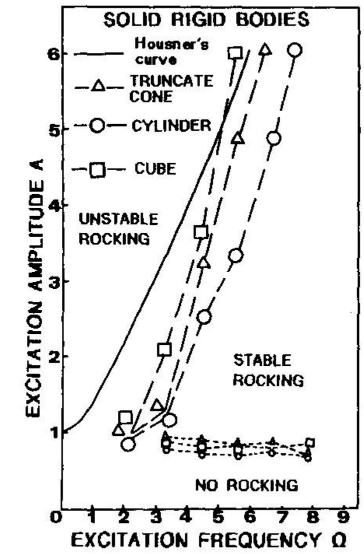


Fig. 7. Summary of sinusoidal tests for solids

The dotted lines in this plot represent the stage where rocking was initiated for the first time during the tests whereas the dashed lines represent the state of overturning of the specimen during the experimental sequence. The same figure depicts with a solid line the stable-unstable boundary of a solid block with properties the same as the ones used in the experiments, as predicted by Housner (1963), when this specimen is subjected to one half-cycle sine-wave. The following observations summarise the main points:

-For all specimens the initiation of rocking occurs for non-dimensional amplitude (A) almost equal to 1.0 for all examined frequencies.
-The non-dimensional unstable rocking amplitude increases rapidly with the non-dimensional frequency, which indicates greater stability of the solid blocks for higher frequencies.
-For small values of the non-dimensional frequency the transition range in terms of non-dimensional amplitude from no-rocking to overturning is very small and it occurs with a minor amplitude increase.
-The behaviour predicted by Housner (1963) overestimates the stability for all the used specimens, especially for small non-dimensional frequencies.

A further numerical analysis has been performed, aimed to simulate the dynamic response of the solid prism used in the experiments (cube), using the non-dimensional linear equations for sinusoidal excitation, as given by Spanos et al. (1984), and the coefficient of restitution, as evaluated from the free vibration tests. This analysis has been performed for various combinations of amplitude and frequency. Figure 8 presents these results in a summary form and as can be seen they exhibit fairly good agreement with the corresponding experimental measurements.

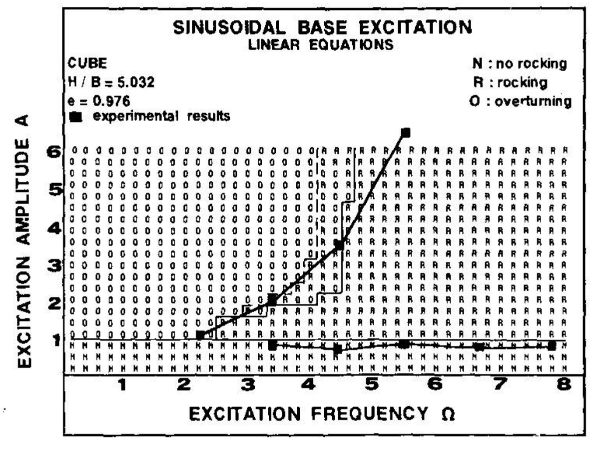


Fig. 8. Summary from numerical analysis

2.1.3. Simulated earthquake test for the solid specimens

A number of tests were performed, based on the 1940 El Centro earthquake record, with progressively increasing intensity. The base acceleration and displacement response was measured together with the rocking response of each specimen. The principal objective of these tests was to observe again the stable-unstable behaviour of the studied specimens, as shown in figure 9. The following points summarise the most important findings:

- During small intensity tests the solid blocks developed either slight rocking or no-rocking at all. In this case the maximum rocking angle is less than 30% of the critical angle.
- For peak base displacement between 10mm and 16.25mm the maximum rocking angle becomes approximately 60% of the critical.
- There was no considerable difference in the intensity of base motion during which all three specimens overturned [9].

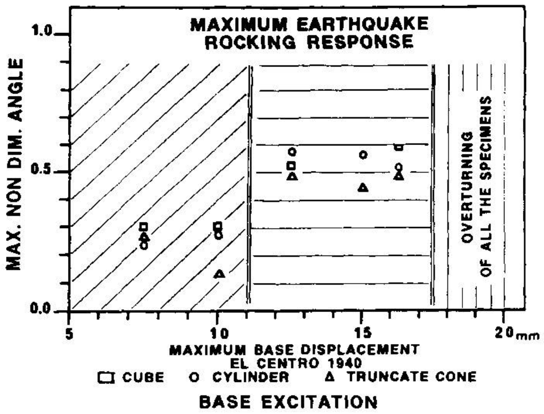


Fig. 9. Maximum earthquake rocking response

2.2. Behaviour of sliced specimens.

2.2.1 Sinusoidal tests with the sliced specimens

This sequence included similar tests with the ones performed for the solid specimens in order to assess the stable- unstable boundaries by studying the response with varying frequency and amplitude of the base motion. One important observation this time is that the response of all the sliced specimens for large amplitude excitations involved sliding as well as rocking in more than one slice contact-level. The overturning this time was caused by large sliding as well as rocking displacements. The measured stable-unstable boundary is depicted in figure 10 in terms of the same non-dimensional amplitude and frequency parameters that were used before and are based on the corresponding solid specimens as was already explained (Eq. 1).

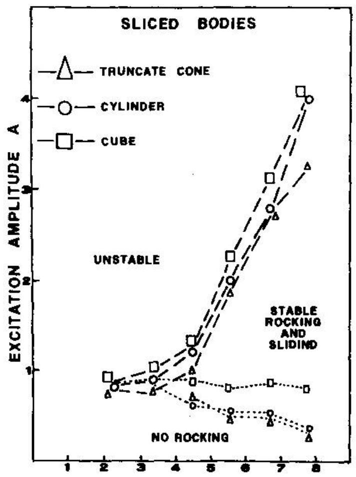


Fig 10. Summary of sinusoidal tests for sliced bodies

The following points can be made:

- From the comparison of the stable- unstable boundary between the solid and the sliced specimens of the same geometry (Figs. 7 and 10) it can be seen that all sliced specimens appear to be more unstable than the corresponding solid specimens.
- Because the sliding displacements are coupled this time with the rocking displacements the overturning or the sliding failure is also dependent on the maximum value of the relative sliding displacement that develops at its slice level as compared with the critical value that it can be allowed from the geometry of the specimen at the same level.

2.2.2. Acceleration response of the sliced specimens

In order to further investigate the response of the sliced specimens during the sinusoidal base motions the following tests were performed [11][12]; the results are presented below in non-dimensional form.

a) The first group of tests includes base motions where the non dimensional peak base acceleration was kept constant equal to 0.6 while the non-dimensional frequency was varied from 2.2 to 7.8 with steps of 1.117 for each test. For the cylindrical specimen the measured response for this series of tests is plotted in figure 11. The following points summarize the most important findings:

- For low non-dimensional frequency values the acceleration response of all the slices was in phase with that of the base motion and with the same amplitude, thus signifying no-rocking.

- For high non-dimensional frequency values, where sliding and rocking develops at many slices along the height, the acceleration response at the various slices is out of phase with that of the base and with amplified peak acceleration values as compared with the base acceleration response. The distribution of the peak acceleration along the height of the specimen changes significantly from that corresponding to low frequency values, thus reflecting the sliding and rocking response mechanisms that develop at the various contact surfaces.

b) The second group of tests included base motions where the non-dimensional excitation frequency was kept constant equal to 5.57 while, for the four tests performed for each specimen, the non-dimensional peak base acceleration took the values 0.45, 0.60, 0.75, 0.90 respectively. For the cylindrical specimen the measured response for this series of tests is plotted in figure 12. The following summarise the most important points:

- For relatively low values of peak base acceleration the slices of all the specimens responded in phase with that of the base motion. A no-rocking stage is indicated from the distribution of the acceleration response along the height.

-For relatively high non-dimensional values of the peak base acceleration the distribution of the peak acceleration changes, thus reflecting the sliding and the rocking response mechanisms involving more than one of the slices.

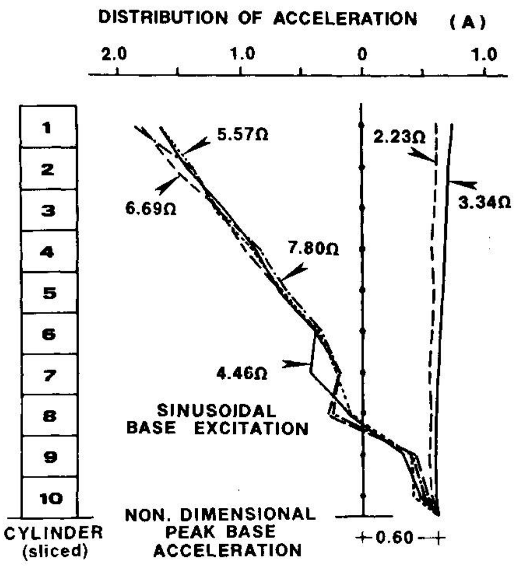


Fig. 11. Acceleration response of sliced bodies with constant base acceleration

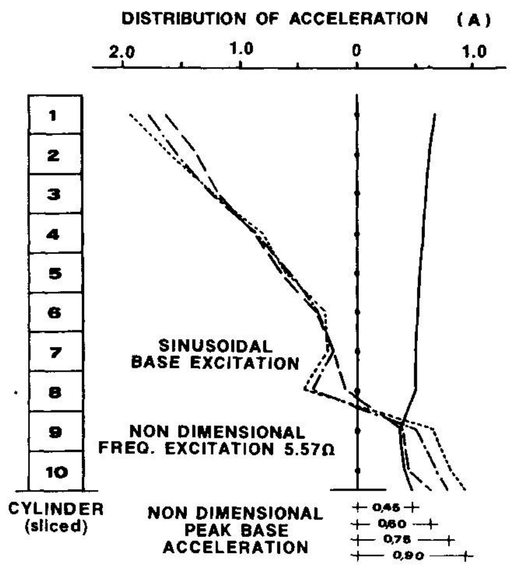


Fig. 12. Acceleration response of sliced bodies with constant base motion frequency

3. CONCLUSIONS

1. The coefficient of restitution can be defined with sufficient accuracy from the free vibration test results in combination with the performed numerical analysis, despite complications from the three dimensional rocking.

2. Similar stability behavior was observed for the three solid specimens of different geometry, as was assessed from the sinusoidal and the simulated earthquakes tests.

3. The numerically predicted upper-bounds for the stable-unstable rocking of the solid prismatic specimen, subjected to sinusoidal base motions, agrees well with the observed behaviour.

4. The stability of the sliced specimens during sinusoidal tests appears to be inferior to that of the solid specimens and it involves both sliding as well as rocking at various levels.

5. All solid as well as all sliced specimens responded out-of-plane of the excitation axis during large in-plane rocking and sliding amplitudes; naturally, this was more pronounced for the cylinder and the truncate cone specimens.

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