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The Earthquake Resistance of Ancient Columns: A Numerical Perspective Developed at the Classical Temple of Apollo Epikourios.

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Abstract

The temple of Apollo Epikourios at Bassai is considered as one of the most remarkable and best preserved ancient monuments; it is recognised as the most important monument of classical architecture after Parthenon. The earthquake resistance of the temple columns was examined using the Distinct Element Method (D.E.E.) for discontinuum modelling. The validation of the code is concerned with the rocking behaviour of a rectangular rigid body and comprises three parts: free vibration dynamics and the energy loss during impact, confirmation of the theoretical results on the rocking behaviour due to harmonic shaking and examination of the earthquake response using the Kalamata time history. The numerical analysis on intact sections of the temple showed substantial resistance to strong ground motions. However, imperfections typical of the present condition of the monument namely, reduced width of the base and initial tilt of the column, substantially reduce the stability threshold.

1 Introduction

The present damaged condition of the temple of Apollo Epikourios is well known: general deformation extending from the foundation to the architrave, settling of the stylobate, vertical and horizontal displacements of the colonnade, and an advanced stage of deterioration of the stone, which have produced considerable cracks, breaks, flaking, crumbling, etc. (Figure 1). In addition to the analytical approximation, the present work introduces a new numerical investigation procedure for the evaluation for the earthquake risk of the 37 Doric columns still standing .

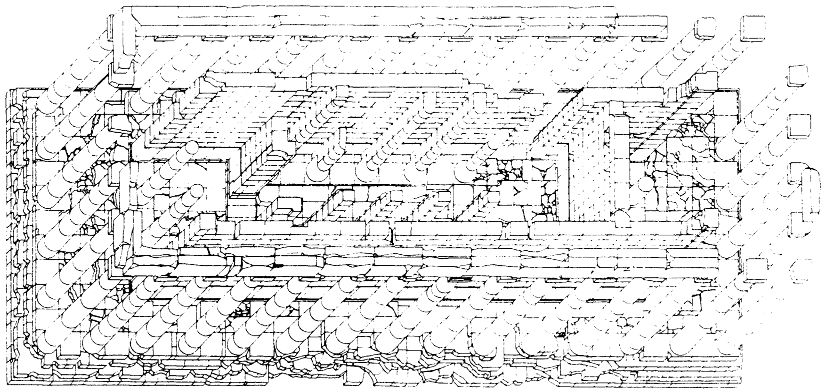

Figure 1: The Temple of Apollo Epikourios (present state condition)

The earthquake resistance of the columns was examined with the implementation of the Distinct Element Method (D.E.E.) for discontinuum modelling. The method uses an explicit time marching scheme to solve the equations of motion directly. The discontinuous medium is represented as an assemblage of rigid or deformable discrete blocks (drums); large deformations along discontinuities and rotations of blocks are allowed. The relative motion is governed by a non-linear force-displacement relation for movements in both the normal and shear directions. The code is based on a "Lagrangian" calculation scheme that is well-suited to model the large movements and deformations of a blocky system.

The Universal Distinct Element Code (UDEC) is a two-dimensional numerical program based on the Distinct Element Method; 3DEC is the three-dimensional version of UDEC. UDEC was developed over the last twenty years and has been extensively applied in problems involving fractured rock masses [1]. Both codes simulate the response of discontinuous media (such as a multidrum column) subjected to either static or dynamic loading. The discontinuities are treated as boundary conditions between blocks. The relative motion of the discontinuities is governed by linear or non-linear force-displacement relations for movement in both the normal and shear directions.

In performing dynamic analysis, proportional Rayleigh damping is typically used to damp the natural oscillation modes of the system. In dynamic finite element analysis the damping matrix is formed with components proportional to the mass and stiffness matrices.. In the computer runs presented below only the stiffness-proportional component of Rayleigh damping was used. For problems involving large movements of blocks, it is improper to use any significant mass damping, because the block motion might be artificially restricted.

2 Validation

The validation of the code is concerned with the rocking behaviour of a rectangular rigid body and comprises three parts:

1. The first part is dealing with the free vibration dynamics and the energy loss during impact.
2. The second part has confirmed in a qualitative way some of the theoretical results on the rocking behaviour due to harmonic shaking.
3. The earthquake response of the rigid block is examined in the third part, using the Kalamata time history.

2.1 Free Vibration

Motivated by the observations of damage to water tanks due to the 1960 Chilean earthquakes, Housner [2] was the first to investigate systematically the dynamics of a rigid block on a rigid horizontal base undergoing horizontal motion. Housner demonstrated that the period of free vibration is strongly and non-linearly dependent on the amplitude ratio; it increases from zero to infinity as the amplitude ratio increases from zero to one. In Figure 2 a comparison is made between UDEC results and the Housner theory for a block with an aspect ratio 1:4; the rocking period T/4 is computed against the normalized peak tilt angle for both cases.

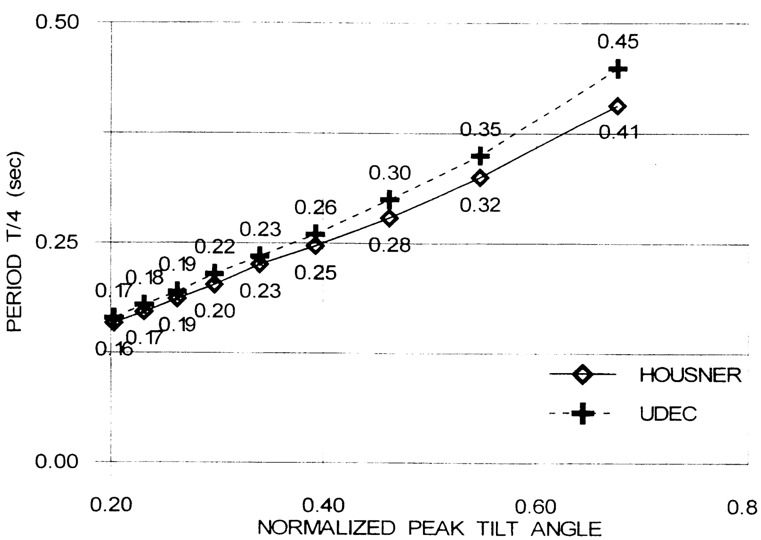

Figure 2: Free Vibration. Rocking Period.

Furthermore, by equating the momentum before and after impact, Housner showed that the kinetic energy reduction factor is related to the blocks' dimensions by the coefficient of restitution; it is independent of both the angular velocity before impact and the size of the block. This coefficient enabled Housner to predict the peak displacement after the n^{th} impact during the natural decay of rocking in terms of the initial displacement. This result is exactly valid for the idealized conditions of rigid block and rigid base, but only approximately valid if idealized conditions do not exist, since the kinetic energy loss depends on the materials of the block and the base. In Figure 3, the normalized peak tilt angle is computed against the number of impacts according to the Housner theory and the UDEC predictions. Although little work has been done in calibrating contact parameters, such as stiffness or damping coefficient, the correlation of the results between the two approaches is satisfactory, especially in the large amplitude area. Nevertheless, the general characteristics of the behaviour are determined; the amplitude decreases markedly with each impact and corresponding with this an increase in frequency of oscillation to an infinite value, is observed.

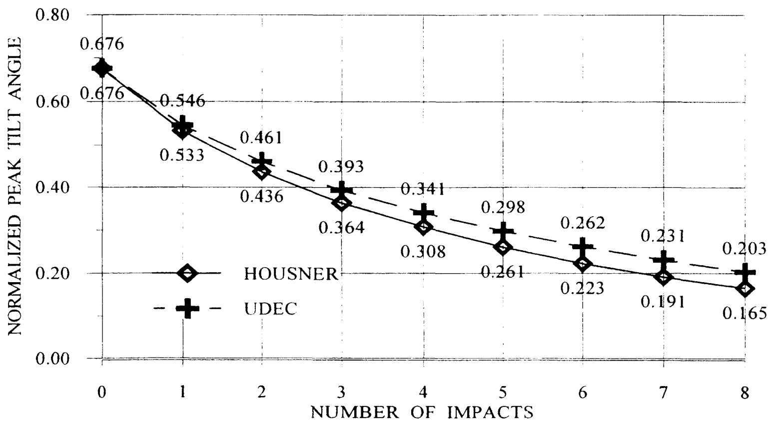

Figure 3: Free Vibration. Amplitude subsequent to n-th impact.

2.2 Harmonic excitation

A parametric study of the rocking response of the rigid block on a rigid plane subjected to horizontal sinusoidal acceleration of dimensionless normalized excitation amplitude (A) and frequency (f) was undertaken. It is well known (Spanos [3]), that the safe region expands towards the (A) direction as (f) increases, indicating that the block becomes increasingly robust against toppling as the excitation frequency increases. Using UDEC, the response of

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the rigid block to a sample of 15 sinusoidal excitations was determined; the results are plotted in Figure 4. From that Figure, where the peak tilt angle is indicated for various pairs (f, A), the following observations can be summarized:

a) Three regions in the amplitude vs. frequency plane can be determined: the 'no-uplift', 'safe' and 'unsafe' regions.
b) The non-dimensional unsafe rocking amplitude increases rapidly with the frequency, which indicates greater stability of the solid block for higher frequencies.
c) For small values of the frequency, the transition range in terms of amplitude from no-uplift to overturning, is very small and it occurs with a minor amplitude increase.

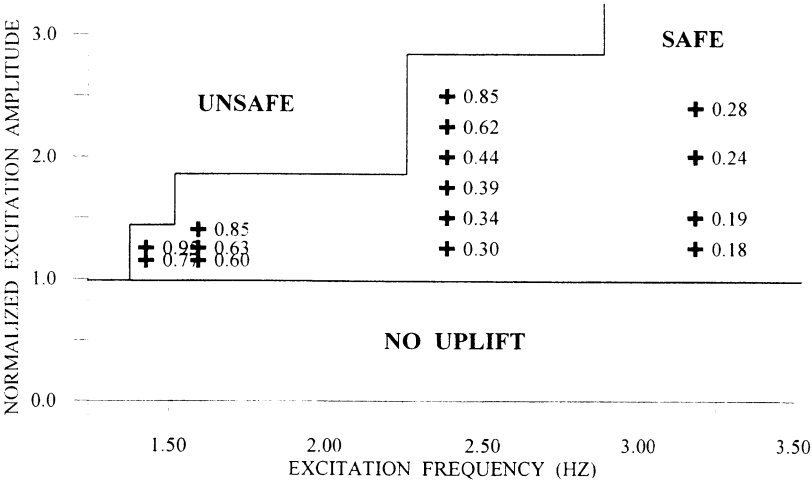

Figure 4: Harmonic Excitation. Response classification: Peak tilt angle.

2.3 Earthquake motion

In order to evaluate the code results for the earthquake response of a rigid body, a time domain step-by-step integration scheme was compiled. Input data for the program are Kalamata earthquake time history amplified by a factor of 5.0. The rocking response of a rigid body with an aspect ratio 1:6, to a prescribed ground acceleration is determined by numerically solving a pair of equations (positive or negative acceleration sign) with the condition for initiation of rocking and the impact condition by either the conservation of angular momentum or by a specified coefficient of restitution. The equations of motion were integrated numerically using the Runge-Kutta method with a time step equal to $\Delta t=0.001$ sec. The appropriate computer program was developed and several runs for different restitution coefficients (r=0.94, 0.96, 0.98) were executed. The time histories, in terms of the rotation angle, are plotted in Figure 5. It should be noted that, although the maximum value of rotation is identical in all cases, the decay of motion shows substantial differences for even slight changes of the restitution coefficient during impact. The decay of motion is sensitive to the coefficient of restitution but not in an apparently systematic way. This study reveals the sensitivity of the rocking behaviour to minor changes in the system parameters.

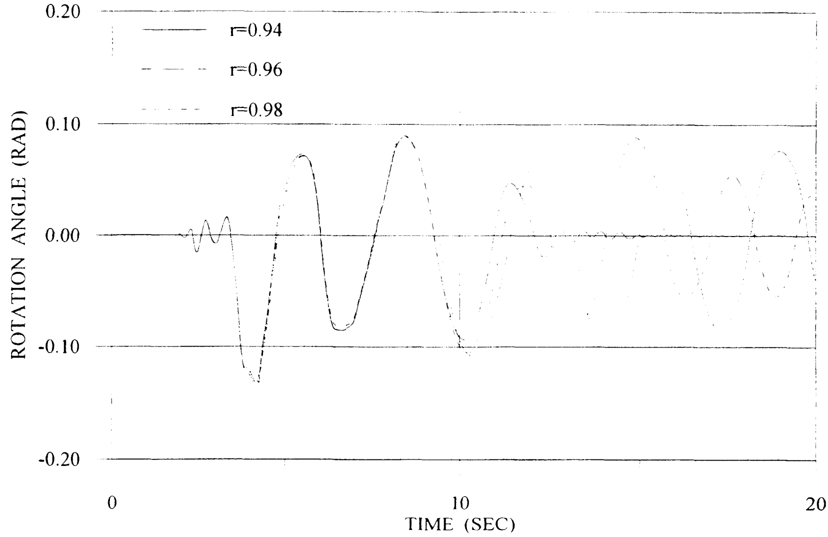

Figure 5: Rocking Block-Kalamata earthquake (HOUSNER).

Housner formulas assume the rocking behaviour of a rigid body on a rigid foundation. Psycharis and Jennings [4] presented a further analysis of the dynamic behaviour of a rocking rigid block supported by flexible foundations which permit uplift. The analysis was limited to two types of foundations: the continuous elastic foundation with viscous damping (the well-known Winkler method) and a two-spring foundation in which the structure is supported by two springs and dashpots placed symmetrically under the base. It is shown that an equivalence between these two models can be established, so that one may work using the much simpler two-spring foundation. Although the overall response of the system is non-linear, the equations of motion for the two-spring foundation can be linearized and solved analytically. On the basis of these considerations the same problem has been analysed using different spring stifnesses (k). The results are plotted in Figure 6. Evidently the trends

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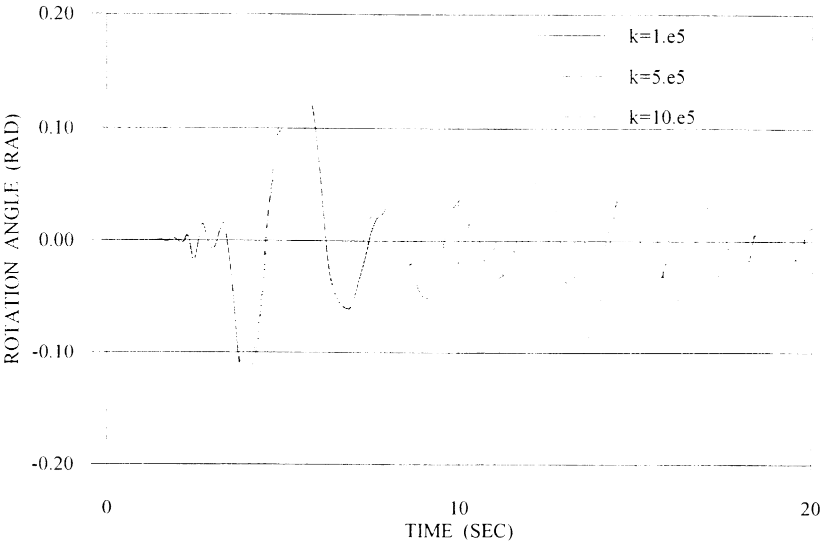

Figure 6: Rocking Block-Kalamata earthquake (2-SPRING MODEL).

observed in Housner model are also valid for the two-spring model; only the duration of the strong motion is substantially different: more than 6 seconds, according to the Housner theory, vs. 2-3 seconds for the two-spring model. UDEC results for different damping coefficients (d=0.03, 0.05, 0.07) are shown in Figure 7.

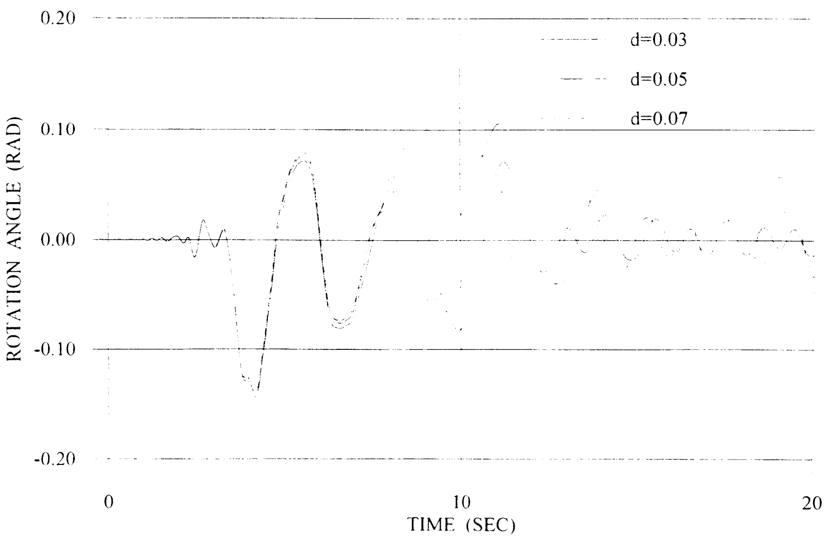

Figure 7: Rocking Block-Kalamata earthquake (UDEC).

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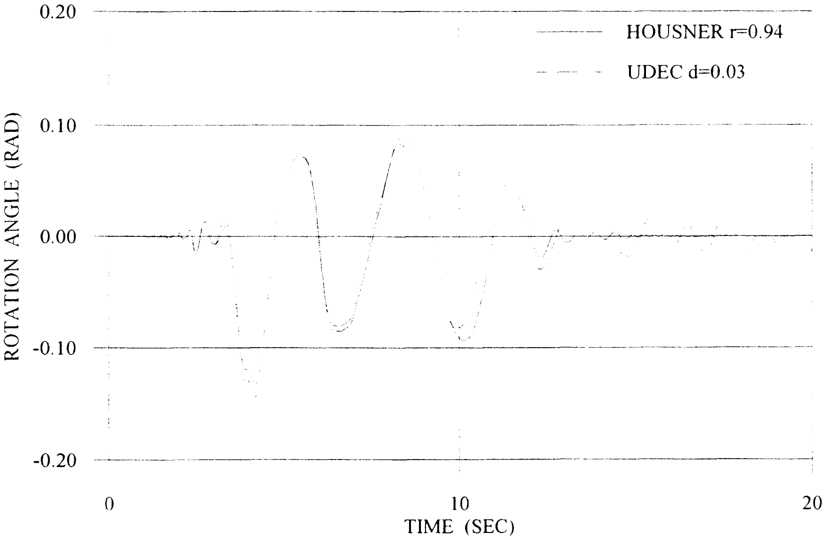

Figure 8: Rocking Block-Kalamata earthquake (HOUSNER-UDEC).

Again, the sensitivity of the response observed in the preceding theoretical models is confirmed; especially the agreement between UDEC results and the Housner theory is surprisingly good, (Figure 8) despite the sensitivity of the phenomenon. However, the parallel run of theoretical and numerical models so far has built-up confidence on the potential of the numerical model to predict the features of the earthquake response.

3 Columns Vulnerability

In order to evaluate the vulnerability of the columns, a parametric study of 3 columns of the temple with an ascending number of drums was performed. The seismic input used was the 1986 Kalamata earthquake (M_S=6.2), with peak horizontal and vertical accelerations 0.27g and 0.18g, respectively. The predominant period of the horizontal component was 0.30-0.35 sec. Table 1 summarizes the results, with multiplication factors ranging from 5.0 to 7.0. Several characteristic snapshots of the failure mechanism are included in Figure 9. It can be seen that all columns are stable with input multipliers up to 4; failing starts for higher excitations. As a rule, there is a range of input magnitudes for which the entire column, or at least several upper drums, may collapse or not. However, overturning by a ground motion of particular intensity does not imply that the column will necessarily overturn under the action of more intense ground motion. The analysis performed so far, shows that free-standing columns, when in good condition, are capable of withstanding large seismic motions with the characteristics of the Kalamata earthquake.

Table 1: Kalamata earthquake-Columns response (u: peak displacement)

Earthquake Multiplier	Column N2 (5 drums)	Column A9 (7 drums)	Column D2 (10 drums)
5.0	failed	stable (u=0.38m)	stable (u=0.53m)
5.5	stable (u=0.65m)	stable (u=0.35m)	5 drums failed
6.0	4 drums failed	stable (u=0.55m)	stable (u=0.65m)
6.5	2 drums failed	3 drums failed	stable (u=0.49m)
7.0	stable (u=0.48m)	5 drums failed	7 drums failed

The existing columns display some important imperfections, typical of the present condition of the monument. Due to the considerable settlement of the foundation, the columns have tilted away from the vertical position; in 16 cases the tilt angle is more than 0.02 rad. On the other hand, the foundation members show serious breakages, which have resulted in reduced contact area at the bases; in 8 columns the lost contact area is more than 25%. In order to evaluate the seismic risk for these cases, an initial tilt angle of 0.026 rad or a 30% reduction of the base area have been taken into account (Chlimintzas [5]). The seismic input used was the 1995 Aigion earthquake (M_S=6.1), with peak horizontal and vertical accelerations 0.42g and 0.19g, respectively. The predominant period of the horizontal component was 0.50-0.55 sec. Table 2 summarizes the results, with multiplication factors ranging from 1.0 to 3.0.

Table 2: Aigion earthquake-Column with imperfections (u: peak displacement)

Earthquake Multiplier	Intact Column	Initial tilt	Reduced Base
1.0	stable (u=0.20m)	stable (u=0.28m)	failure
2.0	stable (u=0.57m)	failure	failure
3.0	stable (u=0.73m)	failure	failure

It is evident, in order to enable the monument to withstand earthquakes, two major measures can be taken, namely reverting the leaning columns to their initial vertical position and restoring the original base area. These interventions will restore the initial geometric configuration and will also improve the earthquake resistance by means of the rocking behaviour, which constitutes the traditional energy absorption mechanism.

References

1. Cundall, P.A. A Computer Model for Simulating Progressive Large Scale Movements in Blocky Rock Systems, vol. 1, paper No. II-8, *Proceedings of the Symp. of the Intern. Soc. of Rock Mechanics*, Nancy, 1971.
2. Housner, G.W. The Behavior of Inverted Pendulum Structures During Earthquakes, *Bulletin of the Seismological Society of America*, 1963, **53(2)**, 404-417.
3. Spanos, P.D. & Koh, A.S. Rocking of Rigid Blocks Due to Harmonic Shaking, *Journal of Engineering Mechanics ASCE*, 1984, **110**, 1627-1642.
4. Psycharis, I.N. & Jennings,P.C. Rocking of Slender Rigid Bodies Allowed to Uplift, *Earthquake Engineering and Structural Dynamics*, 1983, **11**, 57-76.
5. Chlimintzas, G. (greek) *Application of the Distinct Element Method in the Dynamic Analysis of Classical Temples*, Diploma Thesis, Laboratory for Earthquake Engineering, National Technical University, Athens.

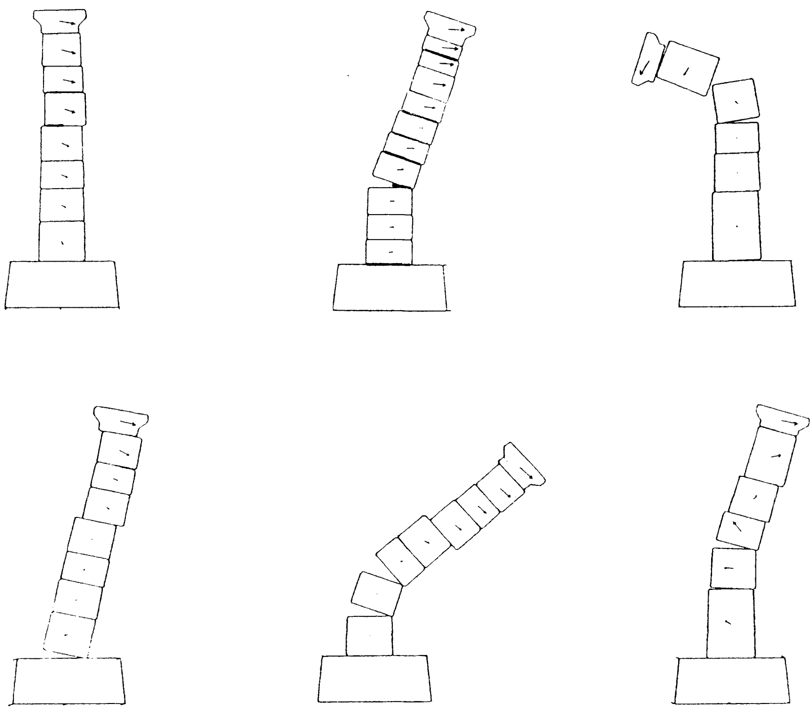

Figure 9: Snapshots from the numerical analysis (UDEC).