The research project is supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the “3rd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers” (Project Number: 7340).

REAL SCALE SHAKING TABLE TESTS FOR THE INVESTIGATION OF THE INFLUENCE OF THE USE OF VERTICAL CONNECTORS BETWEEN THE DRUMS IN COLUMNS AND COLONNADES

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Experimental Programme

In the framework of Workpackage 4, entitled "Shaking Table experimental testing", the following tests were carried out:

• Tests on three free-standing columns in scale 1:1, without connectors;
• Test on subassembly, consisting of three columns without connectors. The columns are positioned to form a corner, with the use of two epistyles-beams;
• Tests on three free-standing columns in scale 1:1, with connectors between the successive drums, and between the base and the first drum;
• Test on subassembly, consisting of three columns with connectors between the successive drums, and between the base and the first drum. The columns are positioned to form a corner, with the use of two epistyles-beams.

The abovementioned tests are performed in order to:

- ➢ Study the seismic behaviour of columns without connectors between the consecutive drums
- ➢ Study the seismic behaviour of columns with connectors between the consecutive drums, and compare their behaviour with that of the columns without connectors
- ➢ Acquire information on whether the seismic behaviour of colonnades is improved (as compared to that of single columns).
- ➢ Get information for the calibration of the models in Work Package 5.

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Selection of the monument

- ✓ Common characteristics of columns with vertical connectors: (a) Common construction period, after the Classical Era; (b) Slenderness ratio of the drums greater than 1.0, or columns of very large total height (in the order of or larger than 10.0m) → large drum diameter, divided in multiple drums (possibly because of practical difficulties, large stone volume).
- ✓ Vertical connectors between consecutive drums: usually two (2), in the ends of the same diameter.
- ✓ Effect of interfaces, reinforced with vertical connectors: realistic shaking table tests and modelling of the columns, continuously interacting within the research programme.
- ✓ Purpose of the programme: reach reliable experimental results, calibrated numerical models and rational simplifications, for application to restoration works.
- ✓ Design of the experimental programme → based on the documentation of the geometry of ancient connections. Selection of the Stadium in Ancient Messene. Limited dimensions of the columns: height 3.82m, base diameter 0.52m → testing of full-scale specimens.

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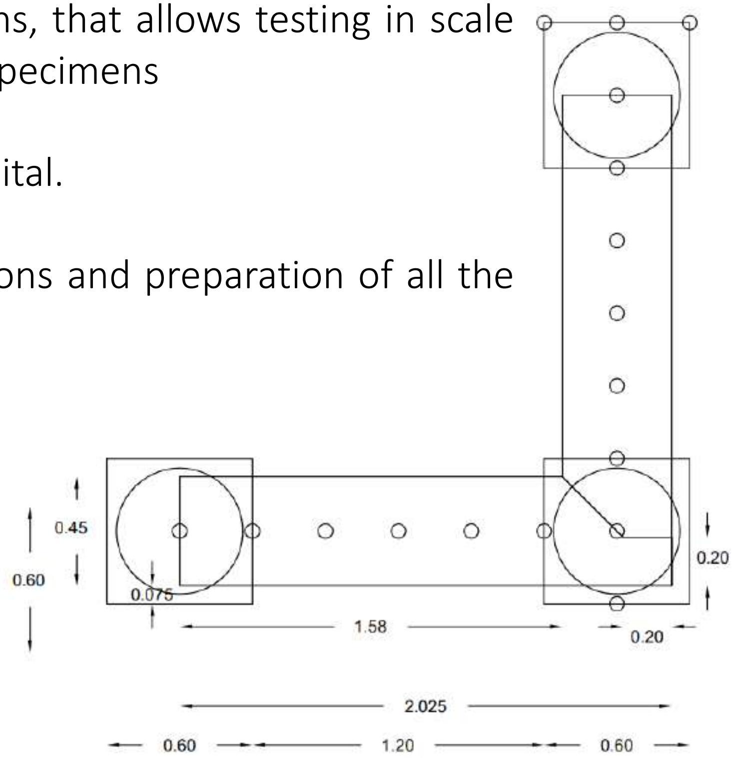
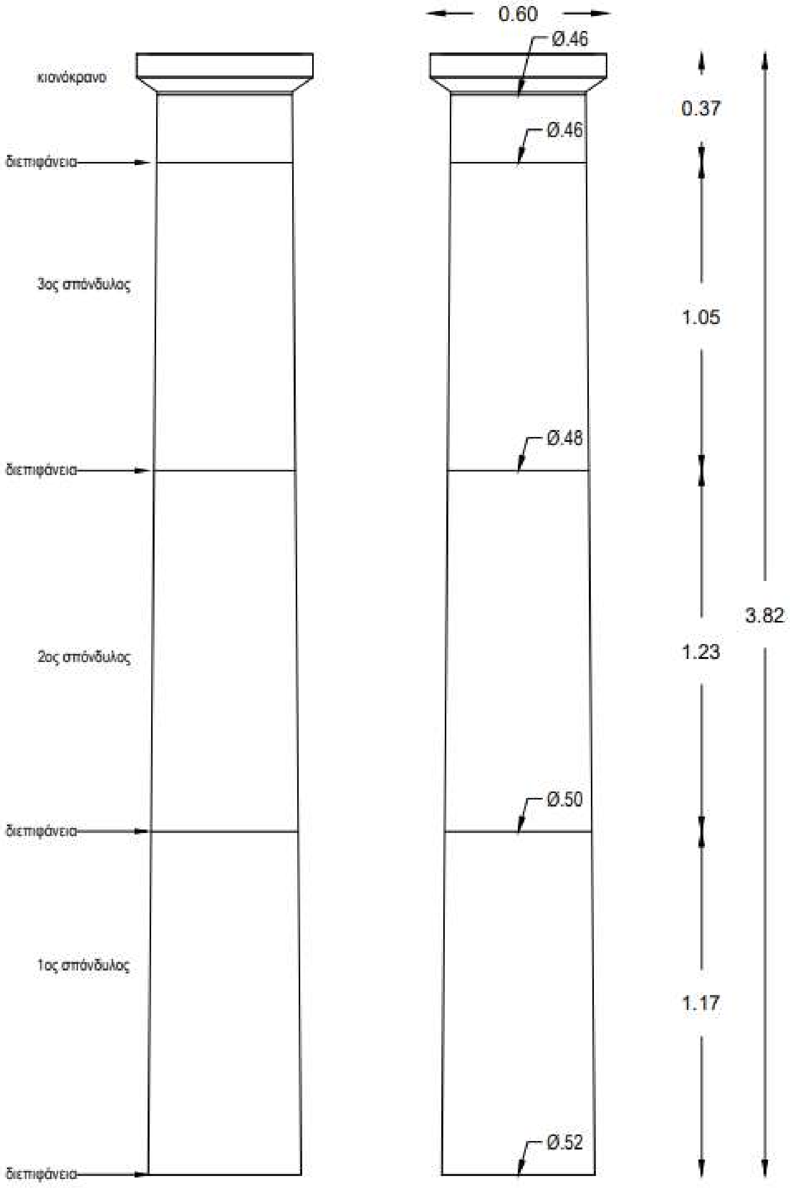
Specimens

The columns of the Gymnasium in Ancient Messene have been selected, because of the following advantages:

(a) The available information that could be obtained for the monument and its construction,
(b) The multiple columns and drums that remain in-situ,
(c) The seismicity of the area in which the monument is located,
(d) The rather small size of the monument's columns, that allows testing in scale 1:1 → usually the tests are performed in scaled specimens

All three columns consist of three drums and one capital.
The dimensions are based upon the Gymnasium.
The three columns are identical in terms of dimensions and preparation of all the interfaces.





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	Type of specimen	Specimen	Description of the structure	Testing Type of tests
1a	Three free-standing columns		Columns without connectors	Shaking table tests. Motion along X, Y, Z axes
1b	Three free-standing columns- repetition of the test		Columns without connectors	Shaking table tests. Motion along X, Y, Z axes
2	Three columns connected in a corner		Columns without connectors, and with two epistyles (beams)	Shaking table tests. Motion along X, Y, Z axes
3	Three free-standing columns		Columns with connectors	Shaking table tests. Motion along X, Y, Z axes
4	Three columns connected in a corner		Columns with connectors, and with two epistyles (beams)	Shaking table tests. Motion along X, Y, Z axes

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Construction of the Specimens

Materials:

✓ Marble from Dionysus quarry (Kokkinara): 65.00-70.00MPa

Bases: dimensions 1.00m*1.00m and height of 16cm

→ anchored to the shaking table with 4 steel dowels, 32mm in diameter

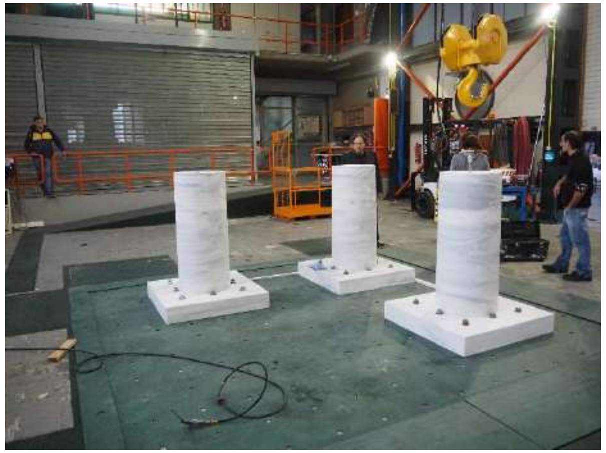
Dimensions of the columns: Based on the dimensions of the monument (full scale, the similitude laws were avoided)

✓ Vertical Connectors: Made of titanium Grade 2 (f_{yk}=300.00MPa), with dimensions 15mm*15mm*60mm, Length of 30mm in each drum

✓ Grooves: 30mm*30mm*35mm

✓ Filling material: Grout of very high strength and short curing time →Selected for the quicker testing after constructing the specimens (3 days: 44.00-56.00MPa, 7 days: 57.50-64.50MPa)

✓ The specimens with the connectors were assembled on the shaking table, and no other tests could be performed in the meanwhile.



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Testing facility

The columns were tested at the shaking table facility of the Laboratory of Earthquake Engineering, NTUA.
Summary of the characteristics of the shaking table:

Geometrical dimensions	[m^3]	4 x 4 x0.6
Degree of freedom	-	6
Frequency range	[Hz]	0.1 – 50
Peak acceleration to horizontal dimensions	[g]	2
Peak acceleration to vertical dimension	[g]	4
Peak velocity to each axis (simultaneous performance)	[m/s]	1.0
Maximum displacement	[m]	0.10
Reaction mass	[Mgr]	2500
Mass and	[Mgr]	10
gravity center	[m]	2

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Description of the instrumentation

- ✓ The instrumentation consists of accelerometers, positioned at the top of each column, in the case of free-stranding columns (three per test), and in the middle of the beams, in the case of the corner specimen (two per test).
- ✓ Except than the accelerometers, cameras are used for the continuous monitoring of the movement of the specimens. The cameras are positioned in pairs, one pair for the monitoring of the movement along the X direction, and one pair for the monitoring of the movement along the Y direction. Both pairs are monitoring also the movement along the Z (vertical) direction.

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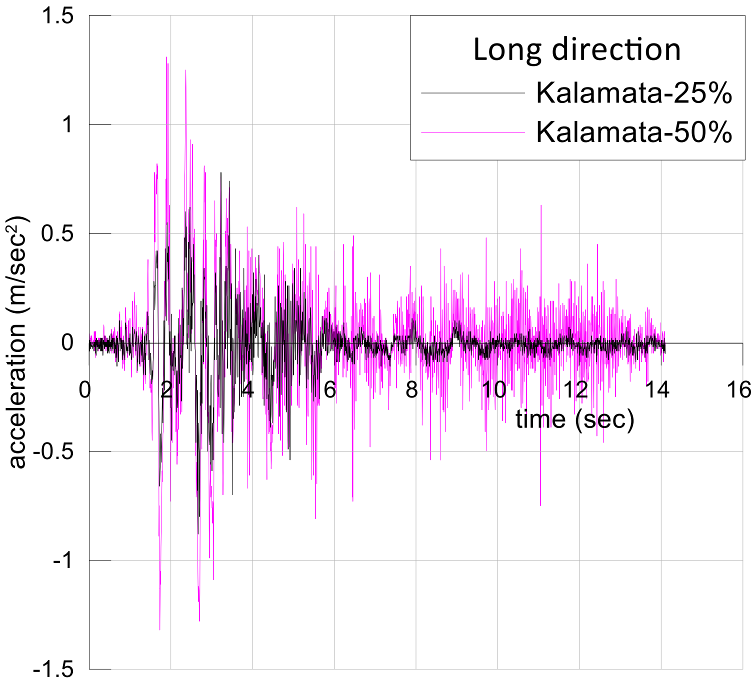
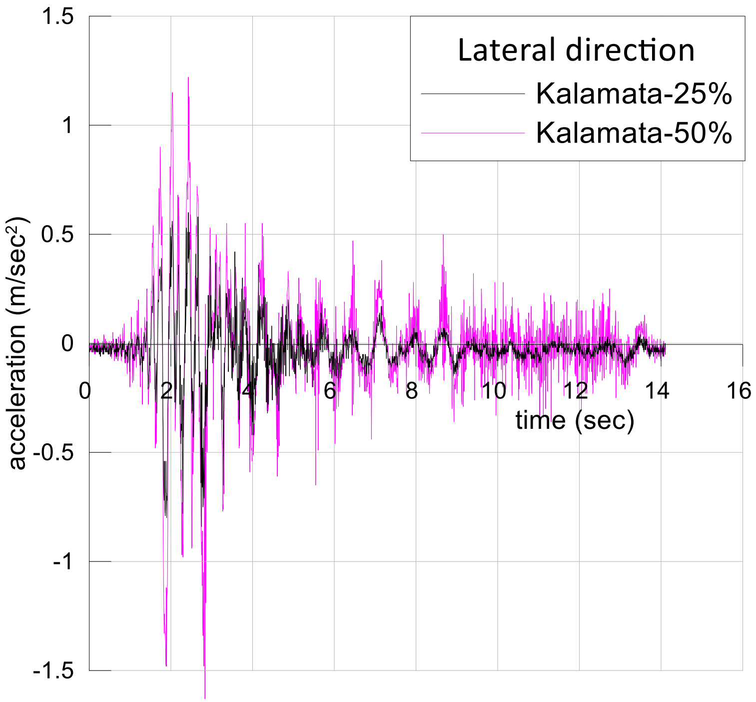
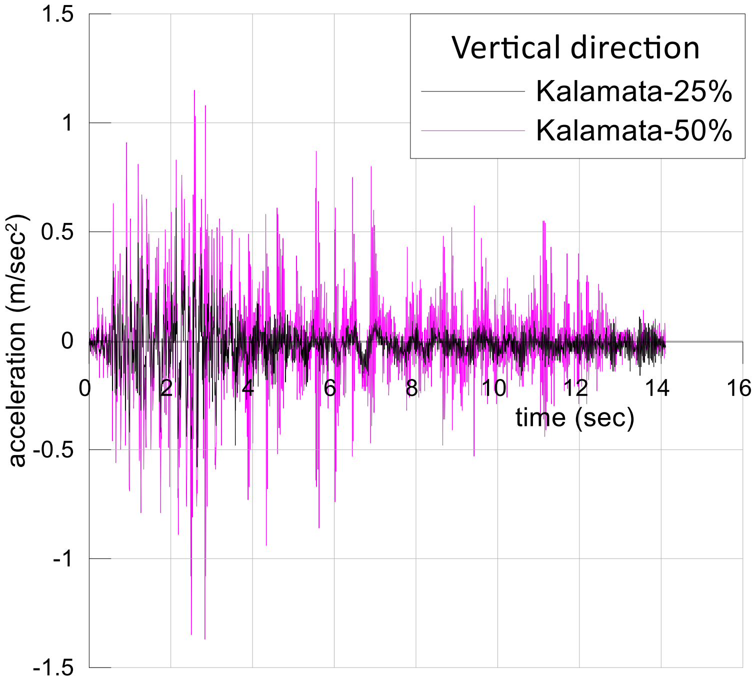
Accelerograms

- ✓ Each specimen was subjected to motions with increasing maximum acceleration. Before the application of the selected seismic inputs, the dynamic properties of each specimen were measured through sine logarithmic sweep excitation of low amplitude (0.03-0.04g).
- ✓ Sine sweep tests were performed separately along X, Y and Z directions. This procedure was repeated before each series of tests, in order to determine changes in the dynamic properties of the specimens.
- ✓ For the tests, one real earthquake record was used, namely, the Kalamata earthquake (1986): The accelerograms were recorded on hard soil in a distance of about 9Km from the epicentre. All three components were used for the shaking table tests. The Kalamata earthquake was scaled to 25% and 50% of the maximum acceleration, to avoid the total failure of the specimens.







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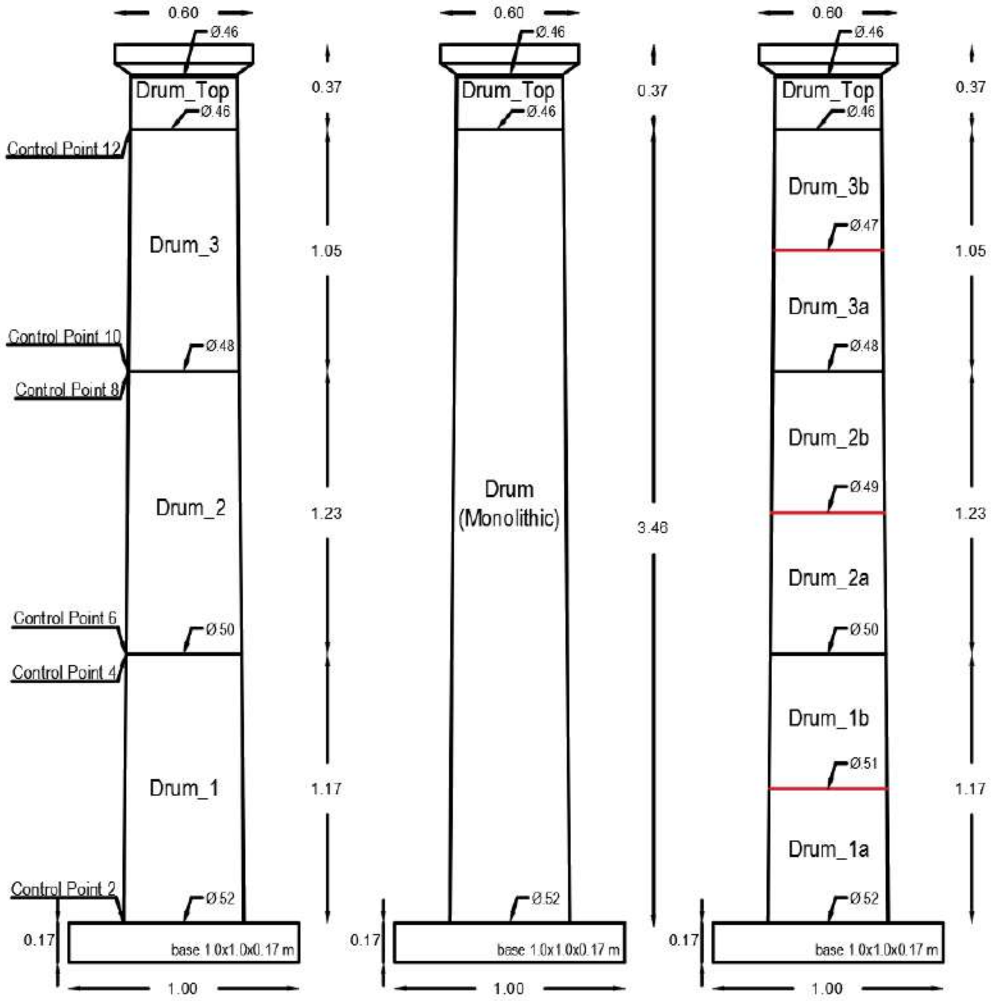
Analysis before testing

- ✓ Two different models were produced using 3DEC [Itasca (2013)] and ABAQUS/Explicit [Simulia (2012)].
- ✓ Three-dimensional numerical models with different number of marble drums were developed.
- ✓ Interface stiffness for the interaction of contact bodies and mechanical joint friction.
- ✓ Tensile strength and cohesion were set to zero since blocks are dry-stacked without any binder.
- ✓ Dynamic analyses with zero viscous damping, proven to be beneficial to the prediction of columns dynamic behaviour.
- ✓ Mechanical joint friction is the only contribution to energy dissipation.
- ✓ Zero dilation angle was assumed.



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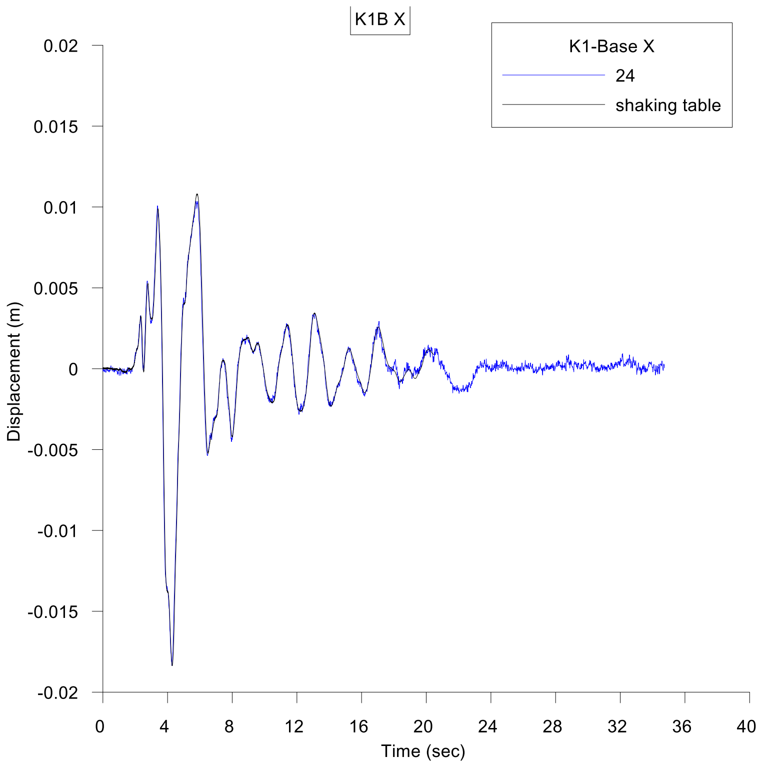
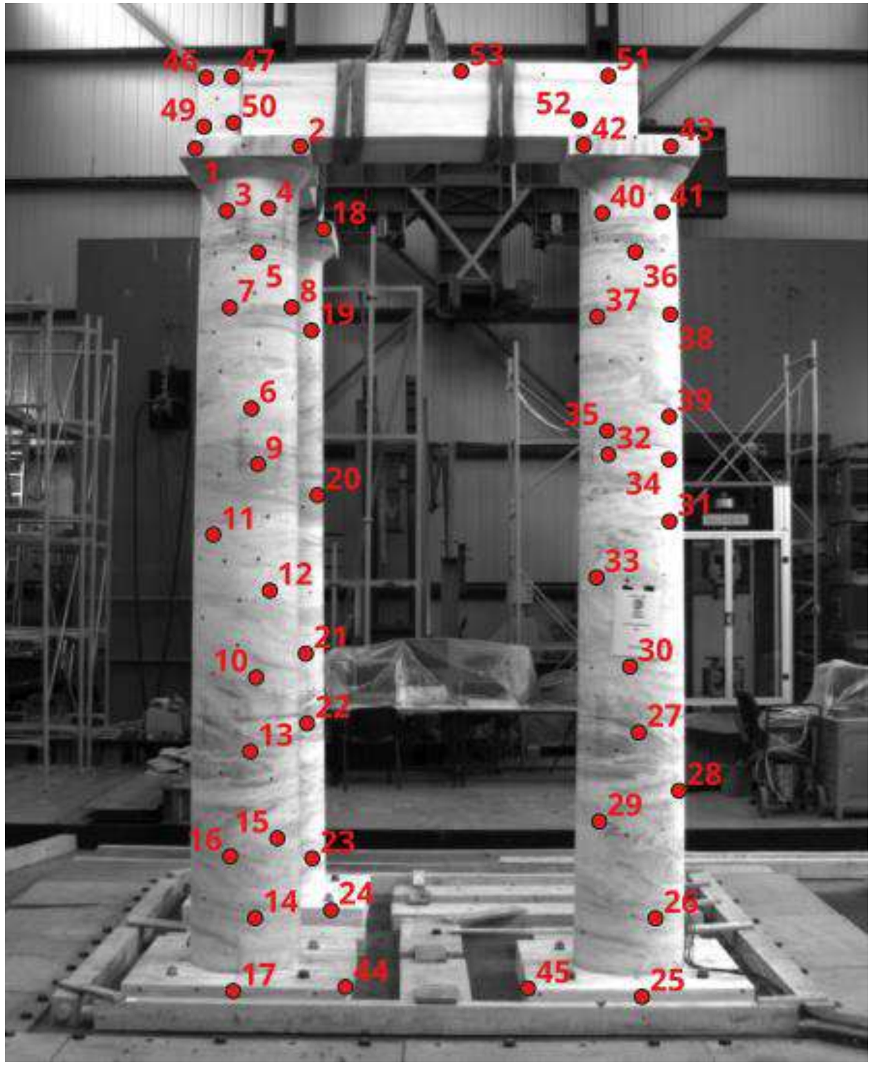
Experimental Results

✓ First step: Comparison of the shaking table displacements with the measurements at the base





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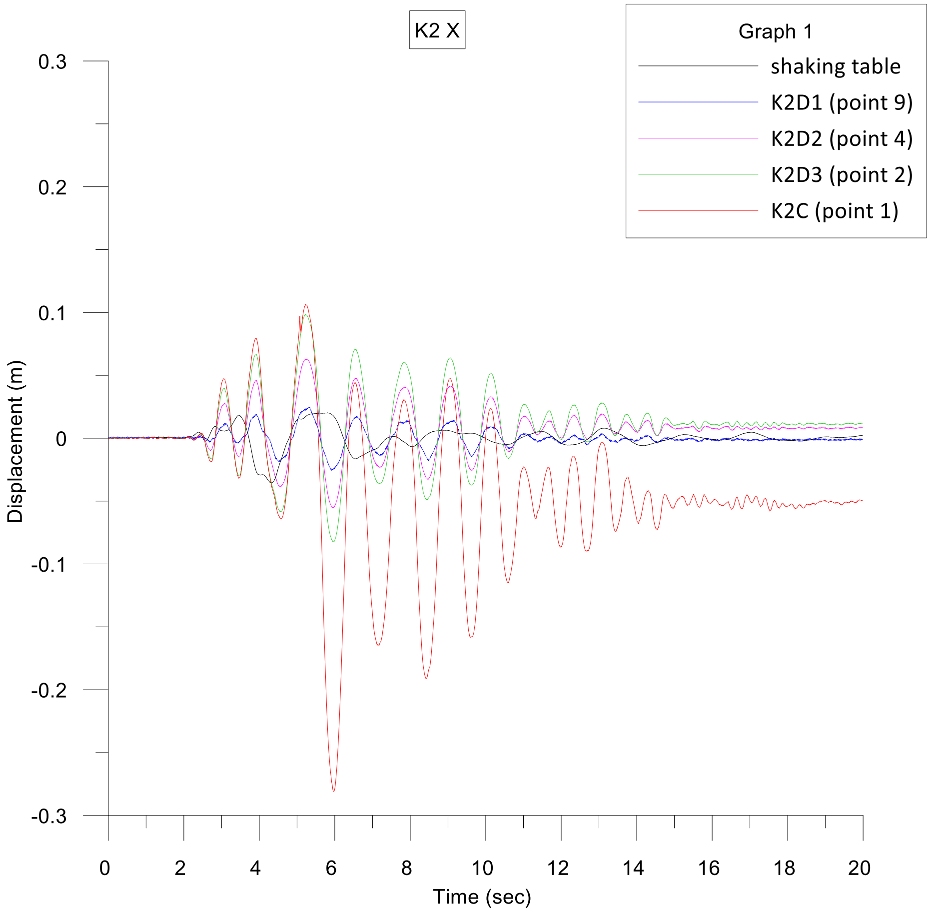
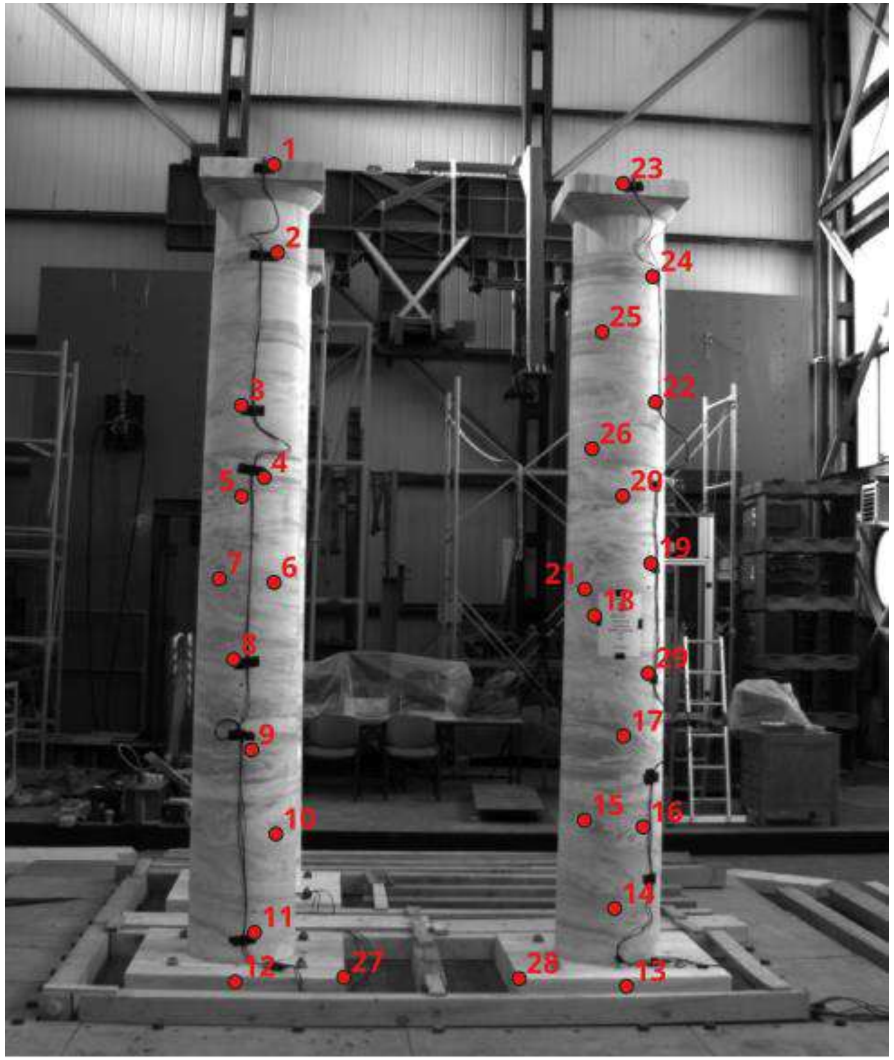
Experimental Results

- ✓ Displacements of each drum, in the same column (example: Freestanding, without connectors, 50% of the earthquake)





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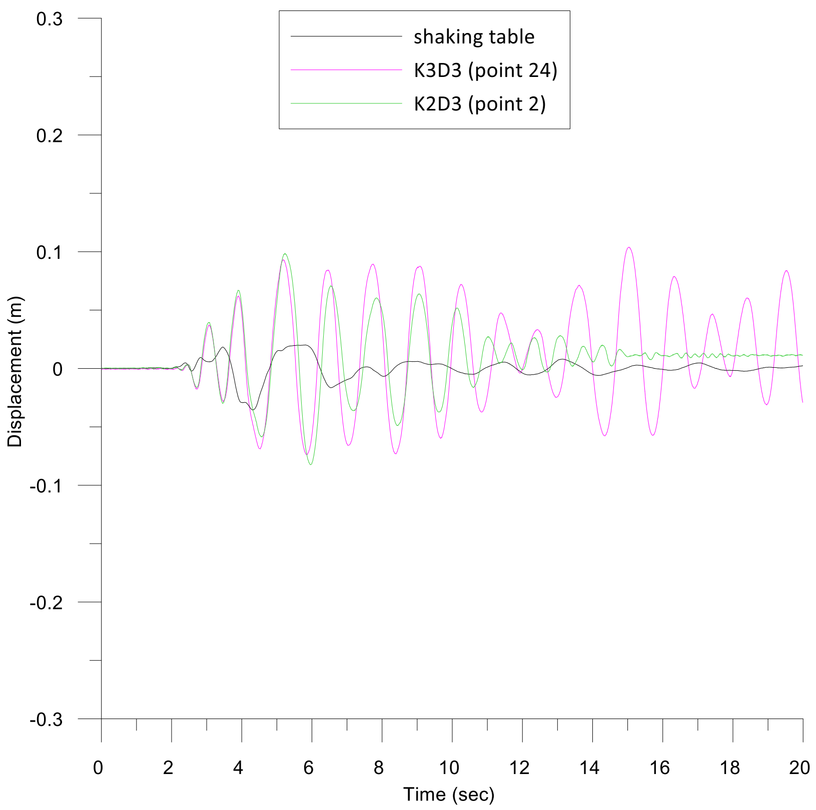
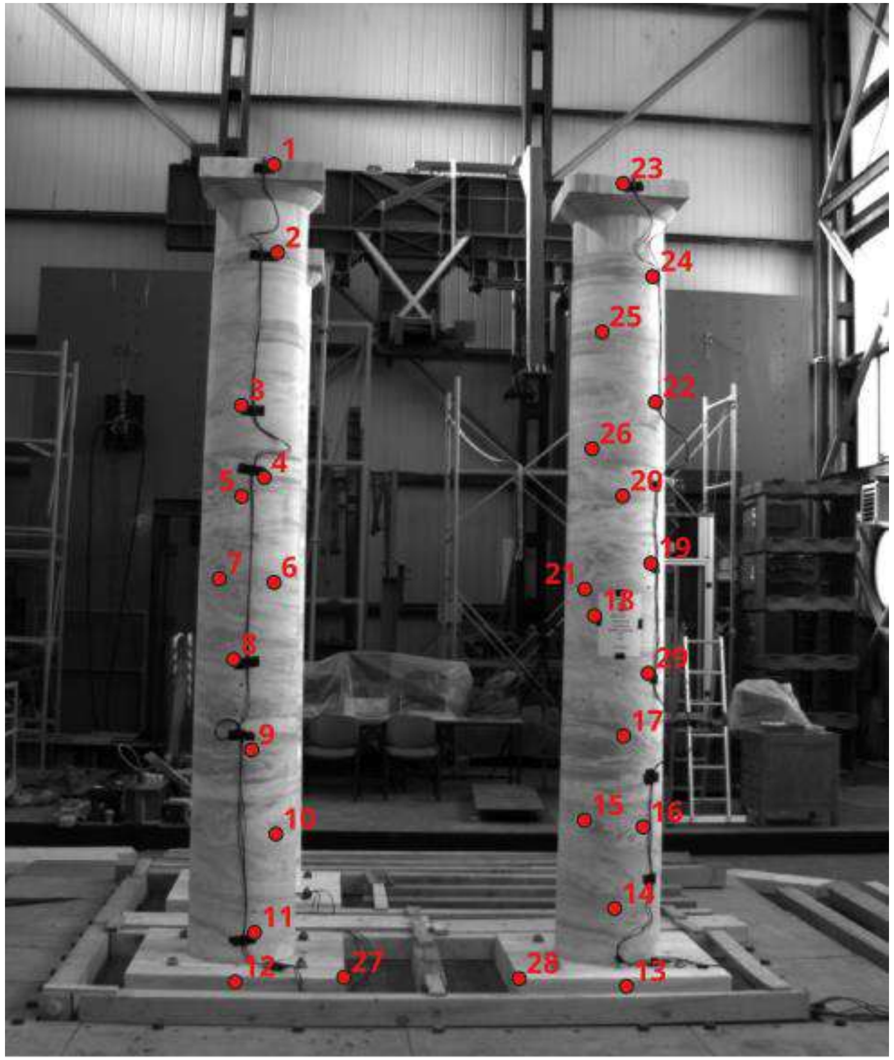
Experimental Results

- ✓ Displacements of the same drum in height, in different columns (example: Freestanding, 3rd drum, without connectors, 50% of the earthquake)





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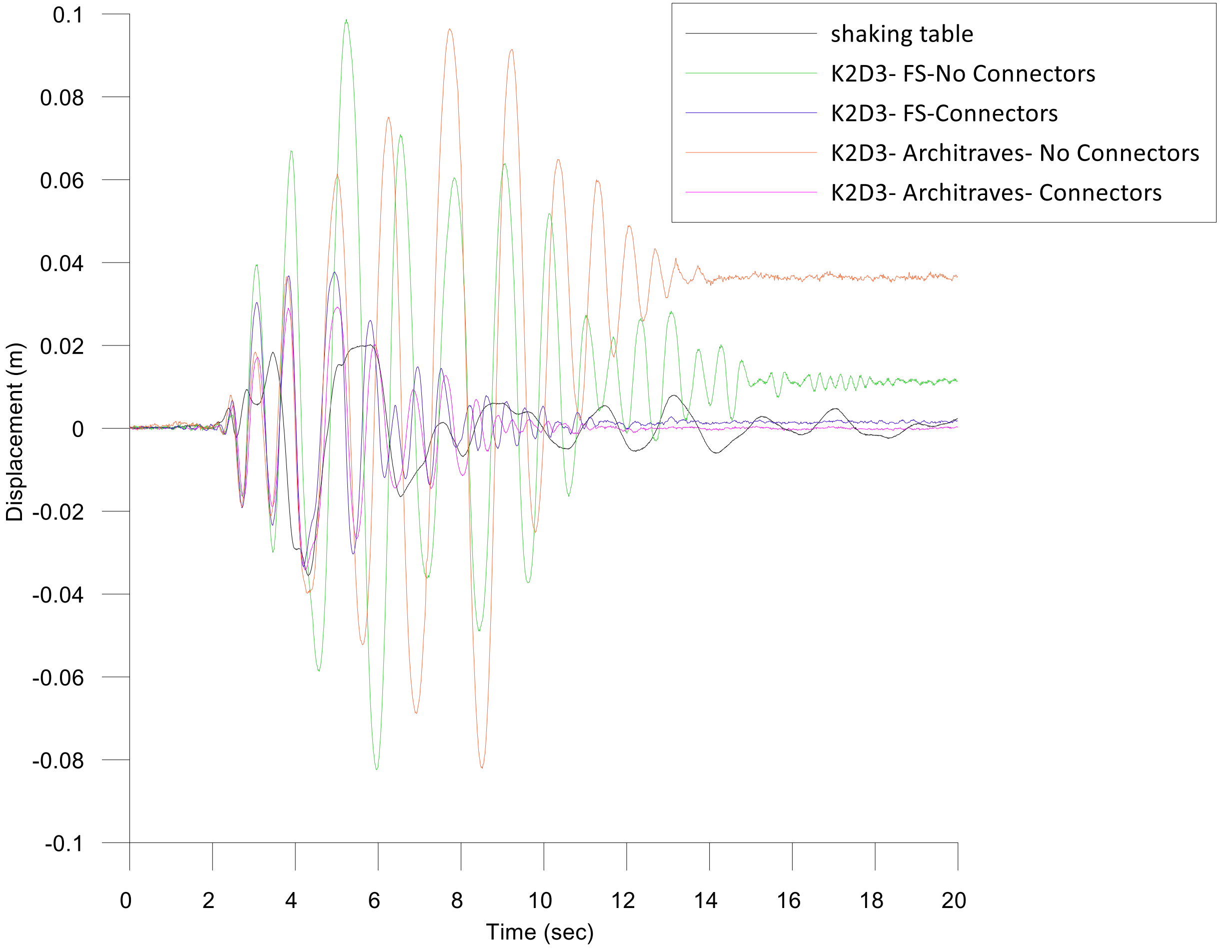
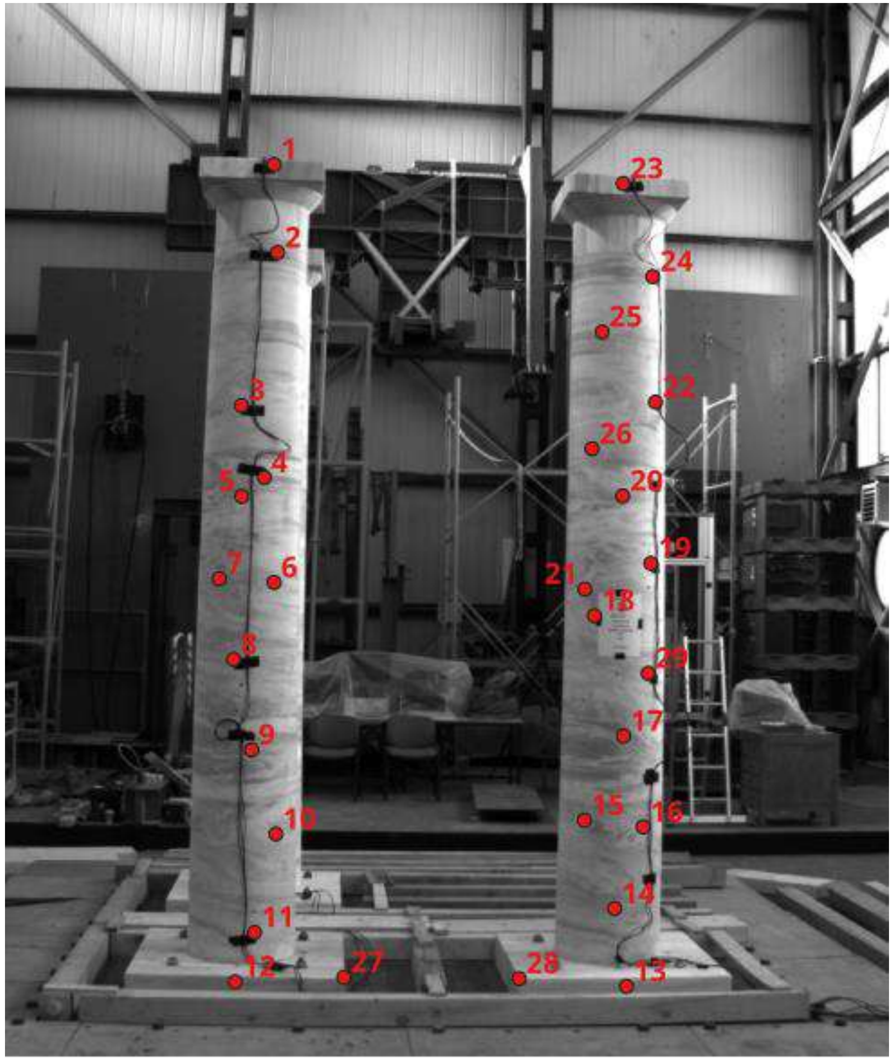
Experimental Results

- ✓ Displacements of the same drum in height, in different tests (example: 3rd drum, column K2, 50% of the earthquake)





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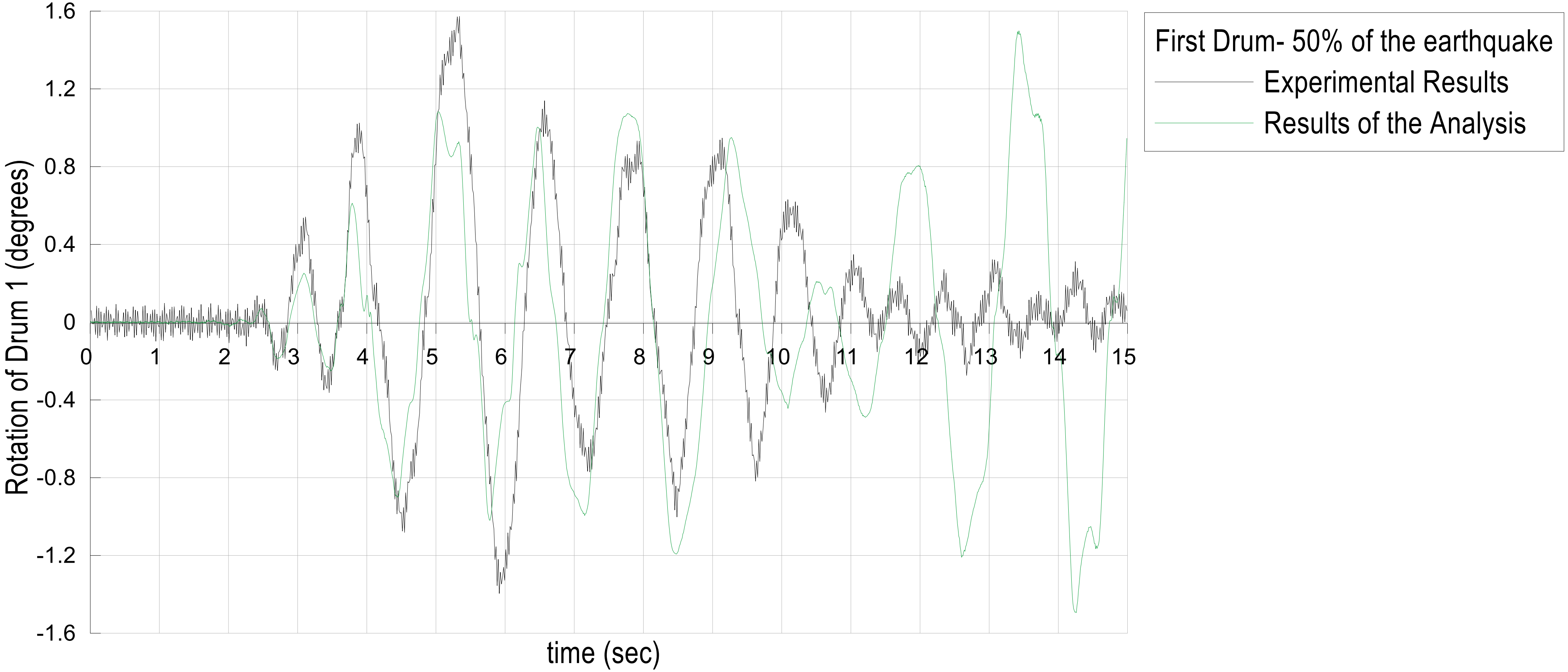
Experimental Results- Comparison with the preliminary analysis

- ✓ Displacements of the first drum, experiment and analysis (example: 1st drum, column K2, Free standing, no connectors, 50% of the earthquake)



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Conclusions

- ✓ The investigated column consists of 3 drums and a capital.
- ✓ The use of vertical connectors seems to improve the column behaviour, leading to smaller overall and remaining displacements.
- ✓ The improvement is more pronounced when combined with architraves.
- ✓ The behaviour of the "identical" columns is not identical.
- ✓ Initial numerical modelling of the seismic response of the multidrum column, is promising.
- ✓ Next steps:
- ➢ Further elaboration of the experimental results: comparison of tests, 3d rotation angles, poles of rotation (wherever possible);
- ➢ Improvement of the numerical model, for the displacements after the maximum.

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Thank you!