

Data set from shake table tests of free-standing rocking bodies

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Abstract

In earthquake engineering, structural models are validated by performing a time history analysis and comparing its maximum to the maximum response obtained by a shake table test. It has been shown that this is a sufficient (but not a necessary) precondition to accept a numerical model. Numerical models can fail to predict the planar rocking response of a rigid block, but may succeed in predicting the statistics of the response to an ensemble of ground motions. As seismic response is inherently stochastic, comparison of the statistics of the numerically simulated response to the statistics of the experimentally obtained benchmark response for the same ensemble of earthquake excitation is a sufficient (and easier to pass) model validation test. This article describes the publicly available data of a set of 12 free rocking vibration and 115 shake table tests of six three-dimensional rocking and sliding columns, designed at ETH Zurich and performed at EQUALS Laboratory, University of Bristol. The data can be used to statistically validate different approaches that aim to model three-dimensional rocking structures.

Keywords

rocking, uplifting structures, statistical model validation, shake table testing, seismic behavior of equipment

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Introduction

Rocking structures are not fixed to the ground, but can uplift and sustain a strongly non-linear motion. It has been suggested that this uplift can be used as a form of seismic isolation (sometimes referred to as “rocking isolation”) for both buildings (Bachmann, 2018; Bachmann et al., 2018b, 2019; Cherepinskiy, 2004; Ríos-García and Benavent-Climent, 2020; Uzdin et al., 2009) and bridges (Agalianos et al., 2017; Dimitrakopoulos and Giouvanidis, 2015; Kashani et al., 2018; Makris and Vassiliou, 2013; Reggiani Manzo and Vassiliou, 2021; Sideris et al., 2014; Thiers-Moggia and Málaga-Chuquitaype, 2020; Vassiliou, 2018; Vassiliou et al., 2017). However, until recently, it was believed that rocking motion is unpredictable by analytical or numerical models, because numerical models often failed to reproduce the experimental data available in the literature (Aslam et al., 1980; Drosos and Anastasopoulos, 2014; ElGawady et al., 2011; Kalliontzis and Sritharan, 2018; Lipscombe and Pellegrino, 1993; Ma, 2010; Mouzakis et al., 2002; Peña et al., 2007; Priestley et al., 1978), especially when it comes to seismic response. Even worse, shake table tests of rocking systems have often proven to be non-repeatable (Anagnostopoulos et al., 2019; Bachmann et al., 2018a). The seismic behavior of non-structural elements and equipment (Bao and Konstantinidis, 2020; Dar et al., 2016, 2018; Di Egidio et al., 2015; Di Sarno et al., 2019; Konstantinidis and Makris, 2010; Sextos et al., 2017; Voyagaki et al., 2018; Wittich and Hutchinson, 2015) frequently involves three-dimensional rocking with sliding—a behavior which is even harder to predict than planar rocking. Thus, to further evaluate their seismic behavior, it is necessary to develop three-dimensional rocking models.

Validation of such strongly non-linear models is a challenging task. Bachmann et al. (2018a) and Del Giudice et al. (2020) have suggested that validation of numerical models in earthquake engineering should be performed statistically. That is, it should require that the model is able to predict a statistical measure of the temporal maxima of the responses to a set of ground motions, for example, their Cumulative Distribution Function (CDF). Predicting the response to each excitation is desirable but not necessary. This is a weaker validation procedure but still suffices for the scope of earthquake engineering, given its inherently stochastic nature. In fact, for tests that are not repeatable, this is the only possible way that numerical models can be validated.

This data article contains the results of multiple shake table tests of free-standing rocking bodies designed at ETH Zurich and fabricated at the University of Bristol. The tests were carried out at the Earthquake and Large Structures Laboratory (EQUALS) of the University of Bristol and were funded by the research project “Statistical verification and validation of 3D seismic rocking motion models (3DROCK).” The project was selected for the Transnational Access part of the ERC Horizon 2020 project SERA. This article presents the data of the conducted tests. The data can be used for the statistical validation of numerical models of the seismic response of free-standing rocking bodies, and complements corresponding data for a wobbling podium structure. The latter is a structure that is allowed to uplift and rock along different directions on horizontal plane, but mechanically restrained not to step out of its original position (Vassiliou et al., 2021a). Given the extent of the tests performed and the breadth of the response quantities monitored, it is deemed that this data set consists a useful and well-documented contribution for future validation of numerical models as it is discussed in the following.

Description of the specimens

First, it is important to clarify that the intention of the rocking specimens was not to represent a *specific* free-standing rocking structure or equipment, but to serve as a benchmark



Figure 1. Free-standing rocking specimens with square bases are lined up in the front row, while those with round bases are aligned in the back row.

for validation of numerical models for predicting the seismic response of a *class* of free-standing rocking bodies. In order for the specimens to serve this purpose, they had to fulfill two fundamental design criteria: (a) remain elastic and not accumulate damage in order to enable statistical validation; and (b) be easy to re-set after a test with or without overturning. Therefore, six free-standing column specimens of three different heights and slenderness were designed. A specimen consisted of a length of round steel pipe with a steel plate welded on top (Figures 1 and 2), both made using S275 steel with a modulus of elasticity of 210 GPa. To make sure that the columns were not oblique, their ends were machined (lathed). The top plate served as a base for attaching markers used to measure displacements. Apart from the top plate, three of the columns had a square steel plate welded at the bottom as shown in Figure 1, so that they were forced to rock on their square base, in contrast to the remaining three columns that were able to wobble on the perimeter of their circular base, deliberately machined to be flat. The bottom and top plates were equal in size and material properties. The supporting surface on the top of the shaking table was made of mild steel (material grade EN24T). The dimensions of the tested columns are presented in Figure 2. Padded frames were placed around the specimens to mitigate the risk of damage in the event of toppling (Figures 1 and 3).

Warping of the square steel plates

The 10 mm thickness of the square steel plates proved insufficient to prevent warping during welding. Therefore, the square-based specimens rocked on an imperfect, non-flat surface. To quantify the imperfections of the square base plates, post-test surface scans were performed using a FaroArm system. During this scanning of the specimen bases, three marker bolts were attached to the side of the plates to mark their orientation, as depicted in Figure 4.

Specimen excitation

The rocking response of the specimens was induced by a bi-directional (two orthogonal horizontal components only) dynamic excitation of its base. To this end, the specimens

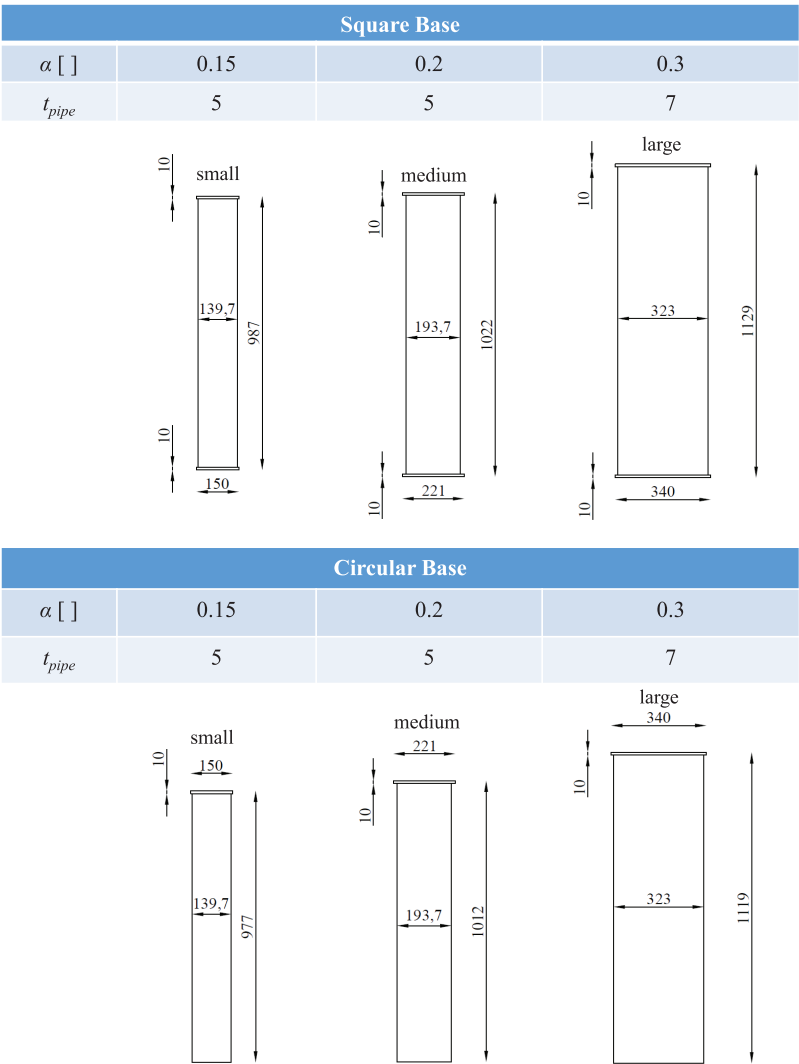


Figure 2. Dimensions (in mm) of the six free-standing rocking column specimens.

were placed on the top of the 6 degree of freedom (DOF) 3 m × 3 m shake table (University of Bristol, 2021). More info on the shake table can be found in Vassiliou et al. (2021b).

Ground motions

The applied ground motions were synthesized using a stochastic ground motion model (Broccardo and Dabaghi, 2017; Broccardo and Der Kiureghian, 2014; Rezaeian and Der Kiureghian, 2008). The 1989 Loma Prieta UCSC Lick Observatory ground motion record was used as a seed ground motion to generate an ensemble of 100 ground motions with compatible elastic spectra with the recorded “seed” motion. More details on the reasoning for this choice of generating ground motions can be found in Vassiliou et al. (2021b).

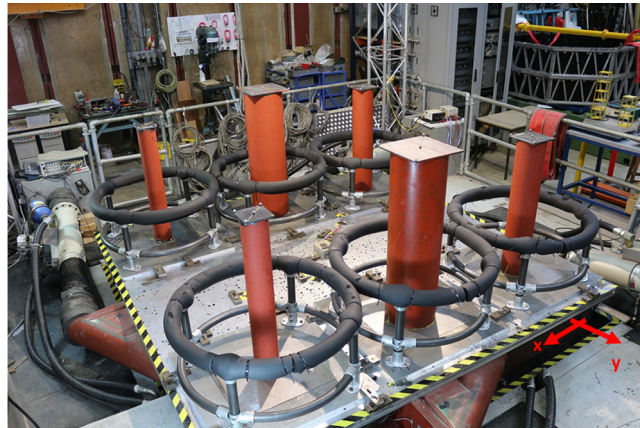


Figure 3. Free-standing rocking column specimens on the shake table at EQUALS Laboratory, University of Bristol.

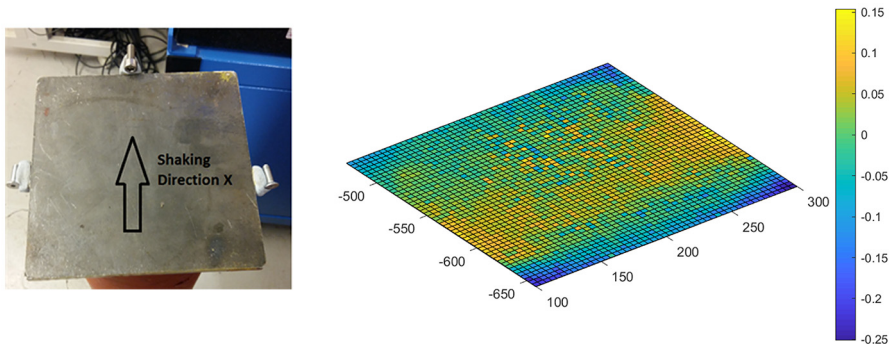


Figure 4. An imperfect square base plate, shown as it was scanned (left). Screws were mounted after the tests to indicate the orientation of the specimen on the table. Three-dimensional scan of the middle-size square column base (coordinates in mm) (right).

The ensemble of the 100 synthetic ground motions was used to drive the shake table during the tests. Vertical ground motion and the three rotational excitations about the horizontal and vertical axes were not considered in this study: thus, the shaking table vertical motion and all three rotations were controlled to remain zero during the tests.

Scaling of the ground motions

In order to comply with similitude laws, time scales with the square of the length scale of the specimen (i.e., $S_T = \sqrt{S_L}$). The time scale of the ground motions was scaled by a factor of two, that is, the frequency of ground motions was increased by two without changing the amplitude. Therefore, at prototype scale, the free-standing rocking columns are four times larger. Detailed info about scaling in rocking problems can be found in Housner's (1963) classic paper.

Figure 5e and f plots the 5%-damped elastic response spectra of the scaled ground motions, as they were applied by the shake table and measured using an accelerometer

that was installed on the shaking table platform. It is worth noting, that for construction of this plot, the measured acceleration recordings offered in the data set were further processed so that a zero final velocity is enforced: This was achieved by subtracting the mean of the record from each element of that record.

It should be noted that the free-standing rocking specimens are distorted models of prototype structures because stress similitude is not preserved. This is common when similitude cannot be retained for all problem variables. Thus, parameters related to the deformability of the specimen (i.e. the material elastic modulus and the natural frequencies of the free-standing rocking columns are distorted). However, previous work (Acikgoz and DeJong, 2012; Chopra and Yim, 1985; Ma, 2010; Oliveto et al., 2003; Psycharis, 1991; Truniger et al., 2015; Vassiliou et al., 2014, 2015) suggests that the deformability of sufficiently large rocking structures does not qualitatively change their rocking behavior. Ultimately, the conducted experiments do not aim at physically modeling a prototype structure, but at creating a data set for model validation.

Testing protocol

Free vibration tests of the square based columns were performed first. The columns were manually given an initial tilt angle and released to rock freely. The tests were performed twice per direction per column resulting in $2 \times 2 \times 3 = 12$ tests. The positioning of the columns for these free vibration tests is given in Figure 6 (left). This resulted in tests N1–N12 as shown in Table 1.

Next, the columns were placed on new positions (given in Figure 6, right) and the shake table was used to induce the 100 synthetic ground motions. Ground motion 10 was used several times to check the repeatability of the tests. This resulted in tests N24–N138 shown in Table 2. Tests N13–N23 are not reported in this article.

After each test, the column specimens were manually restored into their original position, with the same orientation. There was one exception: column C4 was rotated by $+90^\circ$ (counterclockwise) around its vertical axis after test N47 and kept in this orientation for the remaining tests (N48–N138). Since the scans of the warped square base plates were performed after all shaking table tests, the x axis of the scan (see section “Warping of the square steel plates”) follows from the final configuration of column C4, that is, the one after test N47.

Instrumentation

Acceleration and position measurements

The position of each column was tracked by installing four infrared markers on the top plate of each column (Figure 3). Four additional markers were mounted on the shake table to track its position. Therefore, there were 28 infrared markers, the numbering of which follows from Table 3. After the free vibration tests, when the columns were placed at new positions, the markers were re-mounted so that they remain roughly at their initial Cartesian coordinates. The position of the markers was tracked using a Qualisys high-resolution infrared tracking system comprising five type Oqus 400 3-megapixel infrared cameras. The cameras include a near-infrared (NIR) strobe with a 30° field of view and a 16 mm lens.

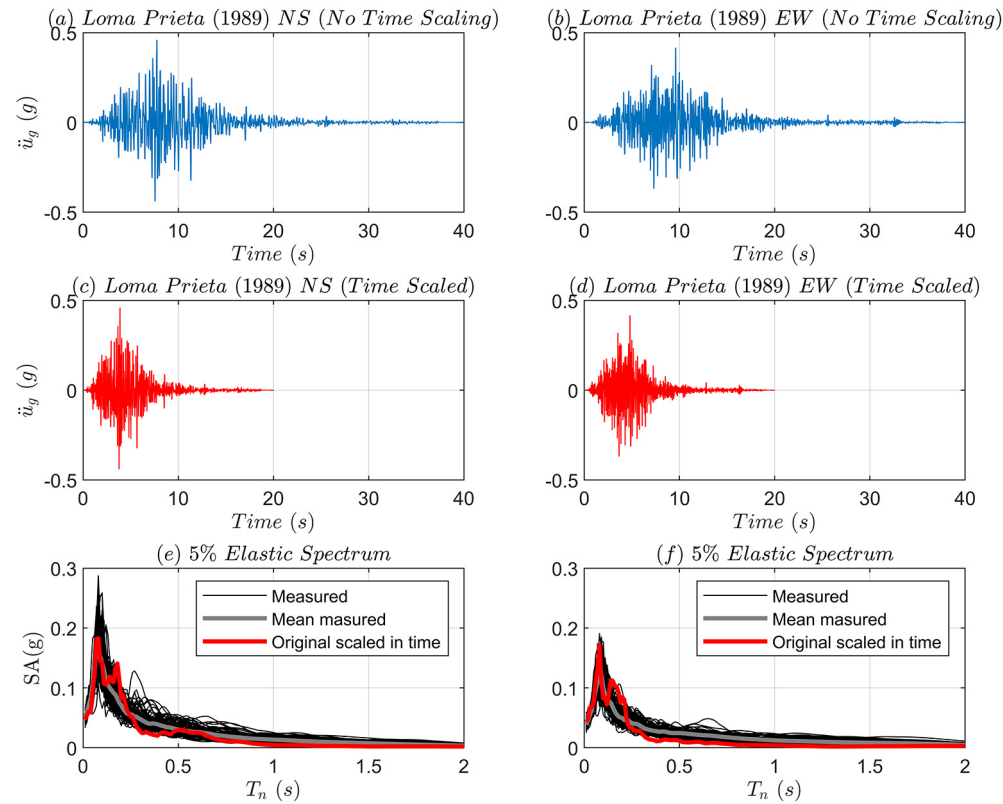


Figure 5. (a and b) 1989 Loma Prieta recorded ground motion; (c and d) Recorded ground motions scaled in time by 2; (e and f) Measured, mean measured and original ground motions 5% elastic acceleration response spectra.

Table 1. List of the free vibration tests

Test no.	Direction	Column
N1	Y	C4
N2	Y	C4
N3	X	C4
N4	X	C4
N5	Y	C3
N6	Y	C3
N7	X	C3
N8	X	C3
N9	Y	C2
N10	Y	C2
N11	X	C2
N12	X	C2

The numbering of the columns was different in the free vibration tests (Figure 6, left) and in the shake table tests (Figure 6, right). Note that after tests N37 and N40 the markers of column C6 fell off and had to be glued again, while after test N47, the markers of

Table 2. List of the shake table tests

Test no.	Excitation	Test no	Excitation	Test no	Excitation	Test no	Excitation
N24	#10	N53	#10	N82	#10	N111	#76
N25	#10	N54	#10	N83	#51	N112	#77
N26	#10	N55	#26	N84	#52	N113	#78
N27	#1	N56	#27	N85	#53	N114	#79
N28	#2	N57	#28	N86	#54	N115	#80
N29	#3	N58	#29	N87	#55	N116	#81
N30	#4	N59	#30	N88	#56	N117	#82
N31	#5	N60	#31	N89	#57	N118	#83
N32	#6	N61	#32	N90	#58	N119	#84
N33	#7	N62	#33	N91	#59	N120	#85
N34	#8	N63	#34	N92	#60	N121	#86
N35	#9	N64	#35	N93	#61	N122	#87
N36	#10	N65	#36	N94	#62	N123	#88
N37	#11	N66	#37	N95	#63	N124	#89
N38	#12	N67	#38	N96	#64	N125	#90
N39	#13	N68	#39	N97	#65	N126	#91
N40	#14	N69	#40	N98	#66	N127	#92
N41	#15	N70	#41	N99	#67	N128	#93
N42	#16	N71	#42	N100	#68	N129	#94
N43	#17	N72	#43	N101	#69	N130	#95
N44	#18	N73	#44	N102	#70	N131	#96
N45	#19	N74	#45	N103	#71	N132	#97
N46	#20	N75	#46	N104	#72	N133	#98
N47	#21	N76	#47	N105	#73	N134	#99
N48	#22	N77	#48	N106	#74	N135	#100
N49	#23	N78	#49	N107	#75	N136	#10
N50	#24	N79	#50	N108	#10	N137	#10
N51	#25	N80	#10	N109	#10	N138	#10
N52	#10	N81	#10	N110	#10		

Table 3. Positions of the markers

Marker number	Position
M1–M4	Shake table
M5–M8	C1
M9–M12	C2
M13–M16	C3
M17–M20	C4
M21–M24	C5
M25–M28	C6

C4 were rotated into new positions, as the column was rotated. The coordinate system is shown in Figure 3. The marker position sampling rate was 100 Hz.

The horizontal components of the acceleration of the shaking table were monitored by a block of mutually orthogonal Setra 141a accelerometers at a sampling rate of 5000 Hz. The acquired data were filtered using a low-pass eight-pole Butterworth filter with a cut-off frequency set at 1400 Hz. The range of the accelerometers was $\pm 8g$.

The synchronization system for the disparate acquisition systems utilizes a master crystal oscillator and a digitally programmable device that derives the DAQ clocks from this

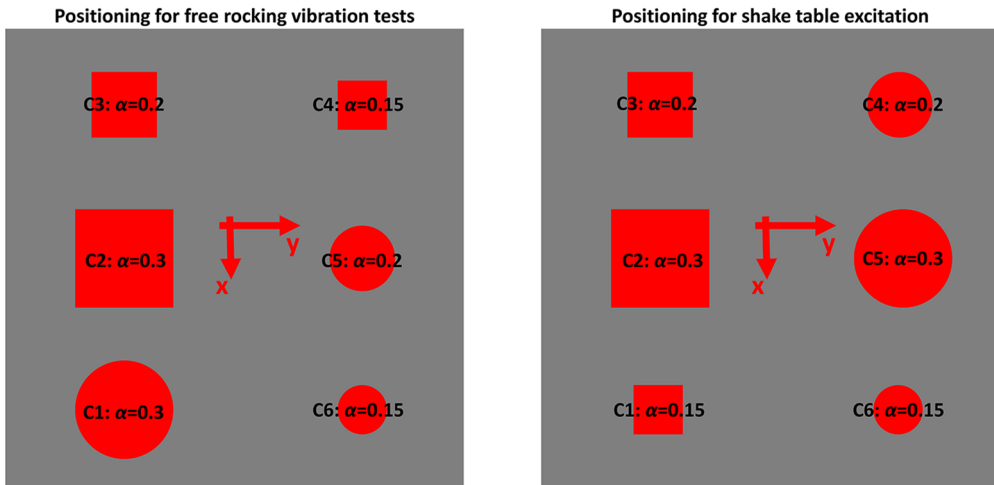


Figure 6. Positions of the free-standing rocking column specimens for the free rocking vibration tests (left) and the shake table excitation tests (right).

master. When triggered, the synchronization system commences with a rising edge simultaneously on each clock output and maintains synchronization thereafter. The clocks are integer multiples (5000 and 100 Hz), so every 50 cycles of the high-rate clock for the DAQ system, the two systems will have coincident rising edge clocks.

Photos and video recordings

Photos of the specimen were taken before, in between and after the tests, so that any potential damage caused by uplifting, minor sliding, and impact of the specimens is recorded. Videos of several of the tests were made.

Test observations

The free rocking vibration tests showed that there was out-of-plane motion due to imperfections, especially for the $\alpha = 0.15$ and $\alpha = 0.20$ specimens.

The specimens suffered no damage during the tests. The imperfections of the square-based specimens caused them to uplift more easily and to exhibit less impact damping, because they were not rocking on the perimeter of their bases, but on the intermediate points.

Test data

Data organization

The test data are publicly available at ETH Research Collection platform (Vassiliou et al., 2020), where there are indefinitely maintained. The dataset comprises five files compressed using the ZIP format, containing (a) the measurements of the position of the markers (from which the displacements relative to the laboratory strong floor can be computed), (b) the acceleration measurements, (c) the surface scans of the base plates, (d) the test

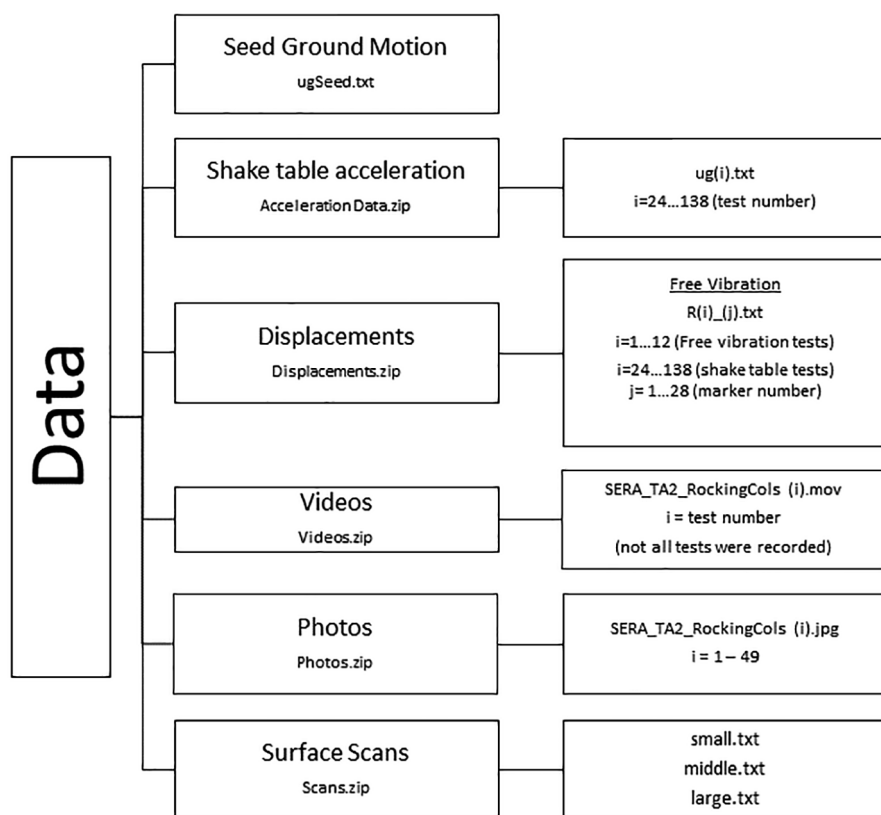


Figure 7. Data organization.

videos, and (e) photos of the specimens. The structure of the data files is summarized in Figure 7.

Displacement data

The time histories of the marker positions are provided as ASCII files. The files are named $Ri_j.txt$, and each one comprises three columns, corresponding to the position of the marker along the x , y , and z directions (in millimeters). The coordinate system is shown in Figure 3. The table platen is horizontal and lies in the x - y plane of this coordinate system. Index i denotes the test number. It runs from 1 to 12 for the free vibration tests and from 24 to 138 for the shake table tests—tests N13 to N23 are not reported herein. Index j denotes the marker/target number: The markers placed on the shake table are $j = 1$ –4, while markers $j = 5$ –28 are placed on the top plates of each column (Figure 3). The data are sampled at 100 Hz and processed by the Qualisys system.

Acceleration data

The filtered acceleration time history records from 115 tests are provided as ASCII files named $ugi.txt$, where $i = \{\text{test number}\}$. Within each file, the first and second columns are the accelerations in the x and y directions in units of the acceleration of gravity g . The

original “seed” ground motion that was used to synthesize the motions is also provided as file “ugOriginal.txt.” Its first column is the time, the second and third are the x and y accelerations in units of g .

Surface scans

The surface scans of the warped base plates of the square-based specimens are provided as .txt files. The files are named “small,” “medium,” and “large” in accordance with the size of the plates attached to the ends of the pipe sections of the specimens. Each file contains three columns corresponding to the local Cartesian coordinates (in millimeters) of the points of the surface scan. The x axis of the local scanner coordinate system is parallel to the global x axis and it has the same direction (sign). The global coordinate Cartesian system is shown in Figure 3.

Derived data examples

Throughout this section, the displacement of the table was derived based on the displacement of Marker M1. This should theoretically be equal to the displacements of markers M2–M4, as no rotations were applied to the shake table. However, small deviations between the displacements of markers M1 and M4 were recorded, because the table did unavoidably experience some small rotations.

Figure 8 plots the displacement of the top of the square-based columns C4, C3, and C2 during free rocking vibration tests N1, N5, and N9, respectively. More specifically, the displacements of the markers mounted at the center of the square plate on top of these columns are plotted. Note that the displacement is computed as the relative position with respect to the position at time instant $t = 0$. As the position recording started during the manual uplift (tilting) of the columns (and not before it), the columns were not necessarily vertical at $t = 0$.

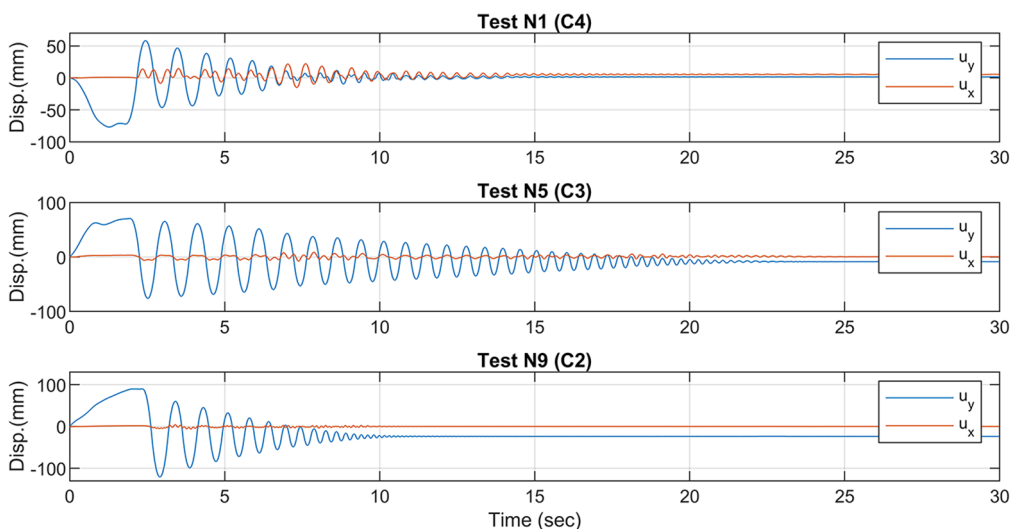


Figure 8. Response history of the displacements at the top of the columns C4, C3, and C2 for free vibration tests N1, N5, and N9, respectively.

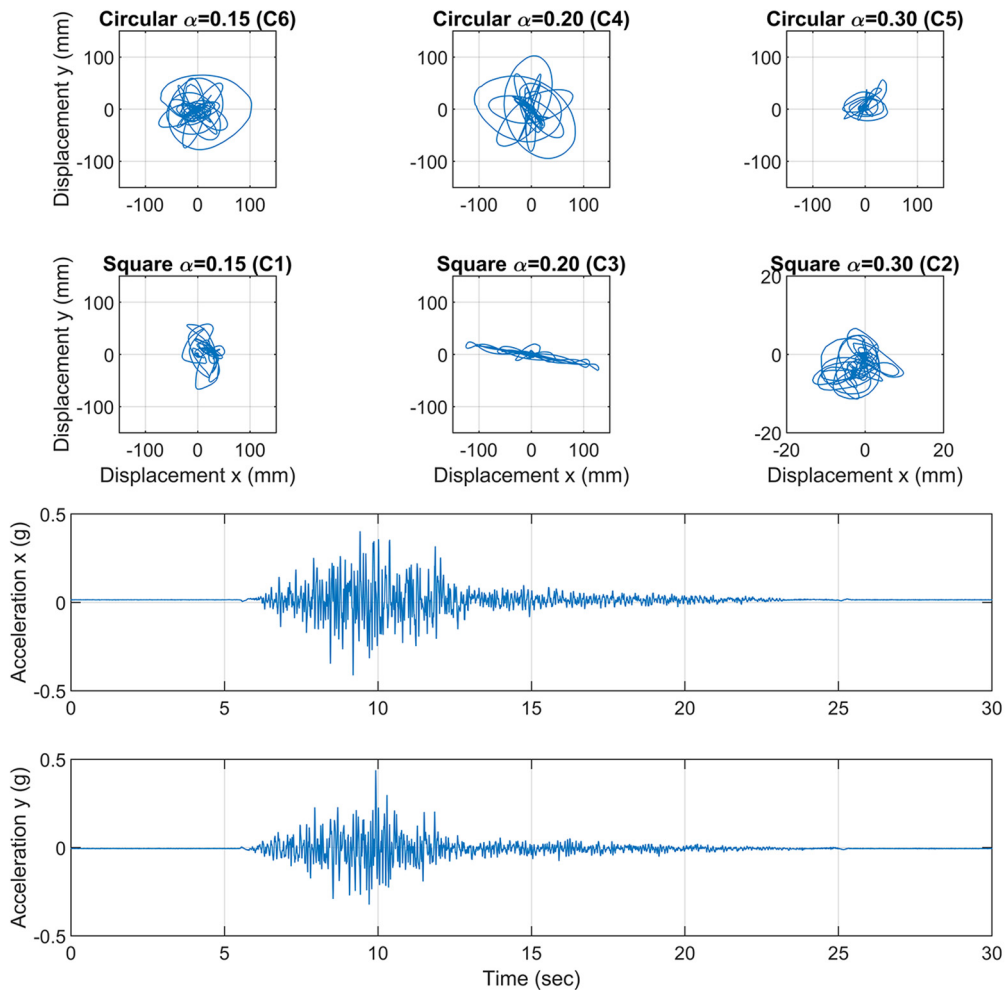


Figure 9. Test N40. Horizontal displacement orbit plots of the top middle markers on all six columns (top two rows) and recorded shake table acceleration (bottom two rows).

Figure 9 plots the orbits of the horizontal displacements of the marker at the top-center position for all six specimens during test N40. It also plots the two horizontal components of the acceleration, as recorded and filtered with a low-pass filter (but without correcting them for non-zero mean).

Figure 10 plots the outcomes of three repeatability tests (N52–N54). In general, repeatability is not observed.

Data use

As stated previously, the main purpose of the generated dataset is to allow for the validation of numerical and analytical models for seismic response of three-dimensional uplifting structures that rock and slide without any constraints. Improving these models will reduce

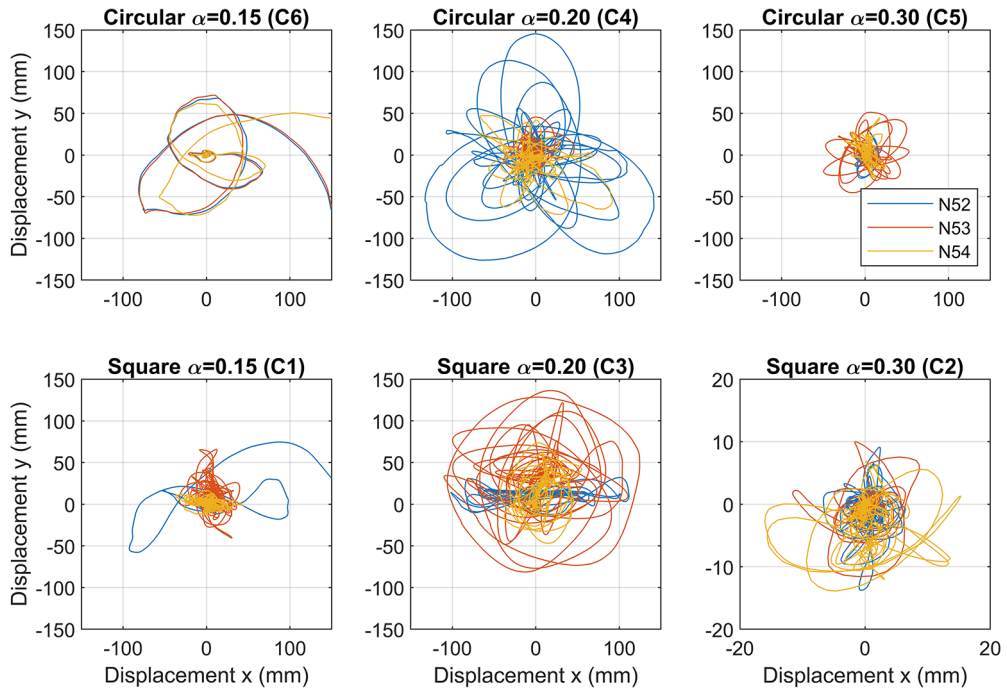


Figure 10. Repeatability test for excitation #10 (tests N52, N53, and N54): Orbits of the horizontal displacements of the top middle markers on all six columns.

the epistemic uncertainty and will enable the better prediction of the response of rocking objects, as well as allow for a better understanding of the seismic behavior of unanchored equipment, museum artifacts, and statues.

As the specimens remain undamaged during the tests, it was possible to perform multiple shake table tests, as the concept of statistical model validation (Bachmann et al., 2018a) suggests. Models can be validated in terms of their ability to predict the statistics of the response to a set of ground motions, rather than the response to individual excitations. This concept was adopted in the PEER 2019 blind prediction contest (Vassiliou et al., 2021a) that involved a wobbling podium structure allowed to uplift, but not to step out of its initial position (Vassiliou et al., 2021b). That contest showed that both finite element method (FEM) and discrete element method (DEM) models can predict the statistics of the response, even though they fail to predict responses to individual records with a reasonable accuracy. Hence, the data presented herein can be used to compare modeling approaches (e.g. FEM models, DEM models, analytical models based on flexible or rigid rocking body assumptions) and to determine the relative importance of the different parameters used in each of these approaches.

Conclusion

This article presents the publicly available data obtained from a series of 12 free rocking vibration and 115 shake table tests on six different free-standing rocking columns. The specimens, designed at ETH Zurich and fabricated at the University of Bristol, represent

rigid objects allowed to slide and rock freely. The tests were performed at the EQUALS Laboratory, University of Bristol. The purpose of the data at hand is to serve as a benchmark response data set for the statistical validation of numerical models used to predict the seismic response of rocking and sliding structures. The authors hope this will lead to a more accurate prediction of the seismic response of unanchored equipment and other rocking objects.

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