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Simulating Responses of Objects to Seismic Input Motion using Multibody Dynamics

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Abstract

Macroseismic intensity is a scale which measures the severity of shaking at a location caused by an earthquake. Each intensity level has a set of intensity indicators which are responsive at and beyond that level. A better understanding of the response of these indicators will lead a reduction in the uncertainty. Ideally the response of the indicators would be determined through physical experiments but this is an expensive and time consuming process. This paper presents a new alternative approach for obtaining the response of an indicator by using computer simulation methods. An example for intensity level V shows that the approach produces representative results.

Keywords: seismic, macroseismic intensity, multibody dynamics, simulation, testing, intensity indicator, ground motion.

1 Introduction

Ideally a seismic event will have been measured on a large number of uniformly distributed recording instruments; however, even in seismically active areas the distribution of instruments is sparse because of the high cost. Macroseismic intensity (hereinafter termed “intensity”) provides an alternative means of measuring ground motion of both new and past seismic events. The use of intensity as a measure has the advantage that it is based on observation and effects on objects, in particular buildings, which means that the higher results remain available for examination long after the event and people’s experiences are reported for the lower intensities. The fact that intensities can be applied to historical events means they provide a way to calculate the magnitudes of historical events. Despite these positive characteristics, for many years, intensity based methods have been regarded as too imprecise; however, recent studies [1] have identified intensity as a useful measure of seismic ground motion. Although intensity based approaches provide a wealth of information and have, as noted, recently gathered support, a major difficulty remains the reliability of interpreting the information.

Intensity of ground motion is measured on a qualitative scale such as the Medvedev-Sponheuer-Karnik Intensity scale (MSK) or Modified Mercalli Intensity scale (MMI) which ranges from 1, not felt, through to 12, which corresponds to destroyed. Each intensity level has a number of specific intensity indicators which are strongly activated when that level is reached. In [2] Belsham showed that intensity levels II to VIII can be characterised by specific spectral frequencies. This paper builds on that previous study by examining the response of intensity indicators to seismic input motion in the form of time histories that are matched to the relevant intensity level via the European Strong Motion Database. The example presented in this paper is for MSK intensity level V.

The approach uses Multibody Dynamics to simulate physical testing of the intensity indicators, which for the example considered, are small objects which are modelled as small rectangular blocks. The use of such simulations is a new approach for determining the range of ground accelerations and spectral control associated with a particular intensity level. By carrying out a large number of simulations, sufficient data is provided from which the mean and the distribution of those accelerations can be determined. The approach also takes account of the frequency content varying with the magnitude and epicentral distance of the event. This approach is a new application in terms of the use of multibody dynamic simulations of the effect of seismic events. The current series of studies is being carried out using a 2-dimensional approximation to a 3-dimensional setting by using a resultant horizontal input supported by methodology presented in a companion paper at CST2012 [3]. For some intensity indicators 3-dimensional simulations are required and they will be investigated in the future.

Contact between bodies is an important factor for many of the intensity indicators. In this study a choice has been made to use an approach which depends on the coefficient of restitution rather than attempt to try and determine the parameters for Hertzian contact using penalty or Lagrange constraint methods. This has the advantage of simplicity which is an important consideration when a large number of analyses need to be performed.

2 The Method

The key feature of the experimental work described in this paper is the use of computer modelling to simulate physical experiments. An interesting element is that the computer simulation represents a physical simulation of earthquake input motions by modelling a shake table. The experiment is to test the response of small objects to seismic input motion that should produce the level of shaking that corresponds to MSK intensity level V. The objective is to explore whether the object behaves in the way described as an intensity indicator.

2.1 The computer model of the shake table

The computer model of the shake table is shown in figure 1 and was implemented using the computer program Working Model 2D [4]. Working model 2D was chosen because it provides a modelling environment that is straightforward to use and incorporates an automatic solids contact capability.

Referring to figure 1, the model of the shake table consists of two main parts, the horizontal and vertical tables with the vertical table being supported from the horizontal. Vertical rails between the horizontal and vertical tables constrain the vertical table to only move in the vertical direction. A horizontal rail constrains the horizontal table to move in only the horizontal direction. The seismic input motions, which are in terms of velocity time histories, are applied to the tables through actuators in the horizontal and vertical directions as shown in figure 1. The horizontal actuator acts between the ground and the horizontal table and the vertical actuator acts between the horizontal table and the vertical table. This arrangement allows the horizontal and vertical motions to be applied simultaneously thereby reproducing the same effects as a real event but limited to 2 degrees of freedom.

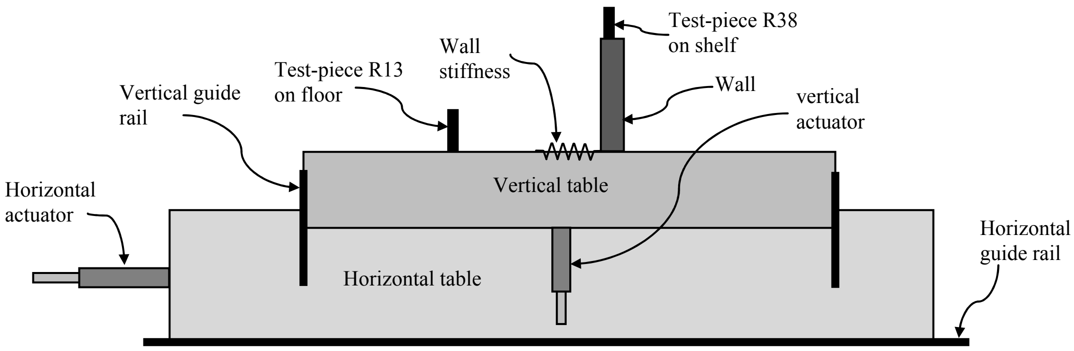


Figure 1: Diagram of the computer model of the shaker table and the arrangement of the test pieces

Two rectangular test pieces are considered in each analysis, one designated R13 is located on the floor and the other designated R38 is located on a shelf, which is fixed to a wall at a height of 1.3m or could equally be a mantelpiece. The width of the shelf is 0.25m and the position of the test piece on the shelf is treated as a sensitivity, which in some cases effectively means a narrower shelf. The stiffness of the wall is represented by a spring between the vertical table and the wall, the stiffness of the spring is 5.0e5N/m and the mass of the wall is 500.0kg which gives an effective natural frequency of 5.0Hz. The wall is restrained vertically to the vertical table by rigid rods, which are not shown in figure 1.

The dynamic properties of the rectangular test-piece at the point of toppling are important and depend on the instability angle, which is the angle at which the block topples and the natural frequency of the block at the toppling angle. Referring to figure 2 which shows a rectangular block rocking at angle θ, the angle of instability θ_t is given by equation (1)

$$\theta_t = \arctan\left(b/h\right) \tag{1}$$

where h is the vertical distance to the centre of gravity and b is the distance from an edge to the centre of gravity.

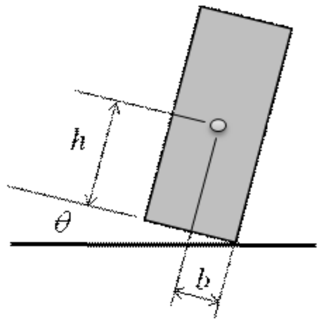


Figure 2: Diagram of the rectangular test-piece

A number of different configurations of the test pieces are tested and are sized to represent small domestic objects such as vases, candlesticks, ornaments, books, etc., namely items likely to be on shelves in typical domestic dwellings. The details are given in table 1 where in column 5 μ is the coefficient of friction, in column 6 e is the coefficient of restitution. The test-piece is positioned at three different locations on the shelf and they are identified in column 7 of table 1 by the codes, e for edge, q for quarter way and m for midway. The rocking natural frequency just prior to toppling f_t is given by setting θ equal to θ_t in equation (2)

$$f\left(\theta,b,h\right) = \frac{1}{2\pi}\sqrt{\frac{3\left(\left(b/h\right)-\theta/2\right)g}{2\left(1+\left(b/h\right)^2\right)\theta h}} \tag{2}$$

where g is the acceleration due to gravity. Whilst the rocking frequency at the point of toppling is given in column 9 of table 1 for average rocking values of θ the rocking frequencies are higher, around 1.8Hz.

Ref.	Mass (kg)	Height (m)	Width (m)	μ	e	position	θ_t rads	f_t (Hz)
tp1	1.0	0.25	0.075	0.3, 0.5	0.75, 0.95	e, q, m	0.291	1.2
tp2	2.0	0.50	0.075	0.3, 0.5	0.75, 0.95	e, q, m	0.149	0.9
tp3	5.0	0.75	0.075	0.3, 0.5	0.75, 0.95	e, q, m	0.100	0.7
tp4	1.0	0.25	0.100	0.3, 0.5	0.75, 0.95	e, q, m	0.381	1.2
tp5	2.0	0.50	0.100	0.3, 0.5	0.75, 0.95	e, q, m	0.197	0.9
tp6	5.0	0.75	0.100	0.3, 0.5	0.75, 0.95	e, q, m	0.133	0.7

Table 1: Details of the properties of the test-pieces

2.2 The Seismic Data

The source of the time histories is the European Strong Motion Database (ESMD) [5], which provides an extensive collection of validated earthquake data amongst which are some with values for the intensity level, in the MSK scale, at or close to the recording site. A number of these records have been accessed for use in the analysis report in this paper and the details are given in table 2. As well as time histories corresponding to intensity level V examples, one each, have been used for intensity levels VI and VII to explore whether the effects of the increased levels were noticeable in terms of the responses of the objects. In addition to the time histories the database provides plots of the response spectra for the events.

ESMD Ref. wcode	Intensity Level (MSK)	Magnitude (Ms)	Epicentral distance (km)	Depth (km)	Peak velocity (m/s)	Peak acceleration (m/s^2)	Duration (s)
24	V	4.5	9	5	0.031	0.81	6.5
43	V	4.5	9	2	0.031	0.39	19.6
112	V	6.5	28	6	0.032	0.92	22.37

Table 2: Details of the seismic events and the readings at the recording stations at the epicentral distances shown in column 4

The ESDM assigns each event a reference number which is used in the references both in the time history files and the response spectra files. These file reference have been used as the referencing system in a program written in the Mathcad [6] programming language which is used to build a table of events which have intensity levels assigned. Sorting this table in terms of the intensity level makes it easy to extract suitable records for a chosen intensity level and at the same time access other information which is included in Table 2. Using the reference the particular time history records are extracted from the time histories folder. The section from the file containing the velocity time history is then obtained from the file using the *submatrix* facility of Mathcad and the matrix is then transformed into a column vector and combined with the times to form a *.dta file for input into Working Model 2D.

Details of the ground acceleration spectra for the 3 events in table 2 are shown in figures 3. These have been selected from the ESMD because each event has different spectral characteristics. Despite having a short duration, recording 24 has a full frequency content and has a peak horizontal spectral acceleration of 6m/s^2

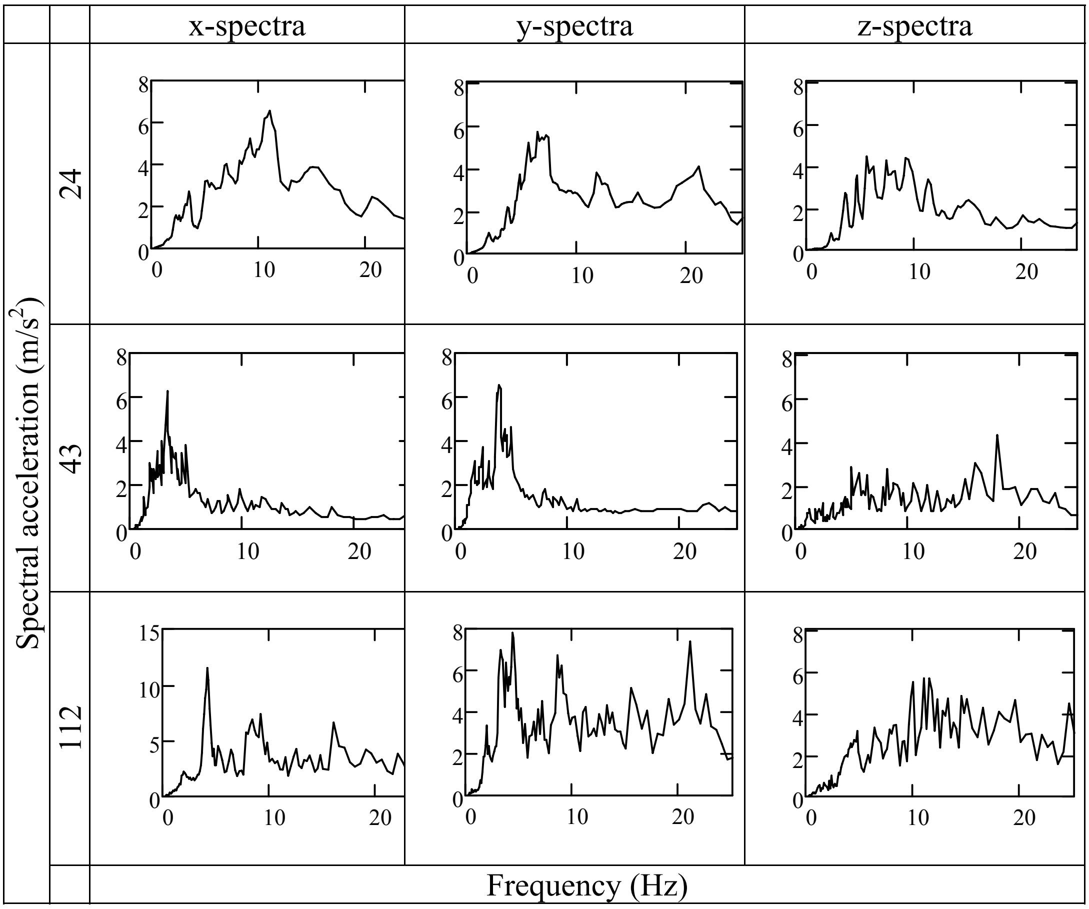


Figure 3: The ground acceleration spectra in the X, Y and Z directions for the example earthquakes in table 2

although the peak is not at the frequency of the wall. Recording 43 has similar peak horizontal spectral acceleration of 6m/s^2 and in this case it is at the frequency of the wall. Recording 112 has peak horizontal spectral acceleration of over 10m/s^2 which occur close to the frequency of the wall and also has a long duration. One of the objectives of the tests is to explore whether these characteristics of the input motion have a discernable effect on the output.

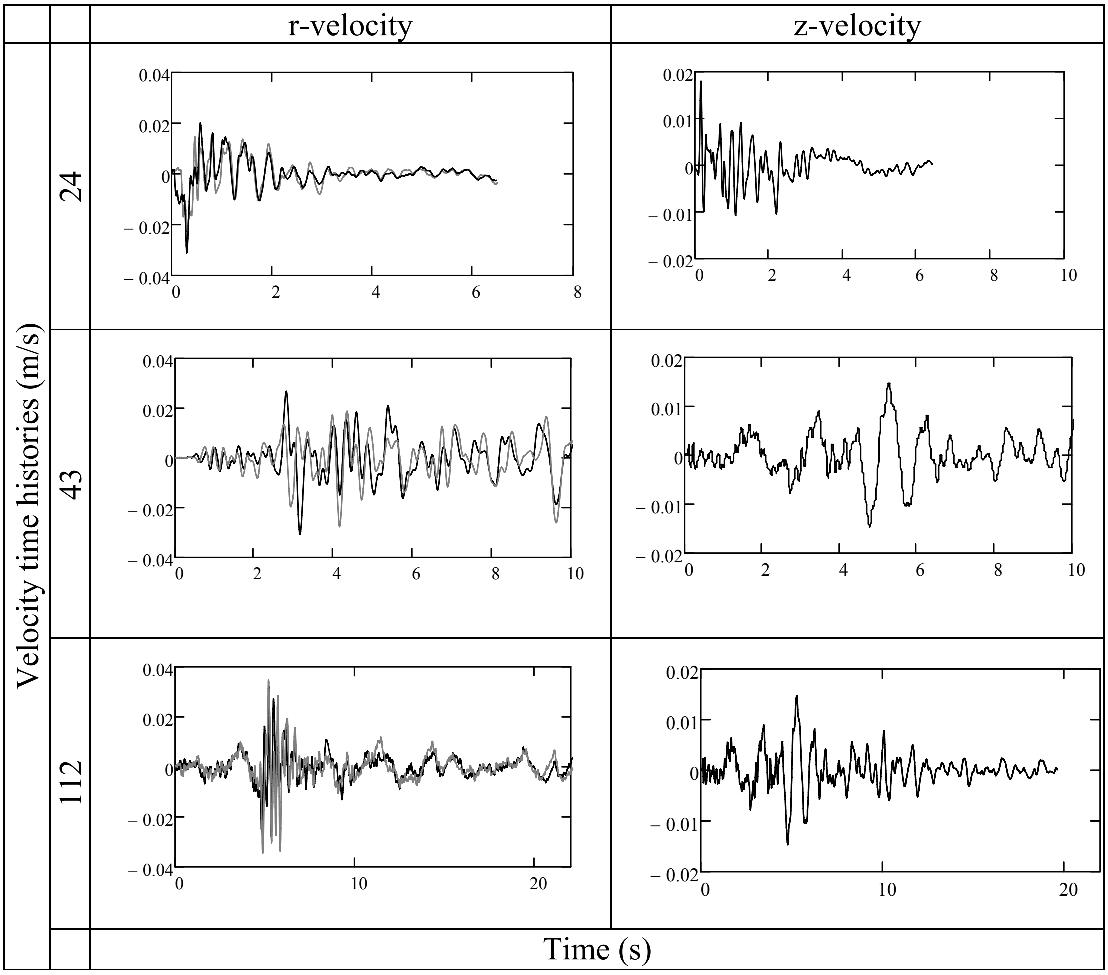


Figure 4: The velocity time histories for the example earthquakes in table 2 the third column shows the X-direction time history as the grey line and the resultant time history as the black line. The right column shows the Z-direction time history

In [3] Belsham shows the significance of considering the horizontal input motion as bi-directional and shows how the resultant can be determined probabilistically from the Power Spectral Density of the input motions. In this it is necessary to deal with the time histories and an alternative means of deriving the resultant is used. The approach makes the assumption that the likely maximum effect is with the resultant at an angle of $\pi/4$ from each component so that the combined effect is given by equation (3)

$$v_r(t) = \cos\left(\frac{\pi}{4}\right)\left(v_x(t) + v_y(t)\right) \tag{3}$$

where $v_r(t)$ is the resultant velocity time history and $v_x(t)$ and $v_y(t)$ are velocity time histories in the X and Y directions respectively.

The processed velocity time histories for the recordings in table 2 are shown in figure 4. In column 3 the resultant of the horizontal velocity time histories are shown as the black line with the X-direction velocity time histories shown as the grey line. Column 4 shows the vertical velocity time histories. The horizontal velocity time histories typically have a maximum velocity of 0.03m/s. It is seen that each time history has different characteristics in terms of where in time the maximum velocities occur.

2.3 The analysis

The definition of intensity level V in the MSK Intensity scale is:

> The earthquake is felt indoors by all, outdoors by many. Many sleeping people awake. A few run outdoors. Animals become uneasy. Buildings tremble throughout. Hanging objects swing considerably. Pictures knock against walls or swing out of place. Occasionally pendulum clocks stop. 'Few unstable objects may be overturned or shifted'. Open doors and windows are thrust open and slam back again. Liquids spill in small amounts from well filled open containers. The sensation of vibration is like that due to a heavy object falling inside the building.

The tests reported in this paper use the intensity indicator of small objects that may fall because it can be treated as a dynamic system and measured. The approach adopted has been to select a set of earthquakes that are representative of MSK Intensity level V. Using a 2-dimensional computer simulation using [4], each of these events has been applied to a set of small objects which are positioned on a shelf attached to a wall which is supported on a shake table. The seismic input motions in the form of velocity time histories are applied through the actuators.

The measure used in the test is whether the small object topples or not. Shifting and rocking of an object without toppling is recorded as not toppling even though toppling may nearly occur.

A large number of tests have been conducted and many have been recorded but only a few examples can be reported here. The total number of tests is therefore reported using a matrix system which is presented as tables. The main results are therefore presented against the, topple or no topple criteria.

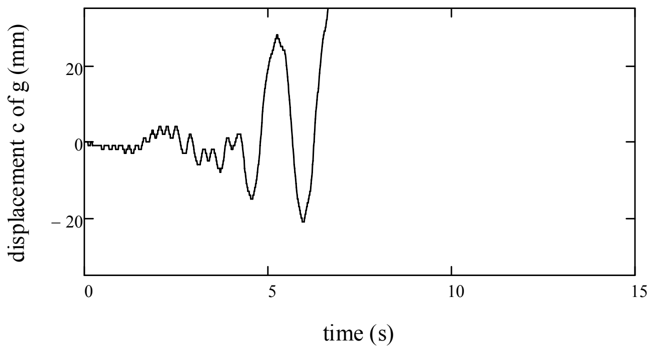
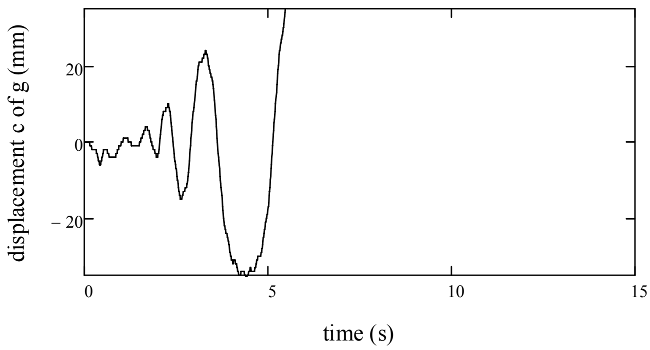
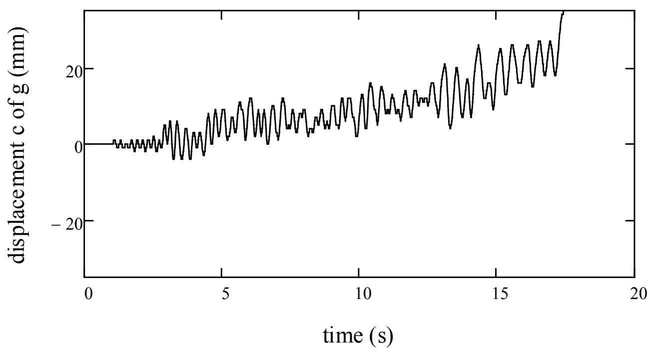
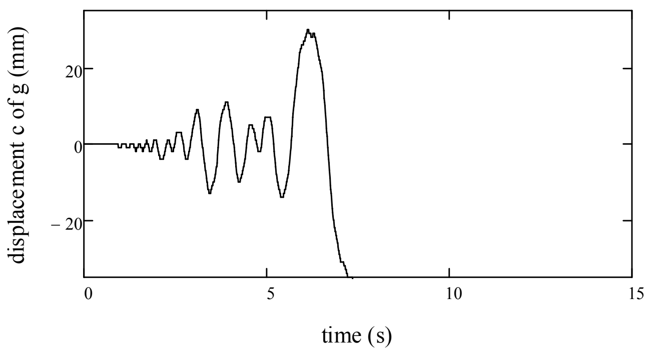
Event Ref	Conf.	Displacement response of the c of g of the test-piece
24	tp3,1	
24	tp3,11	
43	tp1,4	
43	tp3,9	

Figure 5: Sample plots of the displacement response of the centre of gravity (c of g) of the test-piece for recordings 24 & 43 and configuration in accordance with table 3

3 Results

The results of the investigations reported in this paper are for the testing of rocking bodies under seismic loading using a computer simulation. The nature of the test means that it is geometrically non-linear and dependent on the characteristics of the random input motion. This has required a large number of tests and it is only possible to report full results in terms of the response of the test-pieces for a small sample. For the other cases they are reported simply in terms of the key outcome which is toppled or no topple.

An important observation is that the test-piece R13 which is effectively on the ground did not topple in any configuration and as a result the reporting is just in terms of test-piece R38 located on the shelf.

Table 1 gives the different configurations for the test-piece which cover two coefficients of friction, two coefficients of restitution and three locations on the shelf, namely the edge the quarter position and the mid position. This produces twelve combinations and with six different blocks this is a total of seventy two tests for each input motion. In order to report the results in a compact form each of the different configurations for the block have been assigned a reference code between 1 and 12 as shown in Table 3. This is then used as a configuration reference in the

ref	μ	e	position
1	1	1	e
2	1	2	e
3	2	1	e
4	2	2	e
5	1	1	q
6	1	2	q
7	2	1	q
8	2	2	q
9	1	1	m
10	1	2	m
11	2	1	m
12	2	2	m

Table 3: A matrix showing the configuration references for the test-pieces

main results table, which is shown in table 4. Table 4 reports on the results from each event for each of the six different test-pieces in each of the twelve possible configurations. In table 4 an entry of t indicates that the block toppled with the configuration for that column and an entry of n indicates it did not topple. A blank entry means the configuration has not been tested because information gathered during test of other configurations indicated it would not topple.

Due to the large number of tests a degree of rationalisation has been employed during the tests in cases where it is obvious toppling will not occur have not been performed.

Some selected examples of the displacement motion of the centre of gravity of the block are given in figure 5. They cover both cases where toppling has occurred and those where it does not. The references are composed of the event reference, the test-piece reference, the code for the coefficient of friction, the code for the coefficient of restitution and the code for the position on the shelf, where the last three codes correspond to those in table 3.

Event ref	Test piece	Configuration reference											
		1	2	3	4	5	6	7	8	9	10	11	12
24	tp1	n	n	n	n				n				n
	tp2	n		n	t			n	n		n	n	t
	tp3	n	n	t	n	t	n	t	n	n	n	t	n
	tp4	n			t				n	n			n
	tp5	n	n		n	n				n	n		n
	tp6			n	n		n					n	n
43	tp1	n		n	t								n
	tp2	n	n		t								n
	tp3	t	n	t	t		n		n	t	t	t	n
	tp4		n		n						n		n
	tp5	n	n		n						n		n
	tp6	n	n	n	n							n	n
112	tp1		n		n								n
	tp2	n	n	n	n						n		n
	tp3			n	n		n		n				n
	tp4			n	n								
	tp5			n	n							n	
	tp6	n	n	n	n		n		n				n

Table 4: A matrix showing the conditions under which toppling has occurred in terms of the configuration of the test-piece and the characteristics of the input motion designated by the event reference

4 Discussion

The main results are presented in table 4 which reports which objects toppled under which configuration and which seismic recording. To quantify the results the entries where toppling occurs in table 4 are summed by rows and by columns. The rows provide information in terms of the event and the columns on the configurations.

Discussing the results in terms of the configurations, the test-pieces positioned at the edge of the shelf had the largest number of topples followed by those positioned at mid point. When at quarter positions there were relatively few topples. From observations during the tests it appears that the motion of the shelf is similar between the quarter position and the mid position and therefore does not contribute so much to the rocking of the test-piece. At the edge and mid positions, the shelf motion is approximately synchronised with but is out of phase by π with the rocking of the test-piece. The rocking of the test-piece therefore increases at each impact, by gaining energy from the opposing motion of the shelf. However, as this reasoning is based on observation alone, further detailed analysis is required to confirm this hypothesis.

When the test-piece is at the edge the higher coefficient of friction is significant. This is principally because it allows more force to be imparted into the test-piece during the short contact interval and leads to increased rocking and at the same time moves the test-piece over the edge of the shelf, which reduces the width of the base and reduces the stability by shortening the lever arm, albeit slightly. Of the topple cases 11 out of the 15 cases are for the higher friction. In all cases which involve toppling with increased coefficient of restitution it is the factor that leads to the toppling and occurs in 5 cases.

It is concluded that both the coefficient of friction and the coefficient of restitution are important contributors to whether the test-piece topples. In practice the coefficient of friction is likely to vary considerably due to the different material involved but the values used in the test will cover most cases. Also in practical situations the coefficient of restitution will be high as the impacts have low interaction forces and will remain elastic leading to the choices in the test.

The effects of the seismic input motion are clear although the particular characteristics leading to the results are not. Record 24 caused 7 cases of toppling, record 43 caused 8 cases of toppling but record 112 caused none despite having marginally the highest velocity and the longest duration. Inspection of the velocity time histories shown in figure 4 show that record 112 has a much shorter strong motion duration that either records 24 and 43. However record 112 has a significant acceleration spectral content compared in particular with record 43. Further investigation is required to determine the characteristics of the input motion that has such a significant effect on the toppling.

5 Conclusion

From the results and the analysis in the discussion section it is clear that whether an object topples is strongly dependent on the characteristics of the seismic input. Most notable is that higher accelerations and velocities do not necessarily result in more cases of toppling. From the small set of example recordings it appears to be the duration of the strong motion velocity rather than the peak value that leads to the toppling, although a minimum magnitude of velocity is required.

A higher coefficient of friction and higher coefficient of restitution are contributors to increased toppling. Both of these parameters increase the amount of energy that can be transferred into the test-piece.

During observation of the test it was clear that in several cases toppling almost occurred and slight increases in the input motions would have resulted in toppling. This suggests that it might be pragmatic to modify the definition for the intensity indicator to include rocking motion as well as overturning or toppling.

In all cases the test-pieces positioned on the floor did not topple. It is worth noting that the floor rigidly follows the input motion but if a dwelling was on soft soil so that there is horizontal foundation compliance then the results may be different. This situation would also affect the response of the wall, making it an interesting set of conditions for future studies.

The simulation of shake table tests for the toppling of small objects for intensity level V seismic shaking has proved to be a satisfactory way for testing correspondence between the intensity indicator and intensity calibrated input motion. This provides a practical method for exploring other intensity indicators that respond as dynamic mechanical systems. This should lead to an improved understanding of how intensity levels relate to other seismic parameters.

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