13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1634

OVERTURNING OF ROCKING BLOCKS

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SUMMARY

Several previous studies have evaluated the likelihood that rigid blocks will overturn when subjected to dynamic excitation. These previous results indicate a complex theoretical solution that bifurcates depending on the input motion and modeling of the block properties. In general, the studies are not readily useful for engineering purposes to evaluate the possibility of overturning of rocking blocks or rigid equipment during an earthquake. For the current study, we subjected a series of rigid blocks of different sizes and aspect ratios to several recorded ground motions. The analysis of the blocks was done using the program Working Model, a program that analyzes rigid body motion of blocks and includes consideration of friction and the restitution characteristics between the blocks and the supporting surface. Our results show that if the aspect ratio is held constant, overturning is strongly dependent on the size of the blocks and on the size and shape of the displacement response spectra. In general, objects with widths that are relatively large compared to the displacement demand do not overturn independent of their height. Based on results of the current study, some rules of thumb are provided that indicate the relative vulnerability to overturning for different types of rigid blocks subjected to earthquake ground motion.

INTRODUCTION

Industrial facilities, nuclear power plants, commercial and residential facilities, in fact, nearly every type of facility built for human occupation or use contains some number of items that could be characterized as rocking blocks when subjected to seismic ground motion. As used herein, a rocking block is an unanchored rigid object of uniform density that is rectangular both in plan and elevation. While few objects exactly match this description, many objects are sufficiently similar that they can be characterized generally in this way. This might include many types of nonstructural items, equipment, furniture, shipping containers, etc. The task of anchoring all of these items is daunting. More productive perhaps is to assess which ones are most vulnerable to overturning and focus attention on the anchorage or protection of those items.

Makris[1,2,3] et al have previously written about the theoretical bases for overturning of such objects. These studies investigated the overturning of free-standing blocks subjected to cycloidal pulses and anchored blocks subjected to pulse-type motion. The authors indicate that their theoretical solution

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bifurcates into what they refer to as an "overturning zone" and a "safe zone." These studies are theoretical and the results do not readily translate into guidelines for the design engineer.

The current study is based on a series of simulated experiments, that is, experiments conducted by running a large number of nonlinear time history computer analyses. The purpose of this study is to assess the overturning behavior of unanchored rigid blocks situated at or near ground level and to see how the overturning behavior varies with block size, aspect ratio, or the seismic characteristics of the ground motion. Using "common sense," one might predict that a family of thin blocks with aspect ratios of 5.0 would all experience incipient tipping at the same point for a given ground motion, independent of size. Or similarly one might predict that a family of squat blocks with aspect ratios of 1.0 would not overturn at all, independent of size or ground motion. The point of this paper is to investigate the influence of base width and aspect ratio on the overturning behavior of these blocks. Block characteristics were chosen to be representative of some types of unanchored rigid equipment and have varying base dimensions and varying heights. The dynamic behavior of the blocks was studied by subjecting each block to earthquake ground motions using a two dimensional dynamic analysis program with large deformations.

METHODOLOGY

For this study, we have selected a family of four earthquake ground motion time histories and a family of blocks with varying sizes. Each block was subjected to a series of analyses to determine the point of incipient tipping. This procedure is described below.

Ground Motion Records

Four ground motion time histories were selected for use in this investigation. Each record has somewhat different characteristics as shown in Table 1.

Table 1. Ground Motion Records

Earthquake	Station	Peak Acceleration (cm/sec^2)	Peak Velocity (cm/sec)	Peak Displacement (cm)	Portion of Record Used, sec
Santa Cruz Mtns (Loma Prieta)- October 17, 1989 17:04 PDT	**Capitola** Chan 3: 0 DEG	-462.92	36.15	11.02	0.0-16.0
Northridge- January 17,1994 04:31 PST	**Sylmar**-County Hospital Parking lot Chan 1: 90 DEG	592.64	76.94	15.22	2.4-16.4
Southern Peru (Atico)- June 23, 2001	**Moquegua**: EW	295.3	24.9	4.6	39.2- 59.2
Iran, Tabas- September 16, 1978	9101 **Tabas**: Transverse	835.81	121.4	94.58	4.0-16.0

The portion of the station name shown in bold type in Table 1 is used as the record name in the tables or figures that follow. The Working Model analyses are limited to 2000 time steps, so the records were truncated to accommodate these limitations. The portions of the records used for our time history analyses are indicated in Table 1.

Of these records, Moquegua has the longest duration but moderate accelerations. Capitola and Sylmar both had relatively higher accelerations and in addition, Sylmar had a significant velocity pulse. The Tabas record is the highest by all three measures; peak acceleration, peak velocity, and peak displacement.

In all cases, the peak ground accelerations (PGA's) are less than 1.0g; two of the four records have PGA's under 0.5g. Note that these are all ground motion records and thus represent behavior at or near ground or in rigid structures; these are not representative of building response records. To put these records into context, Table 2 provides a summary of ground motion records currently available from the Cosmos Virtual Data Center [4].

Table 2. Summary of Ground Motion Records with PGA Greater than 0.5g

	No of Records	PGA >0.5g	PGA >0.6g	PGA >0.7g	PGA >0.8g	PGA >0.9g	PGA >1.0g
All ground motion records	2,948	46	28	18	11	8	5
Northridge Earthquake only	484	16	9	8	4	4	2

Only 46 of 2,948 available ground motion records have PGA's in excess of 0.5g, representing 1.6% of the available records. For the Northridge earthquake, 3.3% of the 484 ground motion records have PGA's in excess of 0.5g. For most situations it is reasonable to take a PGA of 1.0g as the upper bound of the range of interest.

Rocking Block Properties

The dimensions of the blocks studied were chosen to be representative of typical items, but also to make several points regarding the relative importance of base size compared to the other factors. Six base dimensions were selected ranging from 0.2 meters to 1.5 meters. Six b/h ratios were selected ranging from 0.1 to 1.0. The corresponding aspect ratios, h/b, range from 10 to 1.0. Table 3 summarizes the 36 block sizes studied.

Table 3. Rocking Block Dimensions and b/h Ratios

Ratio, b/h	0.1	0.2	0.3	0.4	0.5	1.0
Ratio h/b	10.0	5.0	3.33	2.5	2.0	1.0
Base, meters			**Height, meters**			
0.2	2.00	1.00	0.67	0.50	0.40	0.20
0.3	3.00	1.50	1.00	0.75	0.60	0.30
0.5	5.00	2.50	1.67	1.25	1.00	0.50
0.8	8.00*	4.00	2.67	2.00	1.60	0.80
1.0	10.00*	5.00	3.33	2.50	2.00	1.00
1.5	15.00*	7.50*	5.00	3.75	3.00	1.50

*Improbable dimensions for freestanding objects.

As indicated in Table 3, the smallest block is 0.2m wide by 0.2m high. The largest block is 1.5m wide by 15m high; improbable dimensions for a freestanding object, but included here to test the hypotheses that blocks with wide bases do not overturn independent of height. As we have used a two-dimensional program for these analyses; the depth or length of each block is unity. Each block is considered to have uniform density of $1 g/cm^2$. We set the coefficients of static and kinetic friction between the base surface and the block to be 1.0 in order to limit the possibility of sliding, although this did not eliminate sliding. The elasticity, or coefficient of restitution for collisions between the base surface and the block, was set at 0.5.

Analysis Procedure

The program Working Model 2D [5] was used for these analyses. An iterative procedure was used by rerunning each case with successively higher or lower scale factors until the block just overturned. The scale factor was then recorded for each run. The scale factor multiplied by the PGA of the original record indicates the PGA needed to overturn the block for that record. On average, it required about 10

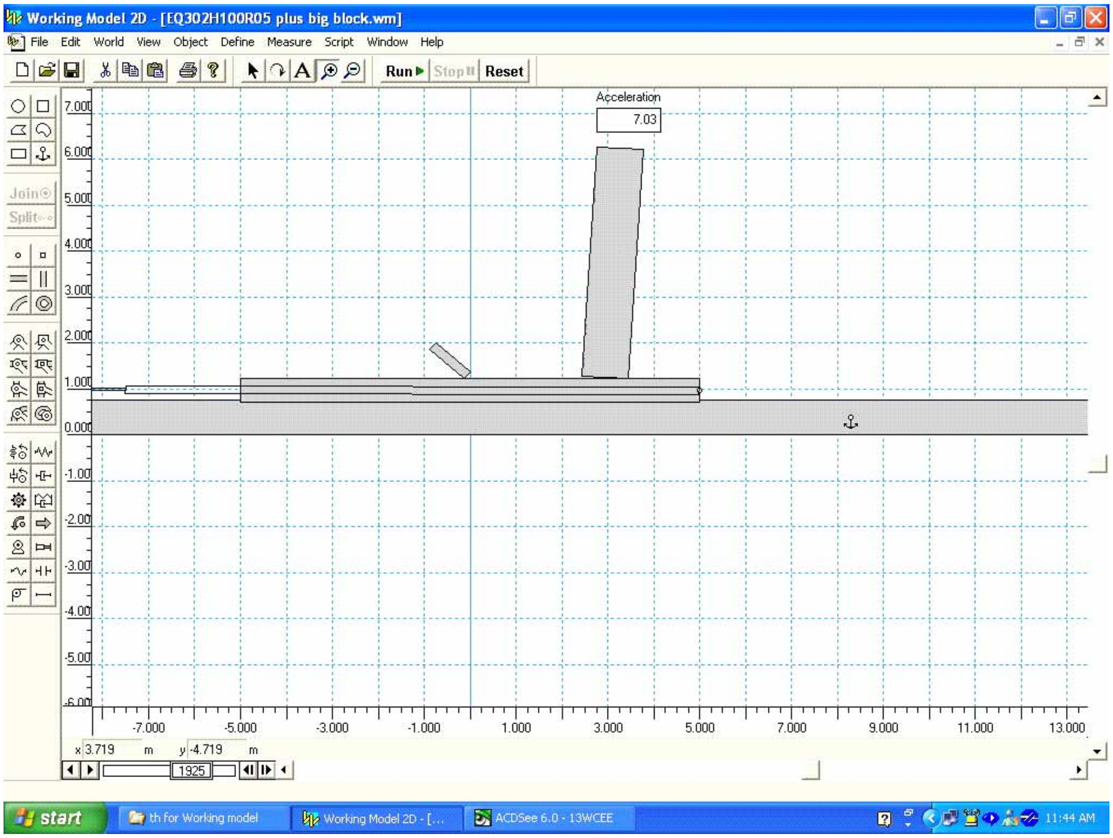

Figure 1. Rocking Block Illustration: B/H=0.2, Smaller block begins to overturn

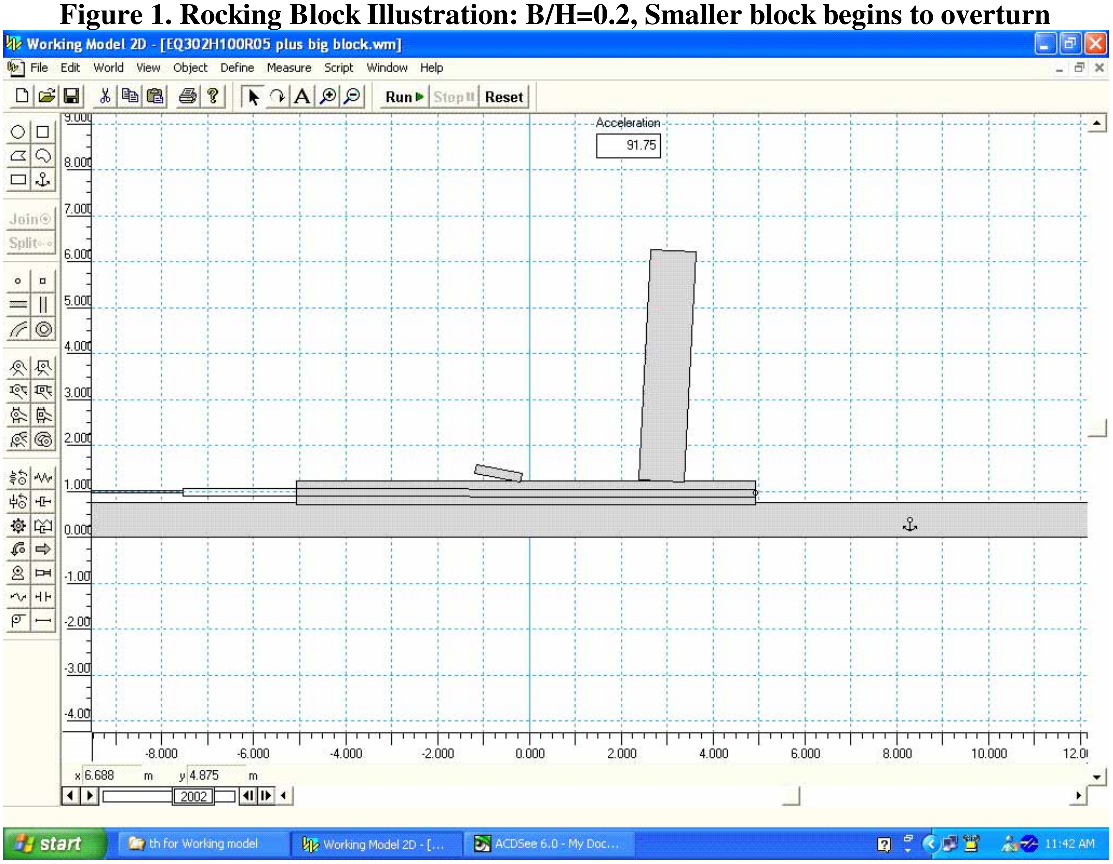

Figure 2. Rocking Block Illustration: B/H=0.2, Smaller block falls

iterations of each run to identify the point of incipient tipping, that is, the lowest scale factor that would cause overturning. The results reported herein represent approximately 1440 separate time history analyses for the 36 blocks and 4 ground motion records.

Two screen shots from Working Model are provided in Figures 1 and 2 above. For our analyses, we ran each block separately, but these figures are illustrative of the behavior. In Figure 1, two blocks with the same aspect ratio, or same b/h ratio, are simultaneously subjected to the same motion. In this case, the b/h ratio is 0.2 or the aspect ratio is 5. The smaller base measures 0.2m and the larger base measures 1.0m. The Capitola record was used for this example. The smaller block begins to overturn in Figure 1 and then falls completely in Figure 2. The block with the 1.0m base does not fall at the same level of excitation required to overturn the smaller block.

ANALYTICAL RESULTS

For each of the time history runs, a scale factor was recorded indicating the multiple of the original PGA required to reach incipient overturning for that particular block size and shape. The original PGA from each record was scaled to find the effective PGA required to overturn each block. Thus, the record "Capitola" refers to the shape of the original record, not to the original PGA which may have been scaled up or down to induce overturning in each block. Scale factors for these records ranged widely as shown in Table 4, indicating that very large PGA's are required to overturn many of the blocks studied. In each case, the minimum scale factor is the one required to overturn the smallest tallest block considered (b/h=0.1, base=0.2m) and the largest scale factor is the one required to overturn the largest squat block considered (b/h=1.0, base=1.5m).

Table 4. PGA Required to Overturn Rocking Blocks

Ground Motion Record	Original PGA, g	Minimum Scale Factor (b/h=0.1, base-0.2m)	Minimum scaled PGA,g (b/h=0.1, base-0.2m)	Maximum Scale Factor (b/h=1.0, base=1.5m)	Maximum scaled PGA,g (b/h=1.0, base=1.5m)
Capitola	-0.47	0.83	-0.39	15.00	-7.08
Sylmar	0.60	0.48	0.29	12.70	7.67
Moquegua	0.30	1.18	0.36	27.60	8.31
Tabas	0.85	0.40	0.34	5.30	4.52

While Table 4 shows that small, tall blocks are vulnerable to overturning, it also shows that it is very difficult to overturn squat blocks with a base of 1.5 meters. The 4-8g PGA required to overturn large squat blocks is way outside the range of expected ground motion. Between these extremes though, the results vary as shown in the plots that follow.

The results are presented graphically with four plots on each of the next 4 pages. In each case, the vertical axis in the plot represents the scaled PGA's required to induce overturning. Both base dimension and b/h ratio are used for the horizontal axes. On each page, the plots on the left side have a vertical scale required to present all the data points from 0 to 9000 cm/sec^2 or roughly 0-9.0g. The plots on the right side are enlarged to show the range of interest from 0 to 1000 cm/sec^2 or roughly 0-1.0g. Figure 3 shows all results together for all blocks and all ground motion records. The two plots at the top of the page use the base dimension for the horizontal axis, thus each curve represents one b/h ratio and one record. The two plots at the bottom of the page use the b/h ratio for the horizontal axis, thus each curve represents one base dimension and one record. Figures 4a, 4b, and 4c are the top two plots from Figure 3 separated out for each b/h ratio, thus each plot has one curve for each of the 4 ground motion records.

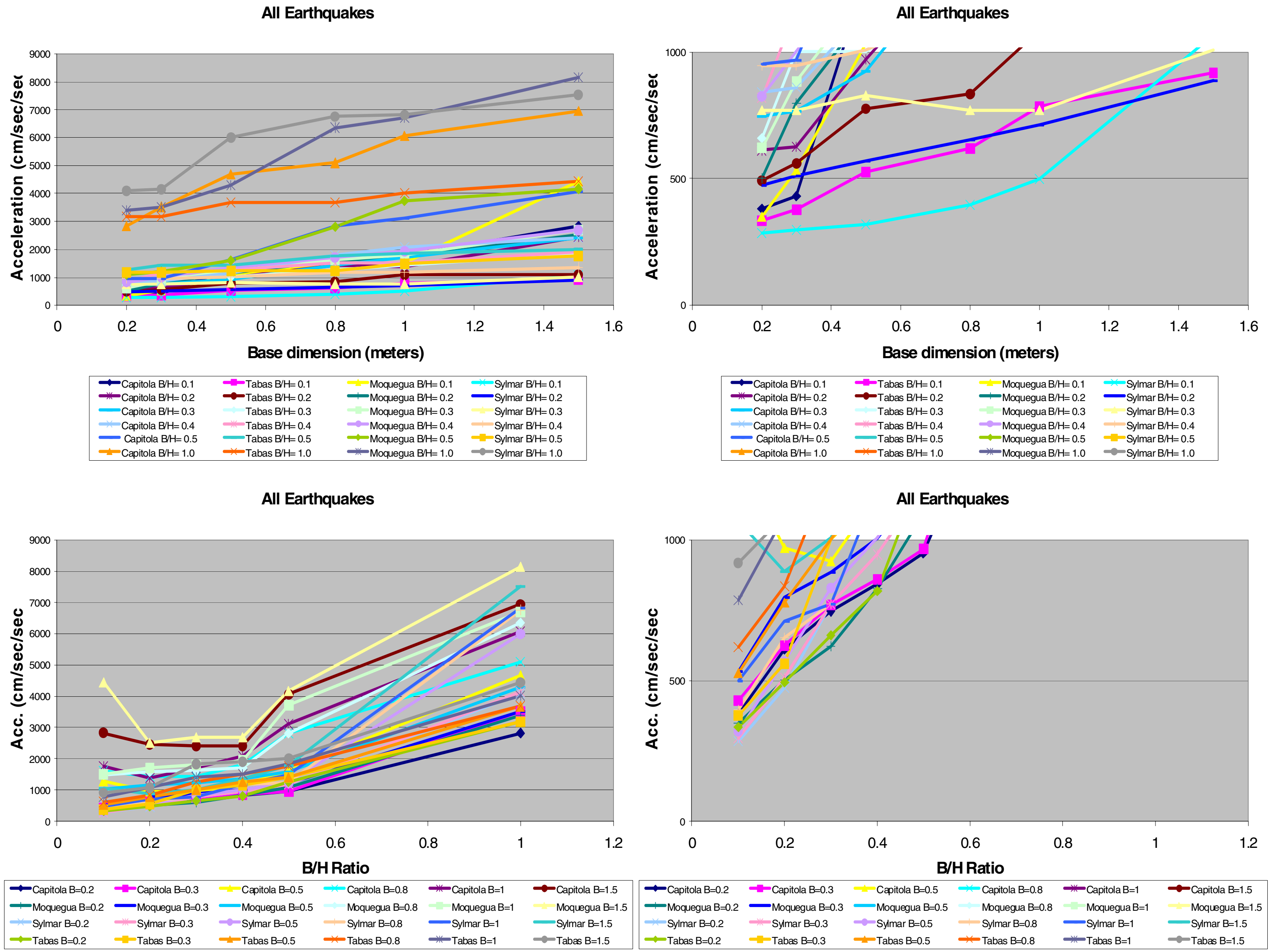

Figure 3. PGA to Overturn Rocking Blocks, All Data Considered

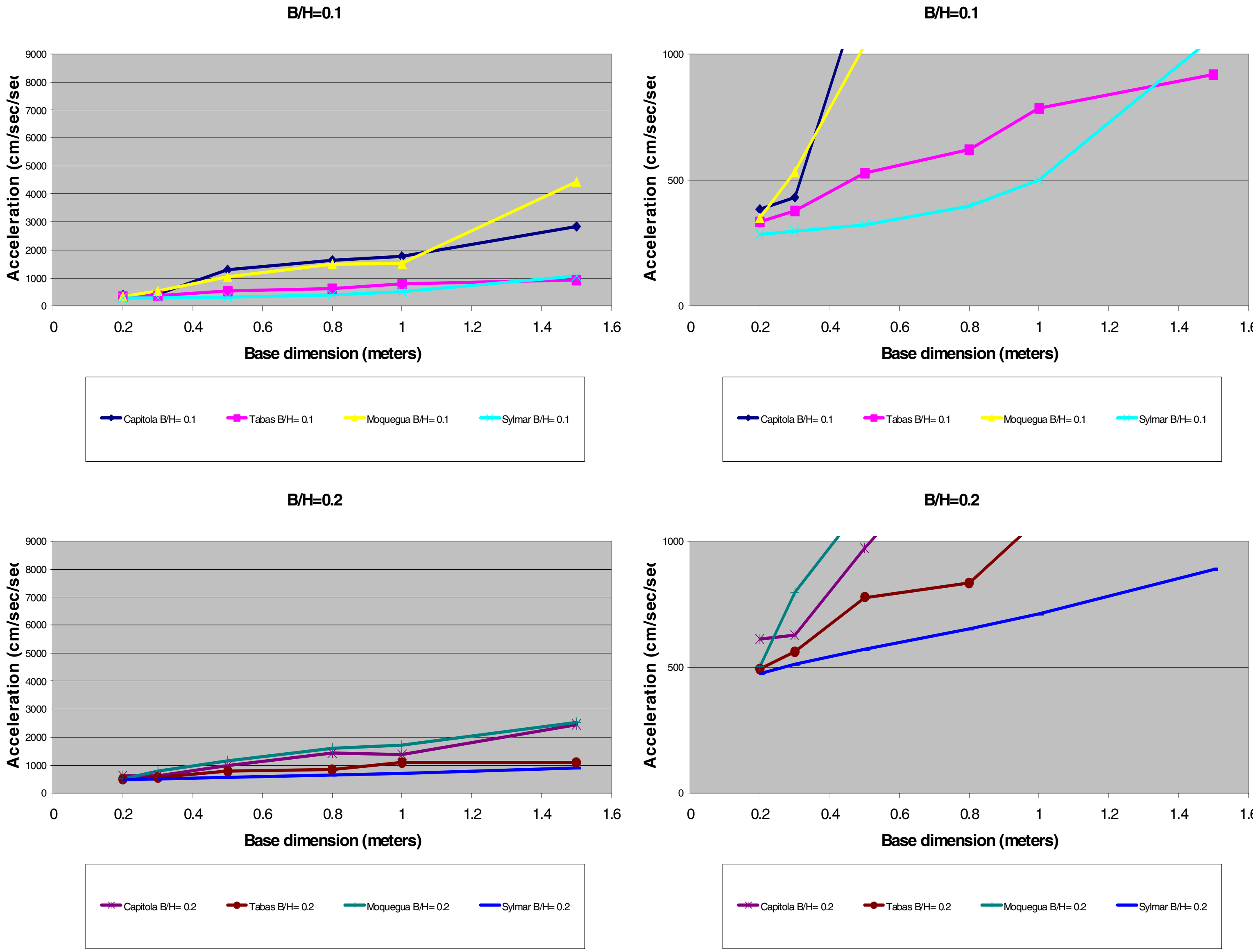

Figure 4a. Rocking Block Behavior for B/H of 0.1 and 0.2 (H/B of 10 and 5)

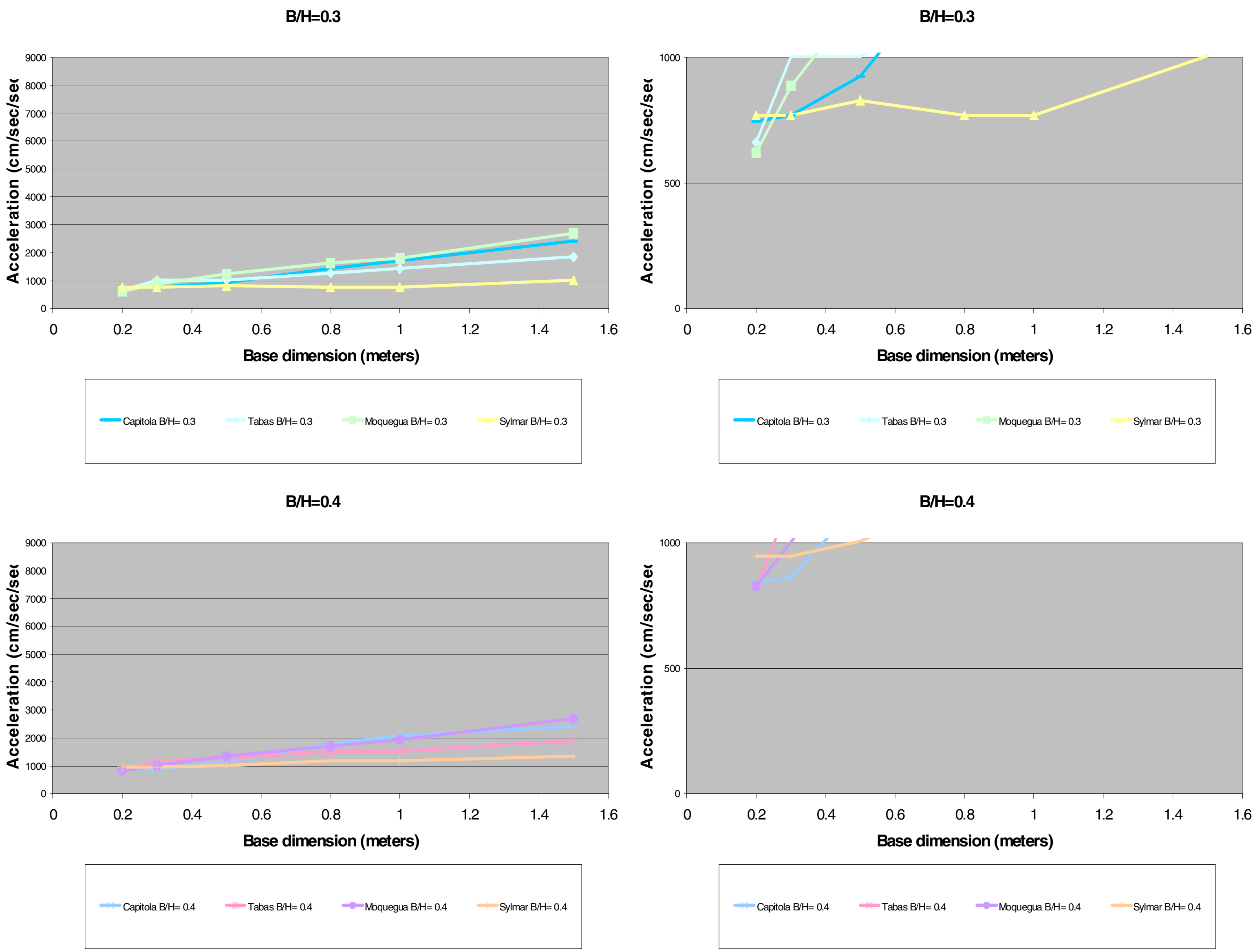

Figure 4b. Rocking Block Behavior for B/H of 0.3 and 0.4 (H/B of 3.3 and 2.5)

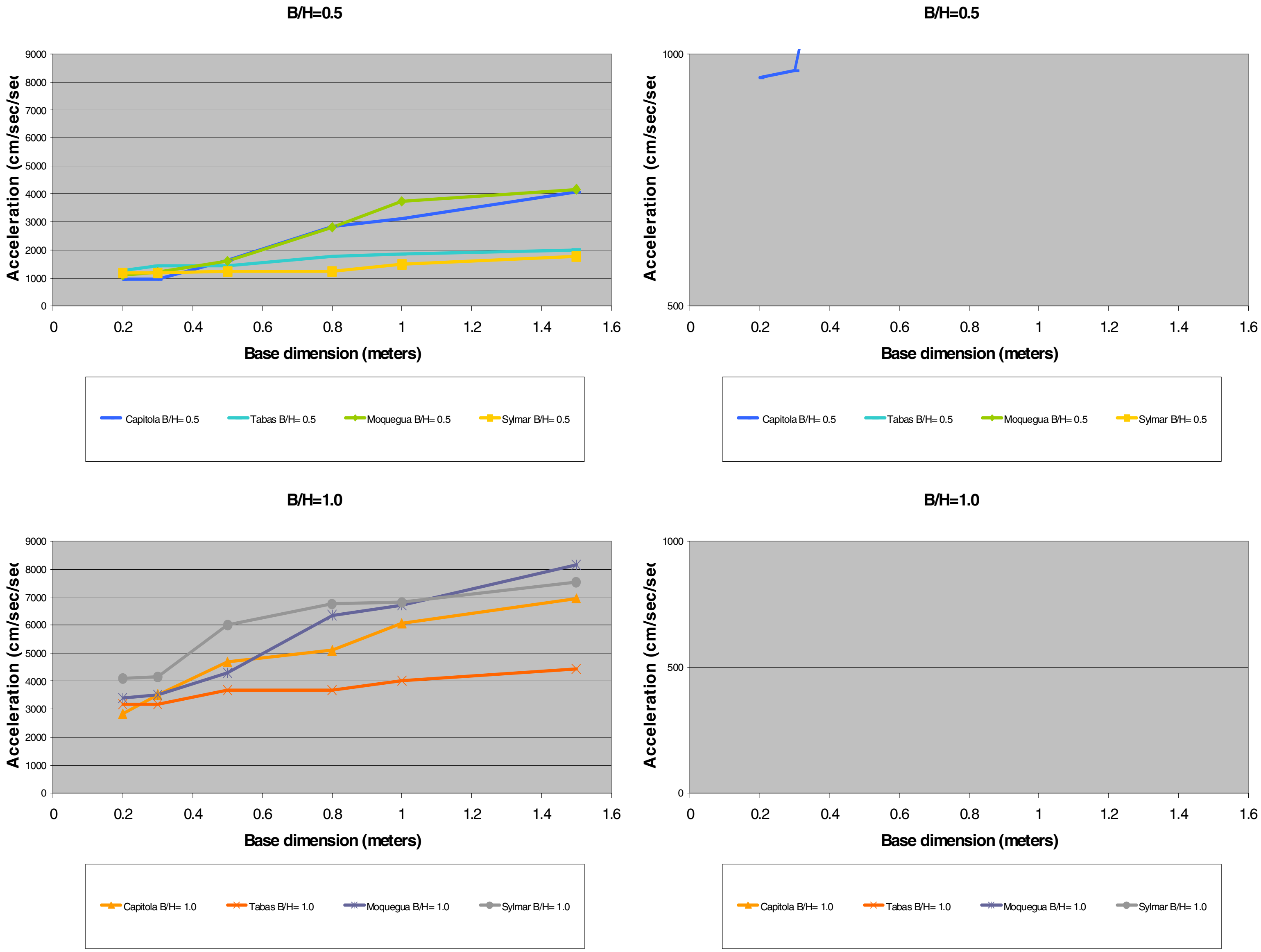

Figure 4c. Rocking Block Behavior for B/H of 0.5 and 1.0 (H/B of 2 and 1)

DISCUSSION

One thing quite apparent from the data presented in Figures 3 and 4 is that many of the blocks studied did not overturn unless subjected to extraordinary accelerations above 1.0g and therefore outside the range of interest. Also apparent, is that items with the same aspect ratio become more stable and less vulnerable to overturning with increasing base dimension. In the range from 0 to 0.5g, only blocks with b/h ratios less than 0.2 overturned, that is, those with aspect ratios greater than 5. In the range from 0 to 1.0g, only blocks with b/h ratios less than 0.5 overturned, that is, those with aspect ratios greater than about 2. Of equal import is that items with large base dimensions of 0.5m or greater do not overturn with accelerations less than 1.0g until the block becomes sufficiently tall with b/h ratios less than 0.3 or aspect ratios greater than 3. Even objects with base dimensions of 0.3m and greater are quite unlikely to overturn with accelerations less than 0.5g as long as the b/h ratio is 0.2 or less.

Tables 5, 6 and 7 summarize the data in tabular form. Blocks that overturned for any of the four records are shown in bold type indicating that these were the block sizes vulnerable to overturning. The blocks shown in italics were not vulnerable to overturning for the ground motion records considered.

The influence of the velocity pulse in the Sylmar record can be seen in Figures 3 and 4 and also by comparing Tables 5 and 6. A number of items that did not overturn below 1.0g for the other three records, tipped over when subjected to the Sylmar record. Below 0.5g, only 3 of the 36 blocks studied overturned for the 3 records excluding Sylmar but 6 items overturned when the Sylmar record is included. The Sylmar record caused the low b/h items to overturn at the lowest accelerations.

Table 5. Rocking Blocks Vulnerable to Overturning for PGA of 0.5g and below (All records excluding Sylmar)

Ratio, b/h	**0.1**	**0.2**	0.3	0.4	0.5	1.0
Ratio h/b	**10.0**	**5.0**	3.33	2.5	2.0	1.0
Base, meters	**Height, meters**					
0.2	**2.00**	**1.00**	_0.67_	_0.50_	_0.40_	_0.20_
0.3	**3.00**	_1.50_	_1.00_	_0.75_	_0.60_	_0.30_
0.5	_5.00_	_2.50_	_1.67_	_1.25_	_1.00_	_0.50_
0.8	_8.00*_	_4.00_	_2.67_	_2.00_	_1.60_	_0.80_
1.0	_10.00*_	_5.00_	_3.33_	_2.50_	_2.00_	_1.00_
1.5	_15.00*_	_7.50*_	_5.00_	_3.75_	_3.00_	_1.50_

*Improbable dimensions for freestanding objects.

Table 6. Rocking Blocks Vulnerable to Overturning for PGA of 0.5g and below (All records)

Ratio, b/h	**0.1**	**0.2**	0.3	0.4	0.5	1.0
Ratio h/b	**10.0**	**5.0**	3.33	2.5	2.0	1.0
Base, meters	**Height, meters**					
0.2	**2.00**	**1.00**	_0.67_	_0.50_	_0.40_	_0.20_
0.3	**3.00**	_1.50_	_1.00_	_0.75_	_0.60_	_0.30_
0.5	**5.00**	_2.50_	_1.67_	_1.25_	_1.00_	_0.50_
0.8	__8.00*__	_4.00_	_2.67_	_2.00_	_1.60_	_0.80_
1.0	__10.00*__	_5.00_	_3.33_	_2.50_	_2.00_	_1.00_
1.5	_15.00*_	_7.50*_	_5.00_	_3.75_	_3.00_	_1.50_

*Improbable dimensions for freestanding objects.

Table 7. Rocking Blocks Vulnerable to Overturning for PGA of 1.0g and below (All records)

Ratio, b/h	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	1.0
Ratio h/b	**10.0**	**5.0**	**3.33**	**2.5**	**2.0**	1.0
Base, meters	**Height, meters**					
0.2	**2.00**	**1.00**	**0.67**	**0.50**	**0.40**	*0.20*
0.3	**3.00**	**1.50**	**1.00**	**0.75**	**0.60**	*0.30*
0.5	**5.00**	**2.50**	**1.67**	*1.25*	*1.00*	*0.50*
0.8	**8.00***	**4.00**	**2.67**	*2.00*	*1.60*	*0.80*
1.0	**10.00***	**5.00**	**3.33**	*2.50*	*2.00*	*1.00*
1.5	**15.00***	**7.50***	*5.00*	*3.75*	*3.00*	*1.50*

*Improbable dimensions for freestanding objects.

The data shows that for earthquake ground motion, where the direction of motion is constantly reversing, objects with large bases may rock for many cycles without falling, while objects with small bases tend to become unstable after only a few cycles and fall. While items with a large aspect ratio are more vulnerable to overturning than items with a small aspect ratio, if the aspect ratio is held constant the tendency to overturn decreases with increasing base dimension.

This study addresses the possibility of overturning; clearly some types of damage are also linked to sliding, particularly if equipment is connected to wires or piping or if the item would be damaged by impact. The Working Model program allows both sliding and overturning and some of the items studied slid prior to overturning, or slid without overturning. The large and squat items not vulnerable to overturning are in fact more vulnerable to sliding than the small and tall ones.

CONCLUSIONS

The overturning behavior of unanchored rigid blocks of uniform density located at ground level varies widely depending on base dimensions, aspect ratio, and the characteristics of the ground motion record. Nevertheless, some generalizations can be drawn from the results of this study:

- For a given aspect ratio, the acceleration required to overturn an object stays constant or increases with increasing base dimension. (Qualification: One minor exception out of 144 data points.)
- For a given base dimension, the acceleration required to overturn an object increases with decreasing aspect ratio or increasing b/h ratio. (Qualification: Exceptions for some items with b/h of 0.1 or less and items marked as having improbable dimensions.)
- Items with narrow bases are vulnerable to overturning, independent of height. (Qualifications: Narrow base here is 0.3m or less, squat items with b/h of 1.0 or less are exceptions, and acceleration required for overturning increases as item becomes more squat.)
- Items with broad bases are not vulnerable to overturning, until the b/h ratio is 0.3 or less. (Qualifications: Broad base here is 0.5m or more, accelerations must be in the range 0.5-1.0g. For accelerations less than 0.5g, only the tall items with b/h=0.1 will overturn.)
- Few items of the sizes studied here will overturn for motion of 0.5g or less but thin items with b/h of 0.1 or less are vulnerable if the record contains a significant velocity pulse.
- Very large PGA's are required to overturn most unanchored objects located at ground level. From observation, we know many items do overturn during earthquakes, but these are largely items located above ground level in flexible structures.

In summary, in order to minimize the possibility of overturning of rocking blocks, it is advantageous to favor items with large base dimensions for any future purchasing, it is more critical to anchor vulnerable items with small base dimensions and small b/h ratios, and the preferred location for any expensive and sensitive equipment is ground level.

While the current study looked at overturning of rigid items located at or near ground level, the authors intend to broaden the scope of this study to included building records in the future, and also to identify the point of incipient sliding in objects that do not overturn.

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