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Shaking Table Tests on Cluttered Levels of Typical Medicine Shelves and Contents Subjected to Earthquakes

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Synopsis

Cluttered situations due to overturned and fallen objects is a frequently observed phenomenon after earthquakes. This study investigates quantitatively cluttered situations due to typical medicine shelves and contents in hospitals by shaking table tests. Three types of typical medicine shelves are adopted: stock shelf, tablet and powder medicine shelves. Input excitations include sinusoidal waves and real earthquake motions. From the results of sinusoidal wave tests, quantitative information on cluttered situations is expressed in maximum input accelerations and velocities. Then, from the results of earthquake motion tests, the results of sinusoidal excitation tests are compared and revised for evaluating the cluttered situations under earthquakes.

Keywords: clutter, overturning, hospital, medicine shelf, shaking table

1. Introduction

Cluttered situations due to overturned and fallen objects is a frequently observed phenomenon after earthquakes. Objects placed in a shelf drop out on the floor and cause a cluttered situation before the shelf overturns. Lots of researches on overturning of furniture have been conducted. The criteria proposed by Ishiyama (1982) are extensively adopted to evaluate whether a piece of freestanding furniture overturns under earthquakes. However, compared with the studies on overturning, so far no researches were conducted on cluttered situations. Because the types of objects, shelves and the methods of their placement are quite diverse, it is difficult to obtain general criteria like those for overturning. While, on the other hand, if the evaluation objects are determined, an experimental approach will obtain direct and reliable results. Hence, this study focuses on typical medicine shelves and contents in hospitals, and investigates quantitatively the cluttered situations by shaking table tests.

2. Shaking Table Test

2.1 Test specimens

The test specimens included three conventional types of medicine shelves: stock shelf, tablet and powder medicine shelves, as shown in Fig 1. Table 1 indicates the dimensions of the specimens. The breadth W and height H of the shelf are the test parameters. Totally, five, three and one specimens are adopted for the three types, respectively. In the tests, to simulate the real situation to the best extent, under a pharmacist's directions, real packages and bottles were infilled with sand bags to have proper weights, and were placed in the shelves following the same method in the hospitals.

2.2 Test setup, loading program and measurements

A series of tests were conducted in the Disaster Prevention Research Institute (DPRI), Kyoto University. The shaking table, with a plan dimension of 5 meter in longitudinal direction by 3 meter in transverse direction, is capable of simulating three-directional excitations. A reinforced concrete (RC) wall was constructed on the shaking table along the table's transverse direction for reproducing the conventional placement condition of the shelf: against a wall (Fig. 2). The floor slab was sprayed with linoleum that is a floor finishing material commonly used in pharmacies and laboratories due to the characteristics of pollution-proof and easy-to-clean. To observe and record test results conveniently, the floor slab is marked with grid lines at an interval of 20 cm.

The input excitations included two types: sinusoidal waves and earthquake motions. As for the sinusoidal wave, this study adopted the same settings as in the researches on overturning of office furniture conducted by Kaneko et al. (2004) and Tamura et al. (2005). The frequency and acceleration magnitude were set for each excitation. The frequencies included 0.5, 0.75, 1.0, 1.5, 2.0 and 3.0 Hz, which are the likely range of equivalent frequencies of earthquakes, calculated by Eq. 1 (Kaneko et al. 1997).

$$F_e = A_{\max} / 2\pi V_{\max} \tag{1}$$

where $A_{\max}$ and $V_{\max}$ are the maximum acceleration and velocity of the input excitation.

At a given frequency, the acceleration magnitude was increased with each subsequent test till the specimen overturned. The increments are 50~100 and 200 gal, respectively, for frequency less and greater than 2.0 Hz. Due to the capacity limit of the shaking table, the input maximum acceleration is 250 and 1000 gal for frequency of 0.5 and 0.75~3 Hz, respectively. The excitation time of each sinusoidal wave was 25 seconds, including transient stages in the first and last five seconds. Fig. 3 shows the input sinusoidal wave of 1 Hz and acceleration magnitude 100 gal. As for the earthquake motions, the adopted records included the 1968 Hachinohe NS, 1940 El Centro NS and 1995 JMA Kobe NS.

The specimens were placed against the RC wall and uni-axially excited along the shaking table's longitudinal direction. After each excitation, the motions of the shelf and cluttered situations were recorded. The cluttered area was recorded based on the grid lines. At the top of the shelf, three accelerometers were attached to measure vertical and two horizontal accelerations. An accelerometer was also attached to the floor slab along the excitation direction to measure the input acceleration.

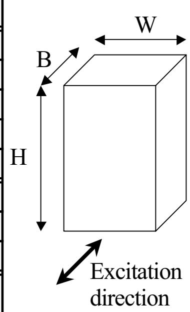
(a) Stock shelf (b) Tablet medicine shelf (c) Powder medicine shelf

Fig. 1 Three types of medicine shelves

Fig. 2 Test setup

Table 1 Summary of test specimens

NO.	Type	Dimensions (cm)		
		H	B	W
1	Stock shelf	180	30	90
2		180	30	150
3		180	30	180
4		150	30	90
5		210	30	90
6	Tablet medicine shelf	180	25	90
7		180	25	150
8		180	25	180
9	Powder medicine shelf	180	15+60	180



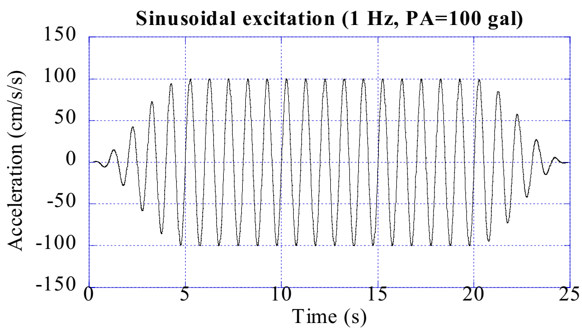


Fig. 3 Input of sinusoidal wave

3. Test Results

3.1 Input of sinusoidal waves

(1) Observed characteristics of shelf motions and cluttered situations

(a) Stock shelf

A predominant characteristic was that objects placed in the shelf began to drop from the lowers rows, while those in the upper rows hardly dropped out (Fig 4). The shelf was originally placed against the RC wall (Fig.5 (a)), and medicine packages were placed along the front edge of the layer panel for taking out and placing conveniently. When the rocking motion was initiated, the shelf rotated backward to its original position and collided with the wall. Due to the collision force the objects slid backward. The collision force was greater at the upper part of the shelf. Hence, the objects placed in the upper rows slid backward much and even hit the back panel, while those in the lower rows slid slightly (Fig. 5 (c)).

On the other hand, Fig. 6 demonstrates the accelerations at the slab and at the top of the shelf in the excitation direction. In the figure, the peaks in the positive direction were due to the collision with the wall. While in the negative direction, the maximum absolute values were approximate for the accelerations at the top of the shelf and the slab. Response amplification was not observed at the top of the shelf, so that the forward sliding displacements of the objects placed at different heights were approximate. As a result, the objects dropped from the lower rows (Fig. 5 (d)), while those in the upper rows rarely dropped out due to the large backward sliding displacement.

(b) Tablet medicine shelf

The tablet medicine shelf showed the same characteristics as observed in the stock shelf. Bottles and cans began to drop from the lower rows (Fig. 7). By contrast, the L-type drawers in the top shelf did not slide out under all test excitations. The 1 mm-high stopper at the edge of the layer panel demonstrated excellent falling-proof effect.

(c) Powder medicine shelf

Different from the stock and tablet medicine shelves, the bottles placed in the top part of the powder medicine shelf began to drop from the upper rows (Fig. 8). Amplification of acceleration was observed at the top of the shelf (Fig. 9). The reason is that the strength of the metal connection between the top shelf and bottom table was not high enough, and the top shelf vibrated from the connection base and showed response amplification. As a result, the bottles placed in the upper rows were subjected to greater excitations compared with those in the lower rows.

(2) Overturning and cluttered levels

The test results are shown in Figs. 10~12. In these figures, the abscissa and ordinate are, respectively, the input acceleration and velocity, calculated as Eq. 1. The results of resting, rocking without clutter, rocking with clutter and overturning are noted as ○, △, ▲ and ■, respectively. The number beside the symbol of ▲ indicates the number of dropped items or the cluttered distance in *cm*. Generally, the observed cluttered area distributed approximately in the shape of rectangular or trapezoidal. Hence, in recording the test results, the cluttered distance is recorded at the grid line where at least 70% around the central part are scattered with fallen objects. On the other hand, when the cluttered area was apparently loose, the number of fallen objects is adopted instead of the distance. While for the powder medicine shelf, the falling ratio is recorded. Because the cylinder bottles roll around after dropping on the slab, it is with less meaning to describe the cluttered distance. In consequent, for the powder medicine shelf, the number beside the symbol of ▲ represents the falling ratio, and the symbol of ■ denotes falling of almost all contents.

For each type of the shelf, the results and discussions on overturning and cluttered levels are summarized as follows. In the figures the bold dashed lines represent the critical acceleration and velocity dividing different cluttered levels of the test results. In addition, the thin solid lines shown in the figures are the lower limits of overturning acceleration and velocity (Eq. 2) proposed by Yazaki and Ishiyama (1996) for the placement method of “against a wall”.

$$A_0 = \frac{B}{H} g$$

$$V_0 = 20 \frac{B}{\sqrt{H}} \qquad (2)$$

where A_0 and V_0 are the overturning acceleration (in

Fig. 4 Objects dropped from the lower rows in the stock shelf

Fig. 7 Objects dropped from the lower rows in the tablet medicine shelf

Fig. 8 Objects dropped from the upper rows in the powder medicine shelf

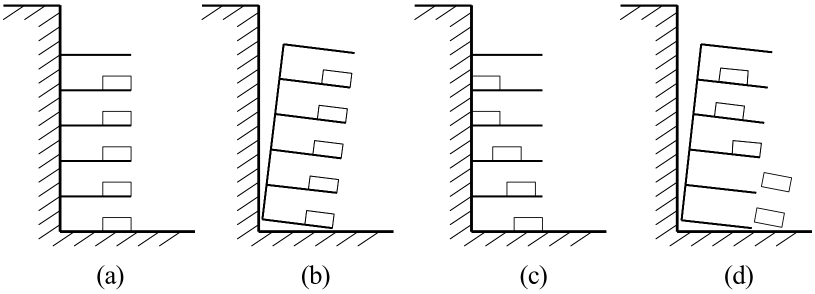


Fig. 5 Motions of the stock shelf and falling of medicine packages

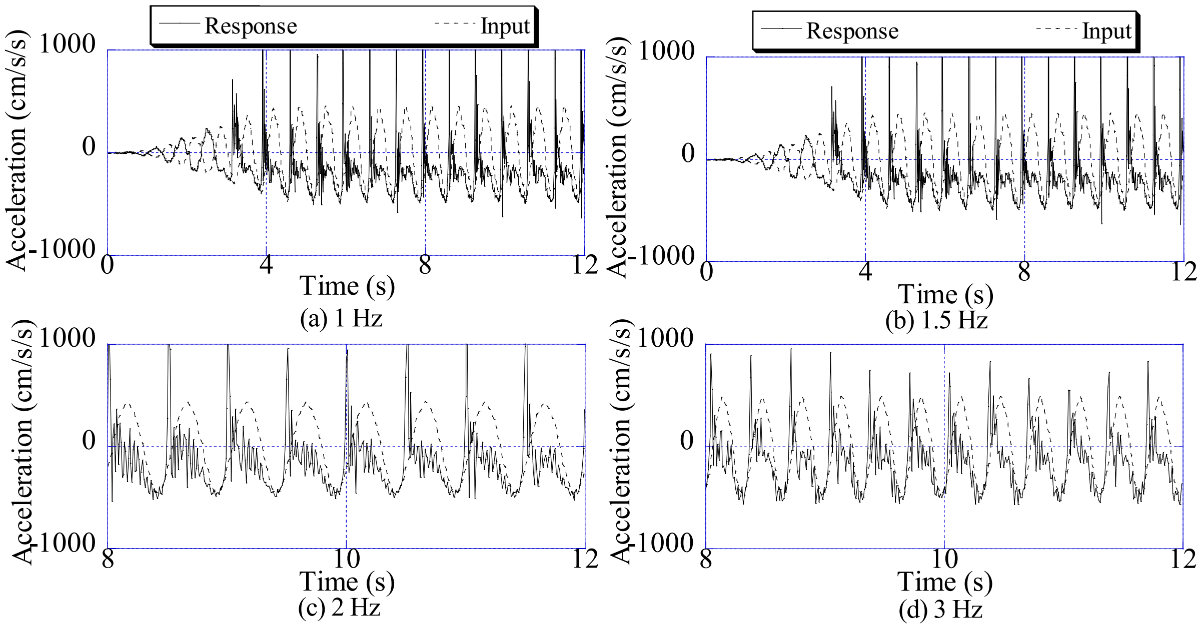


Fig. 6 Response at the top of the stock shelf (Specimen 1) under sinusoidal waves of 400 gal peak acceleration

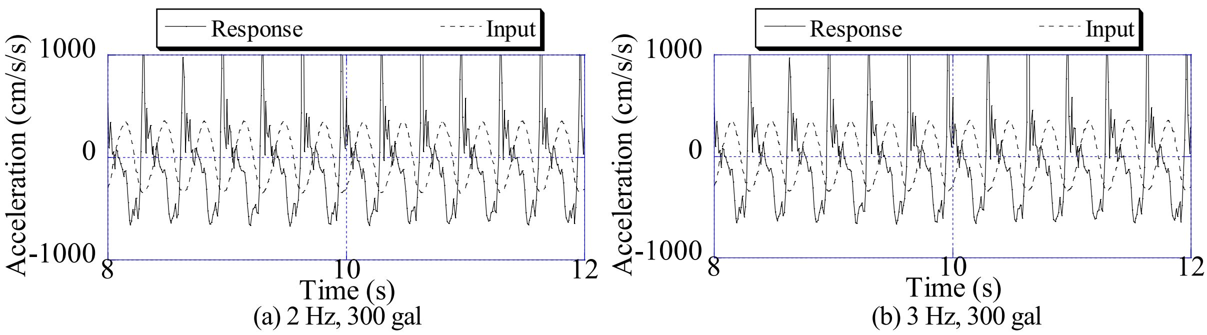


Fig. 9 Amplification of acceleration at the top of the powder medicine shelf (Specimen 9) subjected to sinusoidal waves

cm/s^2) and velocity (in cm/s), respectively. B and H are the breadth along the excitation direction and the height of the shelf in cm, and g is the gravitational acceleration in cm/s^2.

(a) Stock shelf

(i) The rocking motion was initiated when the input acceleration is greater than $\frac{B}{H}g$ (=163 gal), and the overturning velocity occurred at a nearly constant value. The test results showed the same trend as those of Yazaki-Ishiyama's criteria (Eq. 2).

(ii) The cluttered situation occurred after the acceleration reached 400 gal, which is about the value μg. The notation of μ is the friction coefficient, about 0.4, between the medicine packages and the steel panel.

(iii) The initiation of cluttered situation was determined by the acceleration, while the cluttered distance was influenced simultaneously by the acceleration and velocity.

(iv) From the results of Figs. 10 (a), (b) and (c), for the shelves with the same B/H ratio, the cluttered distance was not influenced by the breadth of the shelf perpendicular to overturning direction, noted as W.

(v) From the results of Figs. 10 (a), (d) and (e), the difference of the shelf heights of 150, 180 and 210 cm did not influence the cluttered distance.

(vi) Under the input frequency of 0.5 and 0.75 Hz, no cluttered situation occurred before the shelf overturned. By contrast, under the input frequency of 1.0~3.0 Hz, the cluttered situation occurred before the shelf overturned.

(b) Tablet medicine shelf

It is the same as observed in the test results of stock shelves that the cluttered distance was not influenced by the breadth of the shelf perpendicular to overturning direction for the shelves with the same B/H ratio. Hence, only one specimen's results are shown in Fig. 11.

(i) The rocking motion was initiated when the input acceleration is greater than $\frac{B}{H}g$ (=136 gal), and the overturning velocity occurred at a nearly constant value. The test results showed the same trend as observed in the stock shelf.

(ii) The cluttered situation occurred at the acceleration of 250 gal, less than μg (=400 gal). Different from the stock shelf, medicine bottles were placed in the bottom row for the tablet medicine shelf. Compared with the packages, the bottles were prone to overturn before sliding. Thus the bottles overturned and rolled out of the shelf at a smaller acceleration.

(iii) The number of fallen bottles showed a great deviation. It is due to the collision between the bottles and whether the overturned bottles rolled out of the shelf. Lots of bottles overturned, while many of them may not roll out of the shelf and resulted in fewer fallen bottles on the slab. On the whole, at the acceleration of 300 gal, falling of about half bottles and cans was observed.

On the other hand, after the acceleration reached μg (=400 gal), the cluttered situation increased rapidly, as the packages also began to slide and dropped out.

(iv) Under the input frequency of 0.5 and 0.75 Hz, no cluttered situation occurred before the shelf overturned. By contrast, under the input frequency of 1.0~3.0 Hz, the cluttered situation occurred before the shelf overturned. This is the same as observed in the stock shelf..

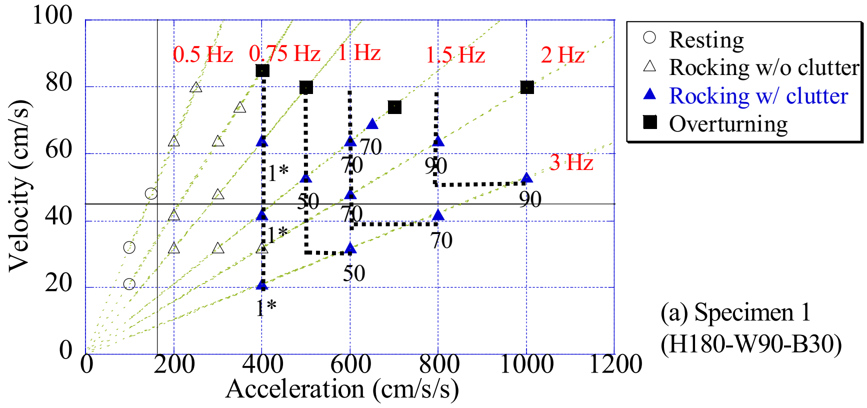
(c) Powder medicine shelf

(i) The friction coefficient μ between the bottles and the glass panel is about 0.3~0.35. While the initiation of fallen objects occurred at 200~250 gal, less than μg (=300~350 gal). It is due to the response amplification of the top shelf, as shown in Fig. 9.

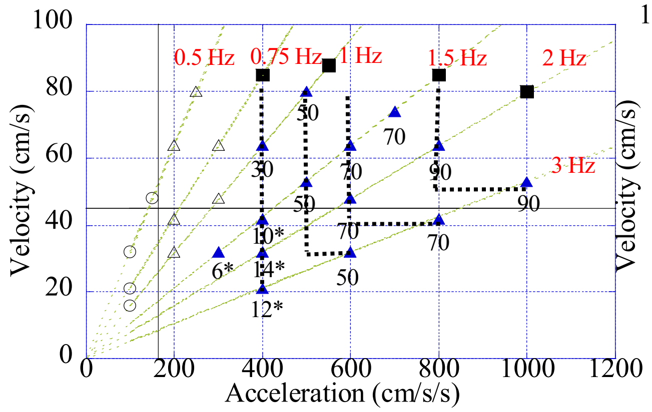
(ii) The initiation of fallen objects was determined by the acceleration, while the falling ratio was highly correlated to the multiplication of acceleration and velocity. The bold dashed lines representing constant value of acceleration multiplying velocity divided the test results well, except the results of 1.5 Hz excitation at 200 and 300 gal. In the figure, the multiplications of accelerations and velocities for falling ratio of 6, 13, 30 and 40% are determined as 7.2×10^3, 1.28×10^4, $1.5 \times 10^4$and 2×10^4 cm^2/s^3, respectively.

3.2 Input of earthquake motions

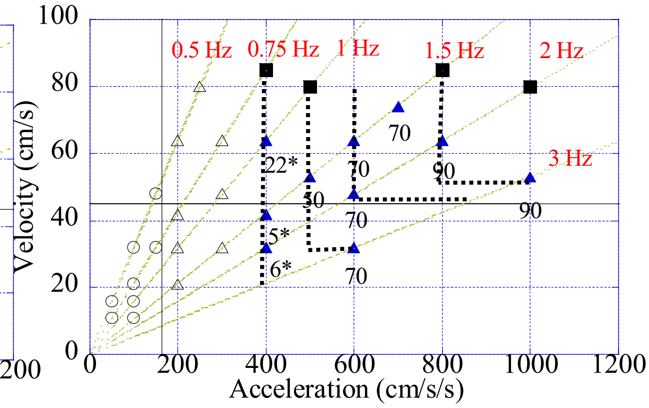
The aim of tests using input of earthquake motions is to investigate how to apply the results of sinusoidal wave tests for evaluating the cluttered situation under real earthquake motions. The tests using input of earthquake motions were conducted on one stock shelf (Specimen 2), tablet medicine shelf (Specimen 7) and powder medicine shelf (Specimen 9), respectively. The earthquake records



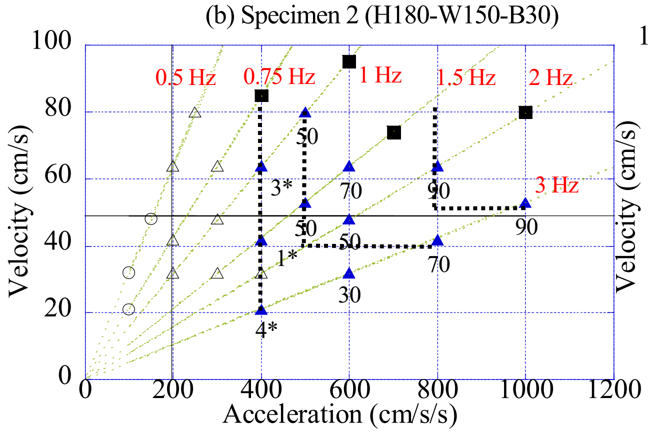
(a) Specimen 1 (H180-W90-B30)



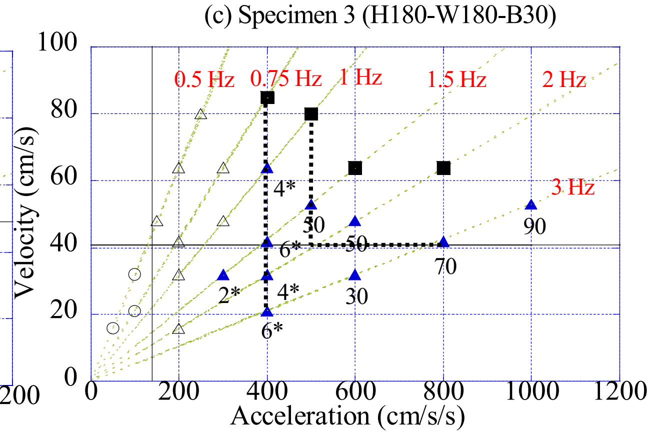
(b) Specimen 2 (H180-W150-B30)



(c) Specimen 3 (H180-W180-B30)



(d) Specimen 4 (H150-W90-B30)



(e) Specimen 5 (H210-W90-B30)

Fig. 10 Test results of the stock shelf subjected to sinusoidal waves (* denotes the number of fallen items)

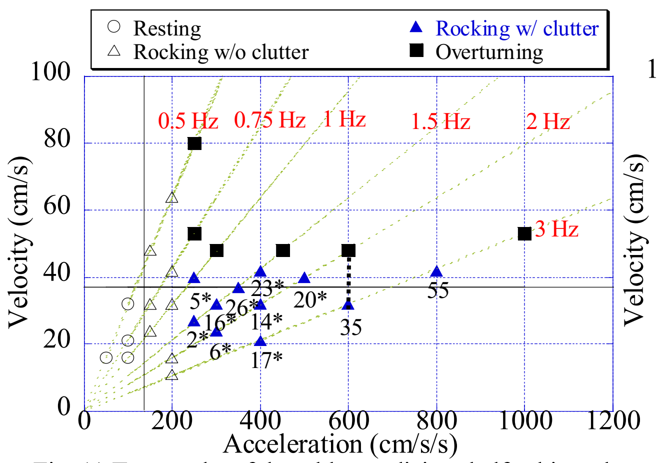


Fig. 11 Test results of the tablet medicine shelf subjected to sinusoidal waves (Specimen 8, H180-W180-B25; * denotes the number of fallen items)

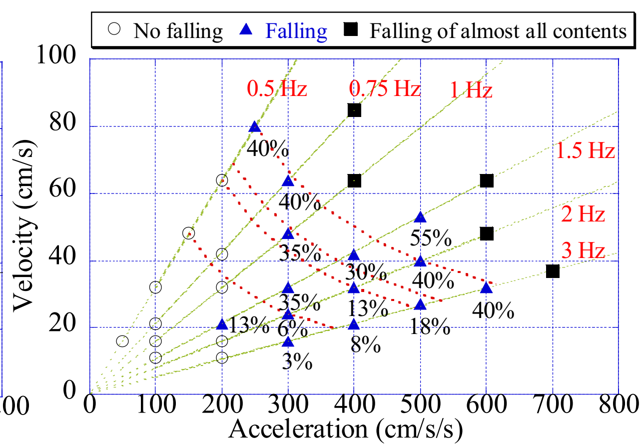


Fig. 12 Test results of the powder medicine shelf subjected to sinusoidal waves (Specimen 9, H180-W180-B15-60)

Table 2 Summary of input earthquake motions

Name	Equivalent frequency (Hz)	Input max. accel. (gal)
1968 Hachinohe NS	1.05	224, 500, 800
1940 El Centro NS	1.50	342, 500, 800
1995 JMA Kobe NS	1.44	300, 500, 818

Table 3 Accelerations for overturning and cluttered levels of the stock shelf under sinusoidal waves and earthquakes (Equivalent frequency= 1.5 Hz)

Input	Initiation of clutter	Dist. of 50 cm	Dist. of 70 cm	Over-turning
Sinusoidal excitation	400	500	600	754
Earthquake motion	500	875	1050	1320

Table 4 Accelerations for overturning and cluttered levels of the tablet medicine shelf under sinusoidal waves and earthquakes (Equivalent frequency= 1.5 Hz)

Input	Initiation of clutter	Falling of half bottles	Over-turning
Sinusoidal excitation	250	300	450
Earthquake motion	438	525	788

Table 5 Accelerations for overturning and cluttered levels of the powder medicine shelf under sinusoidal waves and earthquakes (Equivalent frequency= 1.5 Hz; F.R. denotes falling ratio)

Input	Initiation of clutter	F.R.= 6%	F.R.= 13%	F.R.= 30%	F.R.= 40%
Sinusoidal excitation	200	260	347	376	434
Earthquake motion	350	455	607	658	760

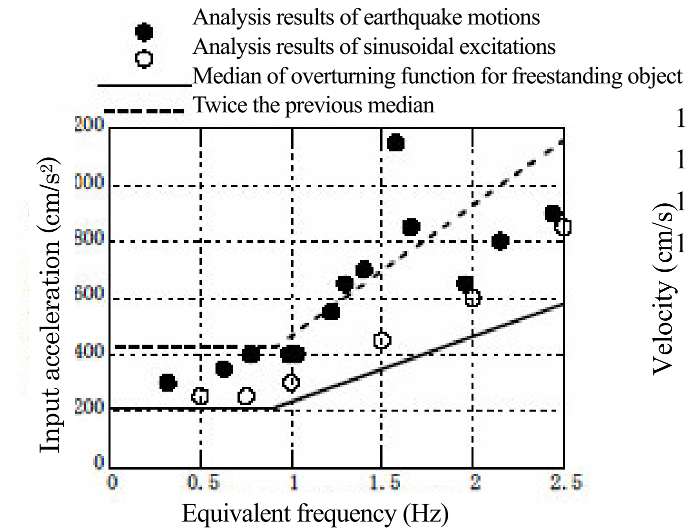


Fig. 13 Comparison of overturning accelerations under sinusoidal waves and earthquakes (Tamura et al. 2005)

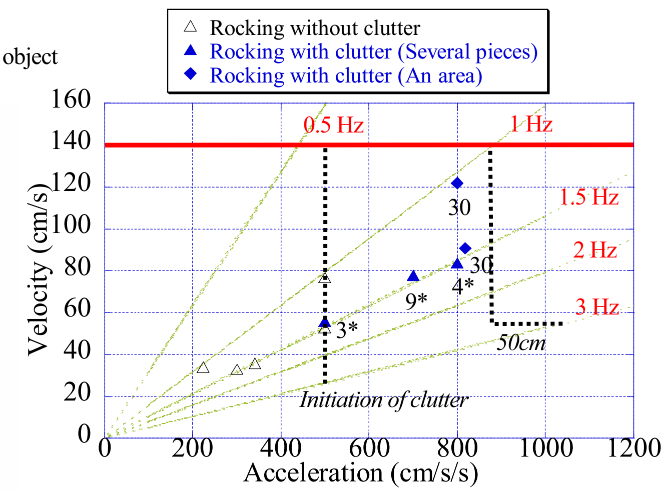


Fig. 14 Test results of the stock shelf subjected to earthquake motions (Specimen 2)

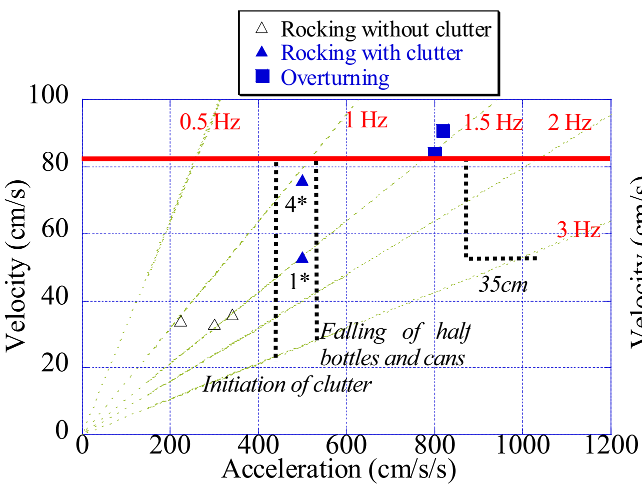


Fig. 15 Test results of the tablet medicine shelf subjected to earthquake motions (Specimen 7)

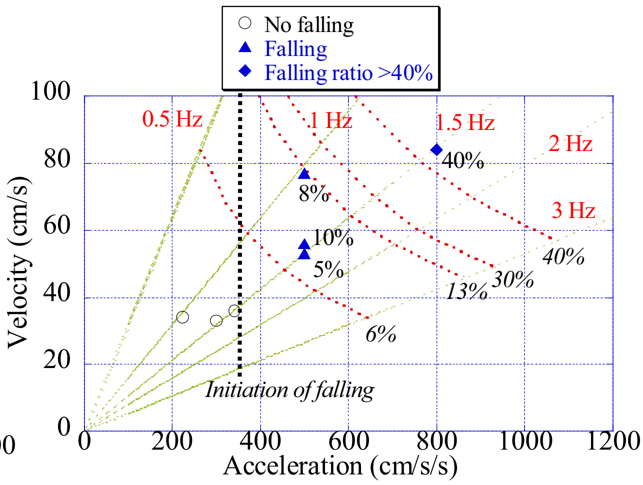


Fig. 16 Test results of the powder medicine shelf subjected to earthquake motions (Specimen 9)

Table 6 Cluttered levels for the stock shelf

Input	Initiation of clutter	Dist. of 50 cm	Dist. of 70 cm	Dist. of 90 cm	Over-turning
Accel. (cm/s^2)	500	875	1050	1400	—
Vel. (cm/s)	—	56	74	93	140

Table 7 Cluttered levels for the tablet medicine shelf

Input	Initiation of clutter	Falling of half bottles	Dist. of 35 cm	Dist. of 55 cm	Over-turning
Accel. (cm/s^2)	438	525	875	1225	—
Vel. (cm/s)	—	—	56	65	84

Table 8 Cluttered levels for the powder medicine shelf
(Initiation of falling: Accel≥350 gal; F.R. denotes falling ratio)

Input	F.R.= 6%	F.R.= 13%	F.R.= 30%	F.R.= 40%
Accel.×Vel. (cm^2/s^3)	22050	39200	45938	61250

included the 1968 Hachinohe NS, 1940 El Centro NS and 1995 JMA Kobe NS (Table 2). Their equivalent frequencies, obtained by Eq. 1, were 1.05, 1.50 and 1.44 Hz, respectively. Besides the original PGA, the previous earthquake motions with maximum acceleration adjusted to 300, 500 and 800 gal were also input.

For placement of "against a wall ", Tamura et al. (2005) conducted numerical analyses to compare the overturning accelerations under sinusoidal waves and earthquake motions, as shown in Fig. 13. Since this study adopted the same settings for sinusoidal waves as those in the researches of Tamura et al. (2005), their analyses results were referred to. As shown in Fig.13, their analysis results indicated that averagely the overturning accelerations under earthquake motions is much greater, about 1.5~2 times, than those under sinusoidal waves. Accordingly, in this study the overturning acceleration for earthquake motion tests is calculated as 1.75 times that obtained by sinusoidal wave tests. The last columns of Tables 3~5 indicate the overturning accelerations under sinusoidal waves and earthquake motions. The tables show the results at frequency of 1.5 Hz, as one of the equivalent frequencies of the input earthquakes is around this value. In the tables, for the accelerations dividing different cluttered levels, it is also assumed that the ratio is 1.75. While for the stock shelf the acceleration of initiation of clutter is revised to 500 gal according to the results of earthquake motion tests. Figs. 14~16 demonstrate the results of earthquake motion tests. In the figures, the bold line and dashed lines represent, respectively, the predicted overturning limit and the critical values dividing different cluttered levels under earthquakes, as indicated in Tables 3~5. It is found that well agreement between the predicted and test results for all the three types of shelves.

4. Criteria for Cluttered Levels of Typical Medicine Shelves and Contents under Earthquakes

Due to the limited frequencies and accelerations of the input earthquakes, not all the results obtained in the sinusoidal wave tests were verified in the earthquake motion tests. However, the predicted values of overturning and different cluttered levels under earthquakes showed well agreement with the limited test results. Based on the test results, the criteria for evaluating the cluttered situation under earthquakes are summarized in Tables 6~8.

5. Conclusions

In this chapter, shaking table tests are conducted on investigation into cluttered situation due to typical medicine shelves and contents. The specimens are the real medicine shelves and contents. The input excitations include sinusoidal waves and real earthquake motions. Major conclusion from the test results are summarized as follows:

(1) From the results of sinusoidal tests, the initiation of cluttered situation occurs at 400, 250 and 200 gal, respectively, for the stock shelf, tablet and powder medicine shelves.

(2) For the stock and tablet medicine shelves, under the sinusoidal excitations of 0.5 and 0.75 Hz, cluttered situations do not occur before the shelf overturns; while for those with frequency of 1.0~3.0 Hz, cluttered situations occur before the shelf overturns. The maximum cluttered distances are 90 and 55 cm, respectively, for the two types of shelves.

(3) With the same B/H ratio of the shelf, the cluttered distance is not influenced by the breadth of the shelf perpendicular to overturning direction.

(4) For the powder medicine shelf, from the results of sinusoidal tests, the falling ratio is highly correlated to the multiplication of acceleration and velocity.

(5) Under earthquake motions, the predicted values for overturning and different cluttered levels, obtained by multiplying a ratio of 1.75 with those of sinusoidal excitation test, correspond well to the test results.

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振動台実験による典型的な薬剤棚・内容物の地震時散乱状況の評価

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要　旨

本研究では、災害拠点である病院の薬剤棚・内容物を対象として、地震時の室内散乱状況について、振動台実験を実施して定量的に評価する。試験体はストック棚、錠剤棚、散剤棚の３種類の典型的な棚を含む。まず、正弦波を入力し、棚の種類による散乱の特徴の違いなど定性的な把握を行うとともに、入力の加速度や振動数による散乱距離の変化などを定量的に評価した。次に、地震波を入力し、正弦波の入力で得られた結果との関係を分析した上で、地震時に棚の内容物が散乱する距離及び面積の予測式を導く。

キーワード: 散乱, 転倒, 病院, 薬剤棚, 振動台