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SHAKE TABLE TEST SIMULATION OF THE ROTATION RESPONSE OF ASYMMETRIC STONE STATUE MODELS UNDER SEISMIC EXCITATION

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Abstract

Rotation damages are common in earthquakes, which usually occur when some form of plan irregularities exist. In 2008 Wenchuan Earthquake, an interesting rotation phenomenon attracts our attention: most of the stone statues, which were placed upon the banisters of one zigzag bridge in Taibai Park, Jiangyou City, Sichuan Province, rotated an angle along the vertical axis and some of them with a small transverse displacement from their original location. To simulate and further study this phenomenon, in April 2013 we made a number of concrete models with different asymmetric characteristics, and then the models were arranged in different directions on the table to do shake tests in Tongji University. Firstly, the results show that the rotation phenomenon of the concrete models appears when loading three dimensional accelerations to the shake table and setting the acceleration amplitude 1.5 times of the original records recorded at Jiangyou station. Also, the test phenomenon is similar to what happened in the Taibai Park in Wenchuan Earthquake. However, when the loaded acceleration is only in two horizontal directions, the rotation phenomenon does not appear even when the amplitude is large enough. Secondly, the rotation phenomenon of the concrete models shows different modes with different model asymmetric characteristics and different acceleration inputting angles. Finally, the more important factor that causes the rotation phenomenon is the vertical direction seismic input. So for this case, vertical seismic action is crucial and cannot be ignored. Also from the shake table simulation test we can know that the transverse displacement and rotation of the stone statues in Wenchuan Earthquake were produced by the composition of three dimensional seismic effects.

Keywords: Wenchuan Earthquake, asymmetric stone statue, rotation response, shake table test, vertical ground motion

1. Introduction

With the emergence of large-span, irregular and complex structures, further study on the seismic rotational component and its effect on the structures [1-12] is necessary. It is not only for developing the seismic theory, but also for the demand of the practical seismic design. Some researchers think the rotational phenomenon is related to the rotational component, and they believe that the research of seismic rotational component and its effect on structures should start from the analysis of rotated structures or rigid bodies in the earthquake.

There are some rotational phenomena of rigid bodies in the earthquake, such as rotation of obelisk in the 1897 Assam Earthquake and rotated tombstones in the 1906 San Francisco Earthquake [13]. Tobita and Sawada examined the rotation phenomenon of tombstone along its vertical axis in the 1994 Sanriku-Haruka-Oki Earthquake in Japan, and they ran simulations with single direction shaking table tests. The loaded acceleration was sine wave, and their tests and numerical analysis showed that one or two cycles of particle motion near peak acceleration caused the rotation [14]. However, so far the analysis of rotational damage mechanics is not enough and we need collect more rotational phenomena, run simulation tests and conduct theoretical analyses.

After the Wenchuan Earthquake (Ms8.0) occurred on May 12, 2008, when Q. Luo and F. Yang made investigation in Jiangyou City which is also in epicentral area, they found the stones, which were placed upon the banisters of one zigzag bridge of Taibai Park , had a small transverse displacement with rotated angles from their original location [15,16]. To simulate and further study this phenomenon, a group of stone statue models with different asymmetric characteristics were used to conduct shake table tests in Tongji University in 2013. The shake table is capable of six-dimensional shaking. Based on this test with loading actual accelerations, the rotational damage of these models will be analyzed in this paper.

2. Rotation of stone statues on one zigzag bridge

As mentioned before, In Wenchuan Earthquake, the stones statues of one zigzag bridge in Taibai Park showed the rotation phenomenon. Fig.1 shows the part of the bridge and the rotation phenomenon. Reference [15] explains the rotation response along its vertical axis of the total 18 stone statues: one statue rotated with angle 60°, one with 30°, two with 20°, two with 15°, one with 10°, five with 5°and six with 0°; Some of them showed a small transverse displacement from their original location.

Fig.1 – Rotation phenomenon of some stone statues of one zigzag bridge
in Taibai Park of Jiangyou City, in 2008 Wenchuan Earthquake

3. Shake table test

3.1 Experimental model design

The shake table test is to replicate the phenomenon happened on the stone statues of the zigzag bridge. The different rotation angles of stones (see section 1) may be caused by the different ground motion loading direction. And the asymmetry of rigid body is also related to the rotation. Due to the complex statue shape, four types of simplified concrete models were built (Fig.2). The size ratio of the second type of models (2nd from the left in Fig.2) was similar to the stone statues on the Taibai Park bridge and Fig. 3 is its design diagram. The other three types of models were designed to study the influence of different asymmetric models. It’s also observed that the eccentricity ratio of the first was identical with the third from the left, but the former was lighter than the latter. Those equivalent models were designed in two parts: top and bottom, The top was an asymmetric structure and the bottom was the supporting foundation. In this test, there were five models from the second type and one from the other 3 types respectively. They were arranged in different directions on the shake table (Fig.4). In this figure, the second type of models are numbered No.1, 4, 6, 7 and 8, the first, third and fourth type of models are numbered No.5, 2, 3, respectively. Fig.4 is a top view of the shake table, which is 4x4 meters, and the dark part of each model is the projection of its asymmetric part. Fig.5 is a layout photo of the shake table.

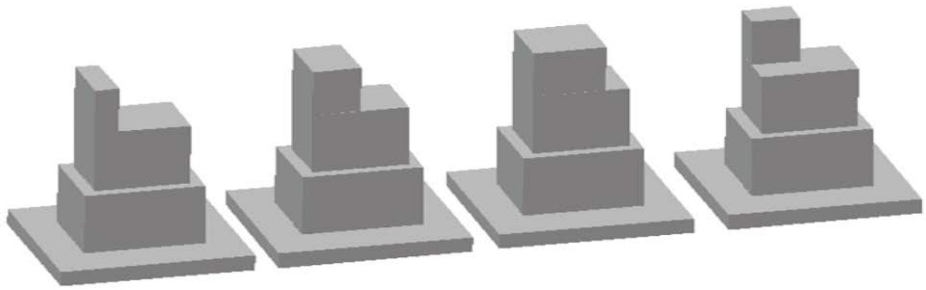

Fig. 2 – Schematic diagram of the four types of models

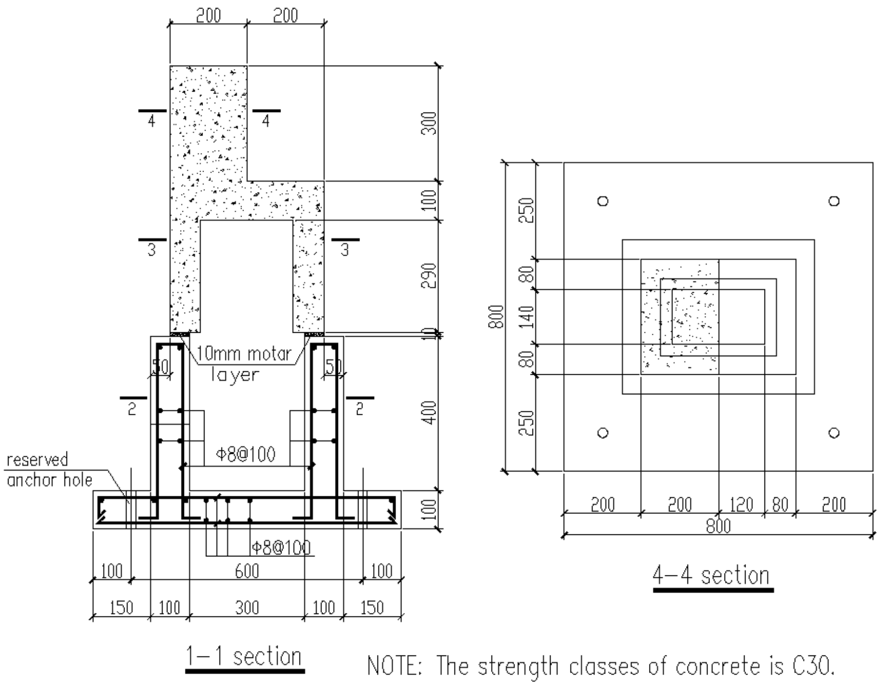

Fig. 3 – Design diagram of the second type of models

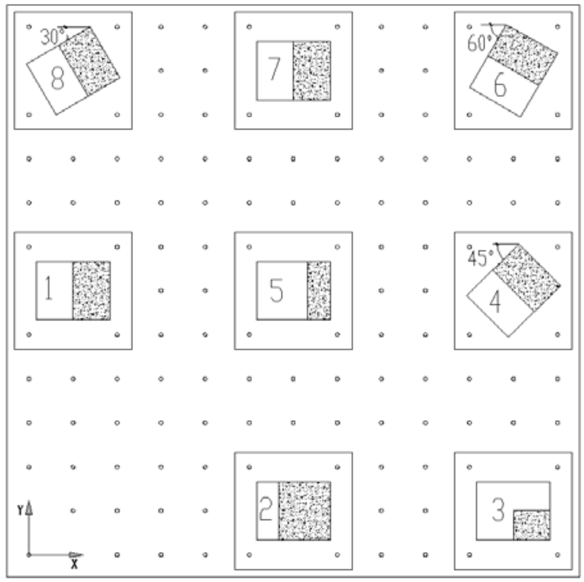

Fig. 4 – Shake table layout and model number

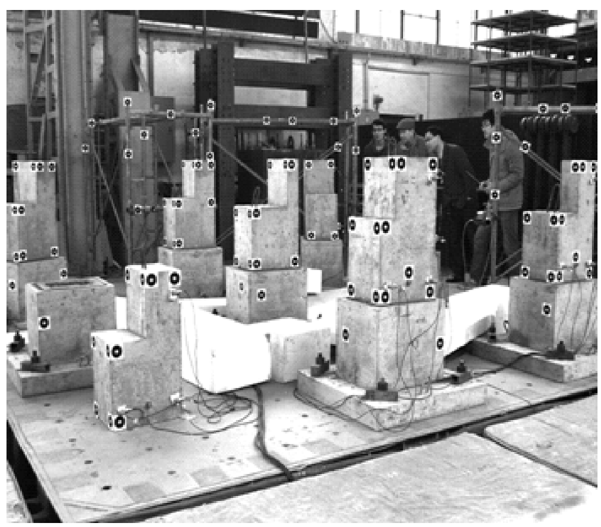

Fig. 5 – Model layout on the shake table before 3-D shake test

In Fig.4, we defined the connection direction of model No.2 and No.3 as the X-axis, and the connection direction of No.1 and No.8 as the Y-axis, vertical direction of the models is Z-axis. All the models were made by concrete and the typical model dimension is shown in Fig.3. The top part of the model was connected to the concrete bottom by thick mortar. The bottom structure was connected to the larger square concrete bed which can be fixed on the steel shake table. One additional note is that during the first shake test, the top part of No.1 model was bonded to the bottom with cement mortar same as other models (Fig.4); after several rounds of tests, the top part was direct placed on the steel shake table without bonding (Fig.5).

3.2 Load acceleration in shaking table test

The acceleration time history recorded at Jiangyou station in the Wenchuan Earthquake was used in the shake test. Fig.6 shows the E-W, S-N and U-D acceleration component. The peak value is 443.97gal , 512.59gal and 171gal, respectively. Time-history was filtered using high-frequency filtering process and the component of 25Hz or above frequencies was filtered.

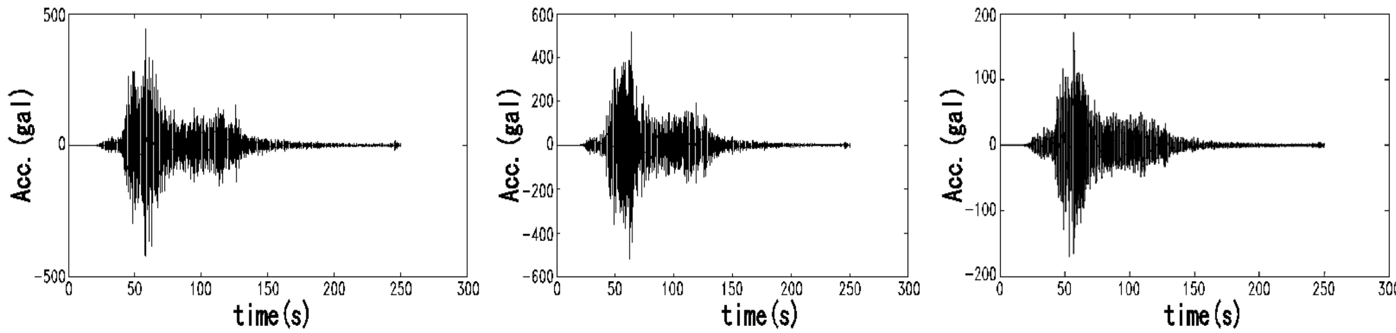

Fig. 6 – Recorded accelerations in E-W, S-N and U-D direction (From left to right) at Jianyou seismic station

3.3 Test measuring points

Two types of sensors were installed to monitor the model response, one for measuring acceleration and another for displacement. The recorded data can be used to analyze the rotation of the models. Also the high speed camera and video camera were used to monitor the test and rotation phenomenon. On model No.1、2、3 and 5, only the acceleration sensors were installed, but on model No.4, 6, 7 and 8, both the acceleration and displacement sensors were installed. The measuring points are shown in Fig.7 where □ indicates Acceleration sensor, and ⊗ is for displacement sensor.

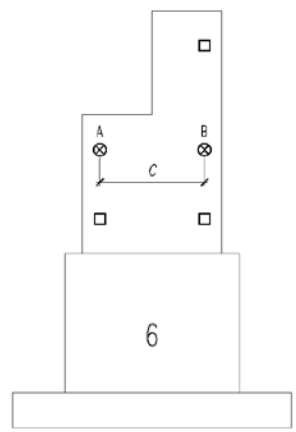

Fig. 7 – Measuring points

3.4 Loading conditions

In the shake table test, the E-W acceleration component was loaded in X-axis, the S-N component in Y-axis, the U-D component in Z-axis. The recorded peak value is too large, so in order to observe how the loading condition affected the rotation of the models, the whole test was divided into 11 loading conditions (Table 1). The seismic wave recorded in El Centro Earthquake was also used in the test, while the peak values of the time history were changed to 0.03g, 0.05g, 0.10g. The peak acceleration of the time history recorded at Jiangyou station was adjusted to 0.3, 0.6, 0.8, 1.0, 1.2 and 1.5 times of the original record. The loading conditions 1 to 6 load the seismic time history in two horizontal dimension, X-axis and Y-axis direction; loading conditions 7 to 12 load the ground motion in three dimension, X, Y and Z axis, simultaneously.

4. Results and analyses

In the loading conditions 1 to 10, there was no obvious rotation or displacement occurred to any model in the shake table test. At first we considered that the two horizontal-dimension loading ground motions would make the asymmetric model show rotation, the shake table test results in load conditions 1 to 6 were contrary to what we expected. In condition 11 only model No.1 showed rotation, but the adhesive mortars between the other models' top portions with their bottoms were broken. In condition 12, when the loading acceleration amplitude was 1.5 times of the original record, the torsion phenomenon occurred on all the models except for model No.3 and 5. Table 2 is the final status of displacement and rotation along the Z-axis. Fig.8 is a top view of those model status before and after the shake test and the table 2 presents the last displacement along the X, Y axis and the rotation along the Z-axis of each model. Fig.9 is a photo which shows the damage state of the models after the shake table test.

Table 1 – Loading conditions of shake table test

Loading condition	Seismic wave	Magnitude	Remark
1	El Centro wave	0.03g	Loading in horizontal two dimensional, X and Y axis direction, simultaneously.
2		0.05g	
3	Jiangyou wave	0.3 times	
4		0.5 times	
5		0.8 times	
6		1.0 times	
7	El Centro wave	0.1g	Loading in three dimensional, X, Y and Z axis direction, simultaneously.
8	Jiangyou wave	0.6 times	
9		0.8 times	
10		1.0 times	
11		1.2 times	
12		1.5 times	

Table 2 – Displacement and rotation of each model

Model No.	X -axis（mm）	Y -axis（mm）	Rotation along Z-axis(^{o})
1	6	80	18
2	33	28	0
3	0	0	0
4	28	27	21
5	0	0	0
6	6	14	21
7	19	21	31
8	34	7	15

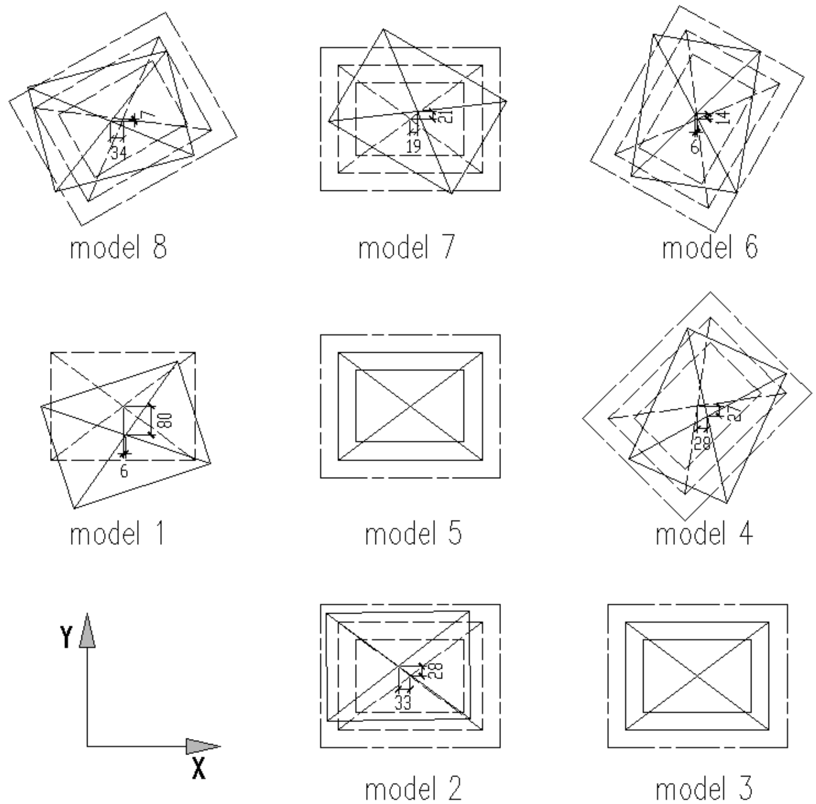

Fig.8 – Displacement and rotation angle of each model after test

Fig. 9 – Damage state of models after 3-D shake test

As shown in Fig.8 and 9, the rotation phenomenon is distinct. With the different displacement recorded at two measuring points (shown in Fig.7), the time history of rotation angle of each model can be calculated. Assuming the distance of the two displacement sensors in Fig.7 is C, the displacement time history recorded at measuring points A and B is $D_a(t)$ *and* $D_b(t)$, which the displacement is the change of distance from the measuring points A and B of the model to the fixed points outside the shake table. Then the rotation time history $R(t)$ of the top asymmetric portion along Z-axis can be calculated by

$$R(t) = \arcsin((D_a(t) - D_b(t))/C) \tag{1}$$

The calculated rotation time history of model No.4, 6, 7 and 8 is shown in Fig.10. From the figure, we can see that the maximum rotation angle of model No.4, 6, 7 and 8 occurred nearly at the same time. Although the maximal angle is different from Table 2, the trend is same. For example: there is the same rotation angle for model 4 and 6, and the rotation angle of Model No.7 is twice as of Model No.8.

With the three-dimension seismic loading, there was no rotation for model No.3 and 5, only transverse displacement for model No.2, and all the other models showed significant rotation in the test. Compared with the rotation phenomenon of the status in the Taibai Park in Wenchuan Earthquake (detailed in Fig.1), the test results are very similar.

What's more, the test results can be analyzed from some other aspects, such as: the structural asymmetry, the input seismic angle and vertical seismic action, and so on.

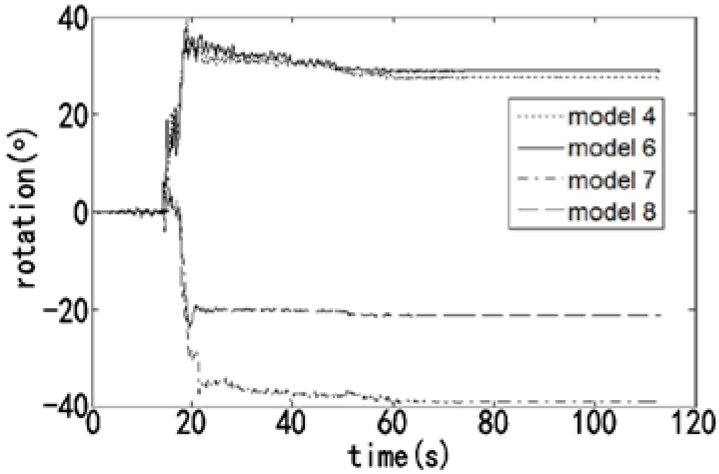

Fig. 10 – Rotation time history of model No.4, 6, 7 and 8

4.1 Effect of model's asymmetry

Fig.4 and Fig.5 show that model No.3 and 5 have the minimum eccentricity and the mass of their top structures are less than others, so there is no rotation occurred for them. But for the other models, such as model No.1, 4, 6, 7 and 8, which have more eccentricity, their top structures show rotation under the three dimension seismic loading. According to the rigid body motion theory, it can be deduced that one important cause of the rotation phenomenon is the asymmetry of structure. The test results essentially in agreement with the theoretical analysis in reference [15]. For model 2, even it has less eccentricity and no rotation occurred, it shifts 33mm on X axis direction and 28mm on Y axis when loading.

4.2 Effect of ground motion input angle

Fig.4 shows that the angles between the long side of model bottom and X-axis are 45° for the model No.4, 60° for No.6, and 30° for No. 8, and the minimum angle is 0° for model No.7. From Fig.10, we can see that model 7 and 8 mainly rotated counterclockwise along the Z axis. And Model 4 and 6 mainly rotated clockwise. It implies that smaller angle between the long side and X axis could make the models rotate counterclockwise, but the larger angle would make them rotate clockwise. Reference [14] also made the same conclusion: rotation effect on the structure was also related to the seismic input angle.

4.3 Effect of vertical seismic wave

When the two horizontal seismic accelerations were loaded on the shake table, all the models did not rotate in the loading conditions 1 to 6, even model 1 which was directly put on the shake table did not have obvious rotation. This phenomenon implies that although sometimes the two horizontal input ground motions could made the non-symmetric structure rotate [14], it could not make the models rotate in our test. It means the two-dimension horizontal loading motions can not overcome the friction forces at the interface between the top and the bottom parts.

From loading condition 7 to 12 in the shake test, the ground motions were loaded in three dimension, which means two horizontal axis X, Y, and the vertical axis Z. All the models did not have obvious movements in loading condition 7 to 10. In loading condition 11, only model No.1 which was directly placed on the shake table rotated. In loading condition 12, model No.3 and 5 that had small eccentricity did not rotate, while model 2 shifted at a certain direction and other models shifted horizontally and rotated. Analyzing the test photos using high speed photography (Fig.11), we can clearly see that the top part of model No.2 showed swing during load process. From it we know that it is the swing that reduced the friction between the top and the bottom part, and made the two parts separated, then induced the shift and rotation of the top part of the model relative to the bottom part. Compare to the shake table tests of two-dimension horizontal loading conditions 1 to 6, the tests in three-dimension loading conditions illustrate that the vertical loading ground motion has a great effect on the transverse shift of model 2, and transverse shift and rotation of other models. Also from the analysis we can draw the conclusion that the shift and rotation of the models are produced by the composition of three dimensional seismic effects.

In the analysis of the rotation response of chimney and other structures, it generally does not consider the effect of vertical ground motions, but the shake table test implies that we should not overlook the vertical ground motion effect when we make seismic analysis of such structures.

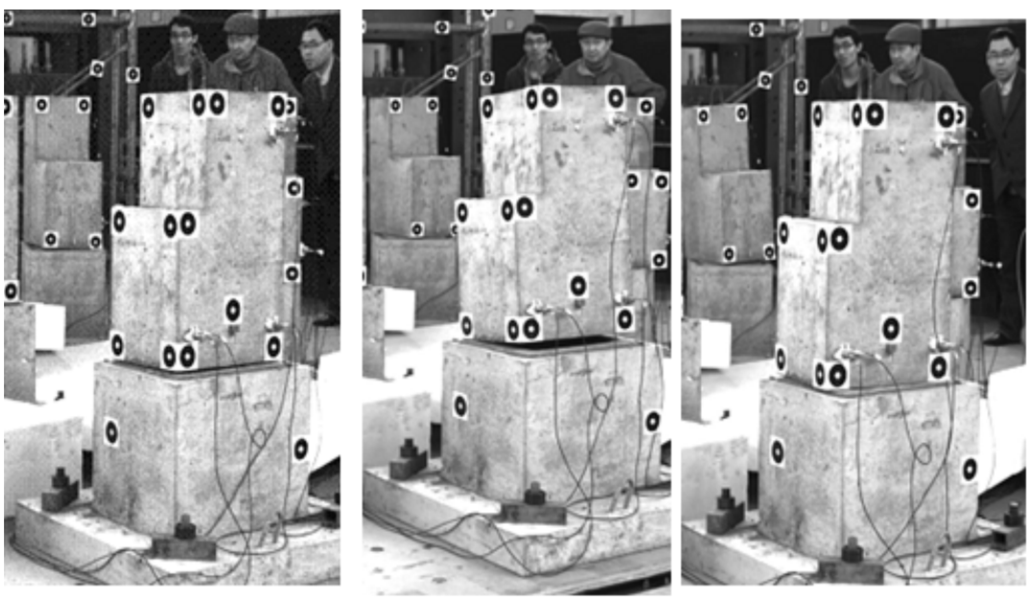

Fig.11 – The move states of model No.2 during shake table test of loading condition 12
(Input ground motions in three dimension)

5. Discussion and conclusion

This paper introduces one shake table test which simulated the rotation response of asymmetric statue models under seismic excitation. This test reproduced the rotation phenomenon which occurred in one zigzag bridge in Taibai Park, Jiangyou City, in the Wenchuan Earthquake, 2008.

Till now, there is little shake table test for the rotation simulation and the rotation mechanism analysis is not enough. Also it is not easy to find the special sensors for measuring rotation and some possibilities which might appear in the test are not considered. All these elements influence the test process and result analyses. For example, when we make the test plan, we are sure that the two horizontal direction accelerations would make the asymmetric top parts rotate along vertical axis, while in fact when the two horizontal accelerations are the same as the Jiangyou records, no movement occurs in the test. After analyses, we decided to revise the test plan by adding the vertical acceleration and loading ground motions in three-dimension. Anther lesson is that loading two-dimension or three-dimension accelerations, the peak acceleration of the first loading condition in the shake test is too small to cause the models to move. The results illustrate that only when the three-dimension ground motions are large enough then the asymmetric structure will show rotation phenomenon.

Based on the test results and preliminary analyses, we can draw the follow conclusions:

1) When the loading three-dimension acceleration amplitudes are 1.5 times of the original seismic records recorded at the Jianyou seismic station, the rotation phenomenon of the statue models appears in the shake table test, and it is similar to the rotation damage of the stone statues of one zigzag bridge in Taibai Park in Wenchuan Earthquake. So the rotational damage is mainly caused by the three-dimension ground motions loaded on the asymmetric stone statues. In another word, the shift and rotation of the models are produced by the composition of three dimensional seismic effects.

2) Different from two-dimension horizontal ground motions loading condition tests, when adding the vertical acceleration in three-dimension loading condition test, it makes the model's top part swing and shift. At last it results in the asymmetric part rotation and transverse displacement. This means the vertical seismic ground motion effect is crucial and should not be ignored in the seismic design, especially for the same structures as the test model.

3) The rotation angle and direction of the asymmetric models are related to the input acceleration angles in the test. For the top parts of the structures with small eccentricity and light mass, no obvious movement and rotation are found in the shake table experiment. For those with small eccentricity and bigger mass, the top parts of the models shift on the two horizontal direction, although it is not easy to rotate along Z-axis.

4. Acknowledgments

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