A DEM SIMULATION OF THE MASONRY STRUCTURE DAMAGE TEST BY SIMPLY HAND-MADE SHAKING TABLE IN UZBEKISTAN

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ABSTRACT

To show the earthquake collapse of unreinforced masonry structure with images is important in understanding the fear of earthquake disasters and disseminating countermeasures. A simulation program of the masonry structure was developed using this calculation method. The Distinct Element Method is used as analysis theory for expressing the collapse phenomenon. This developed program was applied to the test results carried out on a shaking table newly hand-made in Uzbekistan. The shaking table is an one-horizontal hydraulic shaking table of 2.3 m × 2.4 m in size. The masonry test specimen has a brick structure of 1 m × 1 m in size, 1.5 m in height. Before main excitations, the masonry bonds separated partially in adjustment operations. In the main excitation, the shaking table was driven by earthquake and sinusoidal waveforms. Numerical simulations were conducted for the masonry. Numerical simulation results would describe the damages caused by TTPU shaking table tests.

Keywords: DEM; Numerical Simulation; Shaking Table; Brick Masonry

1. INTRODUCTION

Reducing earthquake disasters caused by collapse of structures is fundamental in ensuring safety and security of social life. Many methods have been proposed for developing seismic response programs including collapse of structures. Distinct Element Methods is a suitable method to express the collapse phenomenon. In particular, this method is regarded as effective in masonry structure analysis. One of the authors has already developed a three-dimensional computer program to follow the collapse phenomenon of masonry structure with a brick as a rigid body and a mortal joint as a spring, and compared with the result of the shaking table test (Nakagawa, 2009). In this project, we further advance the method, and develop a simulation program newly assuming each brick as assembly of sphere particle (25mm diameter). The simulation result is compared with the shaking table test. The shaking table test is conducted using a horizontally unidirectional hydraulic shaking table with a size of 2.3 m × 2.4 m newly hand-made in Uzbekistan. The masonry structure specimen used for the test is constructed with low strength bricks, 1m × 1m in size, 1.5m in height and weighs about 1 ton. In 1966, Uzbekistan collapsed many masonry buildings in the capital city Tashkent due to the earthquake of magnitude M5 or higher. Also in 1988 of Soviet era, there was a big earthquake disaster in Armenia (Hirosawa M, 1989), therefore in Tashkent a reaction wall for earthquake resistant structure research was made. However, due to the collapse of the Soviet Union, and reaction wall has left in Tashkent without being used. Turin Polytechnic University in Tashkent(TTPU) was founded in 2009. TTPU planned the construction of a shaking table for effective use of this facility. In this report, the analysis method of DEM, shaking table production in TTPU, shaking table test of masonry structure, and comparison with shaking table test results and simulation analysis are described.

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2. EXTENDED DISTINCT ELEMENT METHOD

The distinct element method (DEM) was originally proposed by Cundall in 1971 to simulate soil in the domain of civil engineering. In the DEM (Cundall 1971), a material is considered to be an assembly of circular particles and there are no forces resisting traction. To give the continuity to this discrete numerical model, elastic springs and dashpots were added by Japanese researchers (Meguro and Hakuno, 1990). This method is called “modified DEM” or “extended DEM”. The model behaves as a continuous medium while the springs are intact; after some of the springs have broken, we are able to trace the movement of the individual parts that were separated from each other and caused the structure’s unity to be destroyed. EDEM has the mortar springs, although the particles are separated each other, and the position of the mortar springs is defined at the initial state of the analytical model. These are the different features from other DE models (Cundal 1971, Dumova-Jovanoska 2009, Lemos 2007). Using this method, it becomes possible to analyze the processes by which fractures develop. In our previous studies (Nakagawa and Ohta, 2010), we developed a new simulating method based on the Extended Distinct Element Method (EDEM). In those studies we performed trial simulations for wooden houses, and our calculating method turned out to be useful for analyzing the process by which wooden houses collapse. Figure 1 explains the DEM and the EDEM.

![Figure 1. Distinct Element Method and Extended Distinct Element Method](image)

2.1 Modeling of Bricks and Contact Forces

In this analytical model each brick was modeled as assembly of sphere particles. The contact forces were substitute to the normal forces, the friction forces and the tensile forces between bricks for simple calculation as shown in Figure 2. These three kinds of force were calculated according to the distance between sphere particles. The normal (repulsion) force and friction force and was calculated according to Equation 1-2, if the particles contact each other. The tensile force of mortar was calculated according to Equation 3, if the distance between the particles was within the threshold \( l_m \).

\[
F_n = K_n (d - l_p) \tag{1}
\]
\[
F_s = \mu F_n \tag{2}
\]
\[
F_t = -K_m (d - l_p - l_m) \tag{3}
\]

where \( F_n \) is the normal force, \( K_n \) is the compressive stiffness, \( d \) is the distance between sphere particle, \( l_p \) is the diameter of sphere particle, \( F_s \) is the friction force, \( \mu \) is the friction coefficient, \( F_t \) is the tensile force, \( K_m \) is the tensile stiffness and \( l_m \) is the threshold distance of mortar.
3. FABRICATION OF TTPU SHAKING TABLE OF ONE HORIZONTAL DIRECTION

Considering the driving systems for the seismic shaking tables, there are several methods such as the electromagnetic systems, the mechanical systems, and hydraulic systems. The electric servo motors are used for earthquake simulators of comparative low power system. However, the electromagnetic systems would not be good, because the seismic test shaking tables require the large driving forces. Most of big test facility uses a hydraulic system. TTPU has a structural testing facility. Therefore, TTPU decided to use the hydraulic system for a shaking table. TTPU shaking table was assembled by students of TTPU mechanical department. A Reaction frame, a base frame, four guide ball bearings for one horizontal movement, and a table members were cut, welded and set. In the facility, there are many kinds of numerical control machine tools for the students, who handled the NC machine tools, and produced the elements of TTPU shaking table.

3.1 Elements of TTPU Shaking Table

An actuator cylinder, valve, valve driver, were purchased from Italy. The actuator cylinder has ready-made single piston rod. The outline of actuator cylinder is shown in Table 1 and Figure 3.

<table>
<thead>
<tr>
<th>Items</th>
<th>Stroke</th>
<th>Push Side Piston Area</th>
<th>Pull Side Piston Area</th>
<th>Position Meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performances</td>
<td>30cm</td>
<td>50.24cm²</td>
<td>25.61cm²</td>
<td>Potentiometer</td>
</tr>
</tbody>
</table>

The valve was a servo proportional valve. The valve was installed to the actuator cylinder through a manifold block. The spool of valve was driven by the solenoid. The solenoid position was detected by LVDT transducer. A valve driver attached to the valve. A valve spool and LVDT transducer has constituted a closed loop control. A flow and frequency characteristics of the valve were shown in Figure 4. Inputs for the valve driver were analog signals. In order to control the actuator, the reference signals and the transducer signals of actuator piston rod positions should constitute a closed loop. In open loop, the actuator of single piston rod makes divergences.
A power unit and hydraulic hoses, were purchased from China. The hydraulic power unite includes an accumulator, a relief valve and an oil filters, an electric motor, a hydraulic pump, and an oil tank. The outline of performance of power unit performance are shown in Table 2.

**Table 2. Hydraulic power unit outline**

<table>
<thead>
<tr>
<th>Items</th>
<th>Motor Power</th>
<th>Oil Pressure</th>
<th>Discharge Flow</th>
<th>Oil tank</th>
<th>Accumulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performances</td>
<td>37Kw</td>
<td>20MPa</td>
<td>900/min</td>
<td>3000</td>
<td>8ℓ(nitrogen gas)</td>
</tr>
</tbody>
</table>

### 3.2 Fabrication of TTPU Shaking Table

The Shaking table was fabricated at the reaction wall floor. At first, the base frame was fabricated by welding with the use of 50mm x 100mm x 4mm steel members. The outline of base frame is shown in Figure 5. On the base frame beams, the guide boxes which confine the shaking table movement to one horizontal direction, welded at four positions. A length of guide boxes of about 45cm was longer than the actuator cylinder stroke. In each guide box, two spherical steel balls placed, which performed as bearings with the glycerin of lubricate agent. The guide boxes which were fixed on the table backside, placed downwards. The outline of guide bearing system which consisted of the guide boxes and spherical steel balls, is illustrated in Figure 5. The payload capacity of guide bearing systems which was checked by a compression testing machine, gave the results of more than 5KN.

![Figure 5. Setting of shaking table, reaction frame, guide bearings and actuator cylinder on concrete floor.](image-url)
The table was made with the steel box beams of 100 x 50 x 4 and the steel plate of thickness 5mm. At first, the horizontal frame was fabricated by the welding works, and the table surface plates were welded on the horizontal frame. Over the table surface plate, there were 64 holes with diameter 20mm for bolt connections of test specimens. The table dimension and the joint of actuator and table are shown in Figure 3 and 5. The weight of table was estimated about 0.5ton. The reaction frame was made with the steel materials by the welding works, and fixed in the concrete floor with 6 bolt nuts of bolt diameter 27mm. The connection between the actuator and the reaction frame was carried out with a fixed eye with the spherical bearing mounting. The installation height of actuator cylinder from concrete floor was about 20cm. The hydraulic power unit was placed near the shaking table, as shown in Figure 5. Electric power was supplied with three phase alternative current. No heat exchanger for oil cooling was equipped. The hydraulic hoses were connected from the hydraulic power unit to the ports of manifold block of actuator.

3.3 Electric and Control System of TTPU Shaking Table

A PC with DA converter (±10V:16bits) for the generation of input signals was prepared. And an actuator control amplifier (analogue controller) which adjusts the piston rod position signals and compares the position signals with input signals, have been provided. In this way, the closed loop system of feedback for shaking table control has been realized. The electric powers for the valve were supplied from an electric direct current power supply of about 140w. The solenoid of servo proportional valve was driven by the direct current 24V with a fuse of 2.5A. The outlines of driving systems of TTPU shaking table are presented in Figure 6.

3.4 Response Characteristics of TTPU Shaking Table

Acceleration responses to displacement triangular waves were measured, Shaking table pulse responses were obtained. Figure 7 presents the response acceleration waves and spectrum. Spectrum shows peak frequency around 12Hz, which is estimated natural frequency of TTPU shaking table. Shaking table spring including oil column spring in the hydraulic cylinder estimated around 30KN/cm. The spring value would be too small in comparison with oil column spring 400KN/cm. Therefore, the low value spring would be given by connection between actuator and reaction frame and joint. For the conveniences, the simple equation of hydraulic shaking table would be given as follows (equation (4)).
\[ m \ddot{x} + k \left( x_T - x_I \right) = 0, \quad \frac{1}{k} = \frac{1}{k_B} + \frac{1}{k_O} + \frac{1}{k_J} \tag{4} \]

\( m \): load mass, \( k \): spring, \( x_T \): table displacement, \( x_I \): servo valve output displacement, \( k_B \): reaction frame spring, \( k_O \): oil column spring, \( k_J \): joint spring

Figure 7. Fourier spectrum of TTPU shaking table acceleration responses to rectangular wave input (no test weight, table weight 0.5 tonf)

Figure 8. Limit performance, and comparison between original and reproduction of TTPU shaking table (after INGV: ITACA-ESM Working Group. et. 2016)

The small amplitude peaks of more than 100Hz were measured. In the measurements, the sampling frequency of 2KHz was selected. The natural frequencies of acceleration transducers were 400Hz approximately. The peaks of high frequencies indicated the rough setting of a shaking table. According to natural frequency of bare shaking table, limit performance curves of considering change of shaking table natural frequency with test weight increments, are provided in Figure 8. Also Figure 8 shows the recorded time history, and its velocity response spectra (damping 0%) of comparing with original wave of Aug. 2016 Amatrice EW strong motion record, with test weight around 1ton. The shock pulses on shaking table wave are estimated to be produced by backlash of many parts, such as joints, reaction frame, guide bearing system, or changes of push - pull area. Pulses and high frequency noise effects would be found in frequencies of more than 8Hz.
4. BRICK MASONRY STRUCTURE MODEL TEST

TTPU decided to prepare for the dynamic damage test of the brick structure model as the first full-scale test using the TTPU shaking table. Then the tests were conducted.

4.1 Brick Structure Model Construction

The brick structure model is about 1 m square and 1.5 m high (15 layers). There is no wall which is subjected to the out-of-plane deformation of the actuator side. The wooden beam are set at the 6th and 13 layers. The opposite side of the actuator is a non-opening wall. Two walls parallel to the movement of the shaking table have the same elevation drawings, in which there openings placed from 1st layer to five layer, and from 10th layer to 12th layer. The widths of openings are about 0.5m. A wooden lintel goes around the model horizontally above the opening. A brick, as shown in Figure 9, has dimension 25cm x 12cm x 8cm with three holes( φ 2cm), weight 4kg, compressive strength 4MPa and compressive strain 1.5%. Young modulus 250MPa approximately. Material test conducted in TTPU laboratory. Assuming a vibration mode of \( \sin(\frac{\pi z}{2H}) \) and using this Young modulus(250MPa), fundamental natural frequency of the brick structure model is estimated as 11.4Hz by Rayleigh - Ritz method (Minowa , 1979). Measured natural frequency shows about 15Hz. The difference between theoretical calculation and measurement would be brought by the rough theoretical modeling. The model was constructed on mortal mat placed over shaking table face. An test was conducted on 3 days after completion of a model structure, as shown in right side of Figure 9. Total load for actuator was 1.45ton ( table 0.5tonf).

![Figure 9. Construction and completed brick structure model](image)

4.2 Vibration Characteristics of Brick Structure Model.

For the purpose of taking the characteristics of the shaking table and the model, small amplitude excitation of the random wave was performed. During this performance, when changing operation mode of servo amplifier from the manual input to the computer input, the shaking table moved suddenly to the neutral position from present position. One pulse sinusoidal was assumed to act to the brick masonry structure model in the missed shaking table operation. This table motion would be described in the displacement expression of \( d(t/T−(1/2 \pi) \sin(2 \pi t/T)) \). The acceleration expression would be given as \( (2 \pi d/T^2) \sin(2 \pi t/T) \). In the expression, shift displacement \( d=15cm \) (half stroke) and period \( T=0.75s \) (max velocity are used. The estimated table motion of erroneous operation is also shown in head of Figure 10.
Due to this missed control operation, the structure model greatly damaged. The bond of wooden lintel and brick broke between the joints 12th and 13th layer. At this damage, the primary frequency representing the rigidity of the specimen decreased from 15Hz to 5Hz as shown in Figure 11. The rigidity of the specimen is reduced to 1/9. The response magnification dropped from 3 times to 2 times, and the attenuation increased from 15% to 25% approximately.

4.3 Damage Test of Brick Structure Model using Earthquake Record and Sinusoidal Wave

The brick structure model tested by the use of earthquake record of Amatrice EW in Italy (AMT EW), August 24 2016 (http://www.reluis.it/) and sinusoidal wave. Input motion sequence are shown in Figure 12. Earthquake acceleration waveform and spectrum characteristics of dominant frequency around 3Hz is shown in Figure 8. There was no damage seemingly in full-scale excitation of Amatrice EW. In next excitation of three times amplitude excitation of Amatrice EW, large slip damages and share cracks were found as shown in Figure 12. However, collapse did not occurred. Even in next same excitation, the damages of brick structure model extended a little, and there was no collapse. In one Hz sinusoidal excitation of 5cm, the collapse was occurred. as shown in Figure 16.
5. ANALYSIS MODEL OF COMPUTER SIMULATION

For TTPU shaking table test results, computer simulations were conducted. The numerical models used here were depicted in Figure 13. The bricks were modeled as a rigid body (brick element). The configurations of the bricks elements were same as in the test specimen. The mass and size of the analytical model was same as the test specimen.

In the following calculation, $K_n$ and $K_m$ in equation (1) was set to 1000kN/m, $\mu$ in equation (2) was set to 0.3 and $l_p$ in equation (3) was set to 0.02mm. Diameter of modeled sphere particle assembly was 25mm.

![Analytical model](image13.png)

6. COMPARISON OF ANALYSIS AND EXPERIMENT

In input sequence of Figure 10, first three times amplitude excitation input of Amatrice EW made the damages of shear cracks in side wall and slip on under surface of upper wood lintels and bricks as shown in Figure 14. The numerical simulation of the same excitation input is shown in Figure 15. In the numerical simulation, it is assumed that all the adhesion of cement has been broken due to an erroneous operation, and it is calculated as an dry masonry. In fact, adhesion remains, and numerical simulation does not consider this remaining adhesion (spring). In addition, wooden lintels of four walls are joined by nails, forming a square horizontal frame. In the numerical simulation, joining of wooden lintels are not considered.

![Damage photos](image14.png)
The excitation input of $\cos 1\text{Hz} \ 5\text{cm}$ of Figure 10 made the brick masonry structure model to be collapsed, as shown in Figure 16. The numerical simulation of the same excitation input is shown in Figure 19. In Figure 18 of the shaking table test, the upper bricks on the upper wooden lintel were moving together. In Figure 17 of the numerical simulation, the effects of residual adherences were not considered, so the unity behaviours on the upper wooden lintel are not expressed, it can be expressed that the wall falls to the right.
7. CONCLUSIONS

A program for analyzing brick masonry structure using the Distinct Element Method was developed, and numerical simulations for results of shaking table test were conducted. It is found from comparison of shaking table tests and numerical simulation, that DEM analysis program developed here can be used for earthquake response analysis of brick masonry structure. The collapsing process simulations by DEM program, although it differed in showing no horizontal cracks and rocking behavior which appeared in the shaking table test. It convinces us that this simulation method would be quite effective and reliable tool to analyze and evaluate proposals of seismic designs of brick masonry structures when the method gets improved further.

An attempt to examine the building safety by reproduction of the movement of the earthquake that caused the damage, is of course thing. Such a thing was seen in many years ago. After 1891 Nobi earthquake in Japan, there is a record that a mechanical shaking table was made (Reitherman R, 2012). In addition, after the San Francisco earthquake of 1906, the shaking table of a mechanical system was created at the Blume Center of Stanford University, and it was used in ground soil experiments and structure model experiments (https://blume.stanford.edu/about/history). Afterward, hydraulic technology and electronic control technology were progressed. It made possible to conduct tests by reproduction of the earthquake records in the shaking table in 1960s (Fukuzawa H, 1966, Penjean J, et., 1967). In 1970, one directional shaking table which had a payload of 500ton, an area of 15m x 15m, a stroke of 6cm (now improved upto 48cm), was constructed in Tsukuba City (Minowa, 1983, NRCDP). Japan. In addition, in 1982, two directional shaking table which had a payload of 1000ton, an area of 15m by 15m, an stroke of 44cm, was constructed in Tadotsu City (Mouri, 2010, NUPEC), Japan. In 2005, three directional shaking table which has a payload 1000ton, an area of 15m by 20m, a stroke of 206cm, was constructed in Mike City (Ogawa, 2004, NIED), Japan. Now, large-scale shaking tables have been built in various parts of the world. When considering this situation, research institutes of developing countries where there are experiences of the earthquake damages, it is understood that say want to have a shaking table to reproduce the ground motion. 50 years ago in Central Asia, Uzbekistan capital Tashkent suffered from catastrophic damages. Therefore, It is natural that they have the hope of having a shaking table for structural testing. The above is the reason why the TTPU constructs a shaking table.

As shown in this paper, a small size shaking table with displacement control was constructed by students. The shaking table moved with earthquake record, and a shaking table test of brick masonry structure was conducted.

The acceleration waveform of the TTPU shaking table includes noise as shown in Figure 8. The noise is the same as what we see on many shaking tables, and noises have high frequency components. In the response spectrum, the effect of the pulses are seen in the frequency range higher than the dominant frequency. It is not known whether the pulses had a strong influence on the specimen. The noises may be emitted from the play in the joint, and also they are emitted from the friction of the guide and the bearing. The pulses in Figure 8 occur at the peak of the acceleration and occur when the direction of motion changes, that is, when the velocity is zero. Therefore, it is assumed that the pulse is caused by the backlash of the joint. In addition, the shaking table uses a single rod actuator, and when the direction of motion changes, the cross section of the piston changes. It is necessary to consider the possibility that the change of cross section causes pulses. The shaking table of the TTPU was made for only twenty thousand dollars. Considering the low budget of twenty thousand dollars, it may be necessary to accept that this level of shock and noise occur (Minowa 2017).

8. ACKNOWLEDGMENTS

The authors express their gratitude to Prof. Kongratbay Sharipof; First Vice Rector of Turin Polytechnic University in Tashkent, and Prof. Davron Matrasulov for opportunity of shaking table construction. Japan International Cooperation Agency supports activities for one of authors as a JICA Senior Volunteer.
9. REFERENCES

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