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SHAKING TABLE TESTS OF TYPICAL B-ULTRASOUND MODEL HOSPITAL ROOM IN A SIMULATION OF THE LUSHAN EARTHQUAKE

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ABSTRACT

Earthquakes have again highlighted the vulnerability of China's health facilities. The current investigation of the seismic status of hospital facilities was conducted after the Lushan M_W6.6 earthquake, and both structural and nonstructural damage are listed. Structural and nonstructural damage of four typical hospitals and clinics are discussed here. Structural damage is here described alongside damage to architectural elements, equipment, and furnishings caused by earthquakes. This investigation indicated that the hospital facilities can lose partial or full functionality due to nonstructural damage or even limited structural damage. Although none of the objects inside were knocked over and only a few decorations fell down, many sets of equipment were severely damaged because of the strong floor vibration. This resulted in great economic losses and delays in rescue operations after the earthquake. Shaking table tests on a full scale model of a B-ultrasound room were conducted to investigate the seismic performance of a typical room in a hospital. The tests results showed that the acceleration responses of the building contents with or without trundles demonstrated different behaviour. Without trundles, the peak acceleration and the peak displacement of building contents first increased with increasing PGA and then decreased when the acceleration exceeded a particular value. Then they both changed a little. Because of the rapid turning trundles, the response of building contents increased only slightly as PGA increased, or even decreased or remained roughly steady.

INTRODUCTION

Health care facilities are expected to remain functional during and after earthquakes. However, investigations have shown that health care facilities are more vulnerable to earthquakes than other types of buildings. Seismic damage to health care facilities results in interruption of hospital facilities immediately even after the moderate earthquake [1].

The M_W8.8 Chile earthquake of February 27, 2010 caused significant nonstructural damage. According to the Ministry of Health of Chile, 71% of the public hospitals were located in the affected areas, providing 63% of the country's total beds. Of these hospitals, 62% suffered nonstructural damage necessitating some repairs. Of the damaged hospitals that were partially or completely closed after the earthquake, 83% lost partial or total functionality because of nonstructural damage. Some of the hospitals suffered various levels of structural damage, most of which was minor to moderate, with an extremely small portion being severe [2]. The nonstructural components of hospitals in the three counties stricken by the M_W9.0 Great East Japan Earthquake on March 11, 2011 performed poorly after the earthquake. Out of the 381 hospitals considered in this study, 8 hospitals suffered from complete destruction of equipment, and 179 hospitals suffered from partial damage to equipment. In particular, in all the 147 hospitals in Miyagi-ken, 5 sets of equipment were completely destroyed, and 179 sets of equipment were partially damaged. Even though some hospitals survived the tsunami, many hospital buildings were damaged due to their poor shock resistance, where the treatment facilities were terminated [3]. Recently, a M_W7.8 magnitude earthquake struck Nepal on April 25, 2015, with the epicentre at Barpak Village Development Committee in Gorkha District. There were continued aftershocks throughout Nepal. More than 25 hospitals and 900 smaller facilities, predominantly village health posts, were completely or partially destroyed in the earthquake. Even so, the earthquakes and the continuing aftershocks in Nepal highlight the importance of the efforts the Ministry of Health and Population and WHO have made for more than a decade to ensure that key hospitals, health facilities, and health care workers would be ready and able to function well in an earthquake. The first earthquake on April 25, measuring 7.8 on the Richter scale, and its aftershocks failed to disrupt services at Kathmandu's largest public hospitals, including Tribhuvan University Teaching Hospital (TUTH), Patan Hospital, Civil Service Hospital, Birendra Army Hospital and the trauma centre at Bir Hospital. A large number of injured people were diagnosed and treated in those hospitals [4, 5].

According to a WHO report, people trapped in earthquake debris rarely survive longer than 48 hours, but 85 - 95% of persons rescued alive from collapsed buildings are rescued in the first 48 hours after the earthquake. The demand for health services is concentrated within the first 24 hours after the event. Camp and field hospitals and rescue teams usually arrive too late to dramatically increase the number of lives saved. For this reason, the normal operation for nonstructural systems of hospitals is important in the earthquake affected area. Damage to nonstructural systems and components typically results in the majority of the economic losses associated with earthquakes. Losses can exceed 50% of the total value of a facility even though the structure sustains little or no damage. In this way, severe damage and enormous economic losses indicates that previous seismic investigations

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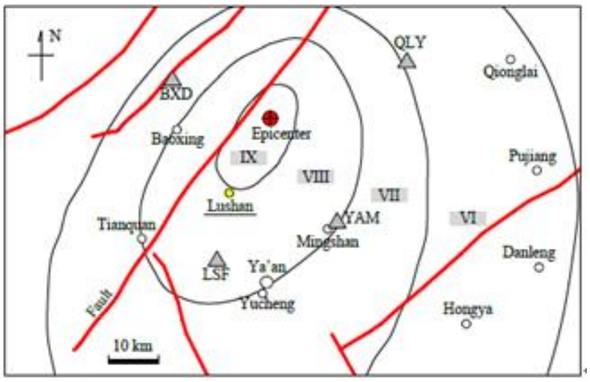
and assessments of nonstructural system of health facilities have been inadequate.

DAMAGE TO HOSPITALS IN THE LUSHAN EARTHQUAKE

The Wenchuan M_W7.9 earthquake caused the collapse of numerous buildings and many deaths, so little attention was paid to nonstructural systems of health facilities. Five years later, the Lushan M_W6.6 earthquake occurred at 8:02 a.m. on April 20, 2013 in southwestern Sichuan Province in China. The peak ground accelerations at the strong motion stations in the near field region of the earthquake are shown in Figure 1 [6].



Station	PGA(cm/s^2)		
	NS	EW	UD
BXD	1029.9	752.6	528.7
YAM	420.1	357.8	105.6
LSF	376.8	380.6	276.1
QLY	268.3	311.0	108.7

Figure 1: The intensities and strong motions stations in the near field region of the Lushan earthquake.

Because neither the damage to buildings nor the death toll were very large, the present seismic investigation focused on health facilities. According to the classification of earthquake damage to buildings and special structures [7] and the Chinese seismic intensity scale [8], the investigation was performed on the 24 hospitals and clinics in seismic area [9]. Here, 4 typical hospitals or clinics were chosen to display the seismic damage to health care facilities.

The Outpatient of the People's Hospital in Mingshan County

Nonstructural seismic damage to the People's Hospital in Mingshan County was severe, but the structure was left intact. Some valuable medical equipment was damaged by vibrations rather than by being knocked over. Many infilled walls shifted and cracked, and decorations on the walls and columns fell. The ceilings sustained over 2200 m^2 of damage. The fire water tank cracked and the outbound device in the elevator was damaged. The facilities sustained severe and widespread damaged that impaired the functionality of the hospital. For example, the colour Doppler ultrasound machine could not be started, and the anesthesia machine worked abnormally because of damaged pipe connections (Figure 2).

(a) Anaesthesia machine

(b) Crack on the stair wall

Figure 2: Seismic damage of the outpatient of people's hospital in Mingshan county.

(a) Crack on the infilled wall

(b) The colour doppler ultrasound machine

Figure 3: Seismic damage of the outpatient of Xindian clinic.

Xindian Outpatient Clinic

The Xindian Outpatient Clinic suffered moderate structural damage and visible cracks formed on many infilled walls. The decoration and architectural elements did not suffer much seismic damage. More than 100 pieces of equipment and furnishings suffered various levels of damage. These included computers, the colour Doppler ultrasound machine, and ventilators. The drug supplies were scattered across the floor (Figure 3). This is typical of the damage sustained by low rise clinics. The structure experienced slight to moderate damage and retained much of its normal function. Meanwhile, nonstructural components suffered severe damage, which can lead to interruptions in medical function, such as in the Qingren Country Clinic and Siyan County Clinic.

New Outpatient Facility of The People's Hospital in Lushan County

The new outpatient facility had an isolation damping system, so the only seismic damage sustained was to this system, and almost all the medical and administrative equipment remained functional (Figure 4). The new outpatient facility was the only functional hospital facility after the earthquake in Lushan County, and played it an important role in emergency response.

(a) Normal function hospital room

(b) Operating room

Figure 4: Situation of the new outpatient of people's hospital in Lushan county after Lushan earthquake.

Old Outpatient Facility of The People's Hospital in Lushan County

The old and new outpatient facilities are next to each other. The old outpatient facility sustained both structural and nonstructural damage, and both structures and other elements were functionally interrupted (Figure 5).

(a) Crack on the infilled wall

(b) Overturning of equipment

Figure 5: Seismic damage of the old outpatient facility of the people's hospital in Lushan county.

Although there are code provisions for the seismic design of nonstructural components for general purposes, there are no specific requirements for design and practical details of hospital facilities under the current Chinese code. Because of this, many hospitals had to cease operations immediately after the earthquake. Both the Chinese seismic code and ASCE/SEI Standard 7–10 establish minimum design criteria for nonstructural components that are permanently attached to structures and for their supports and attachments [10, 11]. Freestanding equipment has tended to receive little attention.

SHAKING TABLE TEST OF A TYPICAL B-ULTRASOUND MODEL ROOM OF HOSPITALS

The hospital facilities, such as the B-ultrasound machine, are important during an earthquake emergency response. The severe damage to the building's contents impairs functionality, which leads to interruptions in service. For this reason, a full scale shaking table test of a B-ultrasound room was conducted to assess the seismic performance of hospital facilities during earthquakes.

Test Programme

Because many clinics are low-rise buildings, a one-storey, one-bay, concrete frame filled in with clay brick infill 120 mm thick was designed according to the current Chinese code. The seismic precautionary intensity was assumed to be 7.0 and the design basic acceleration of ground motion to be 0.1g. The design details of the structure are shown in Figure 6. Cement mortar on the structure was 10 mm thick, and the emulsion paint was brushed onto the mortar. The bottom beam of the model was designed to connect to the shaking table. The structural model before and after decoration is shown in Figure 7. The sensors were set in and around the frame in order to investigate the seismic response of the model room.

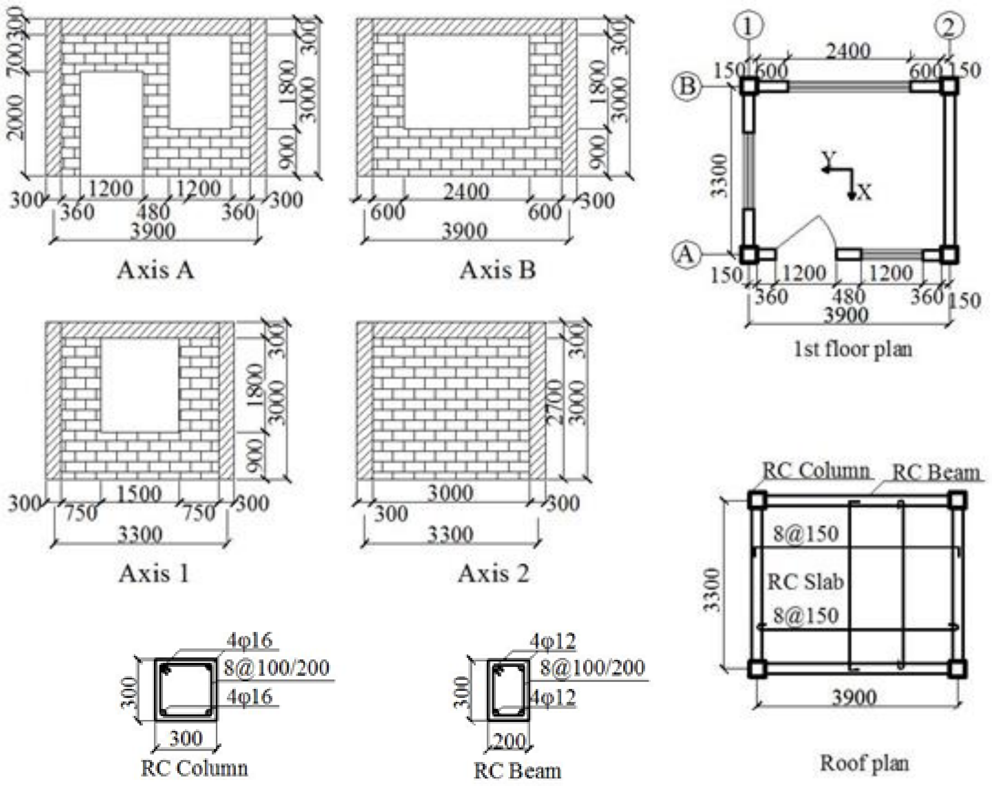


Figure 6: Structural layout and design of the experimental model.

(a) Model before decoration *(b) Model after decoration*

Figure 7: Experimental model room.

Table 1: Building contents of the B-ultrasound room.

Building contents	Mass(kg)	Arrangement	With or without free trundles
Bed	45.2	Standing on the floor	Four free trundles
Dummy patient	51.6	Lying on the bed	without
B-ultrasound machine	101.5	Standing on the floor	Four free trundles
Office desk	20.4	Standing on the floor	without
Display	2.2	On the office table	without
Mainframe	8.6	In the office table	without

The layout of the B-ultrasound room is shown in Figure 8. For investigative purposes, green lines were drawn on the floor at 50 cm intervals. The acceleration transducers were set on the bed. The room also contained a B-ultrasound machine and office desk, which are shown in the blue frame in Figure 8. The mass and other information are listed in Table 1. In addition, the dummy representing the patient was filled with sand to increase its weight.

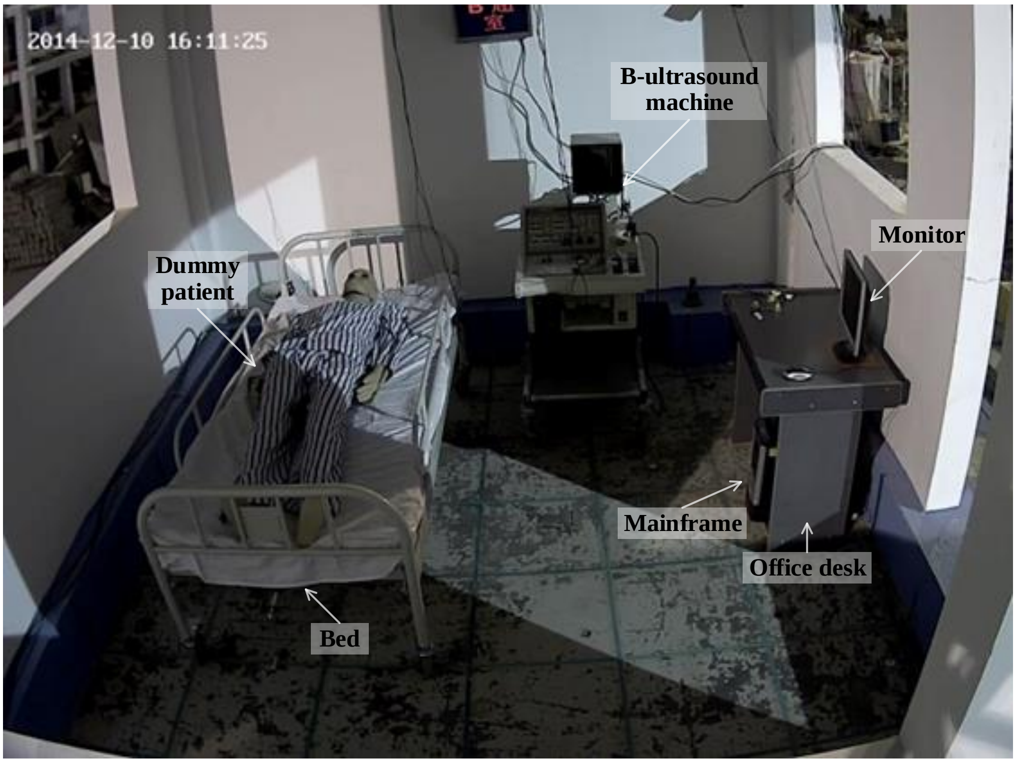


Figure 8: The B-ultrasound room model.

Table 2: The characteristics of the shaking table in IEM, CEA.

Performance	Value
Payload capability	3.0×10^4 kg
Size of shaking table	5 m×5 m
Driving direction	X, Y, Z
Number of DOF	Six
The maximum driving displacement	Horizontal: ±80 mm, vertical: ±50 mm
The maximum driving speed	Horizontal: ±600 mm/s, vertical: ±300 mm/s
Peak value of acceleration	X: 1.0g Y: 1.0g Z: 0.7g
Range of frequency	0.5～40 Hz
The maximum overturning moment	7.5×10^4 kgm

Table Motions Applied

Shaking table tests of a B-ultrasound room model were carried out using the earthquake simulator system at the laboratory of the Institute of Engineering Mechanics, Chinese Earthquake Administration (IEM, CEA). The characteristics of the shaking table are listed in the Table 2.

Then the tests were carried out at four seismic intensity levels with peak accelerations ranging from 0.2g to 1.1g. One of the acceleration time-histories recorded in the Wenchuan earthquake was used as the basic input motion in the shaking table tests. The horizontal peak ground acceleration in the controlling direction (y-direction) was intended to be incrementally increased from 0.20g to 1.10g through the ten runs, as is listed in Table 3.

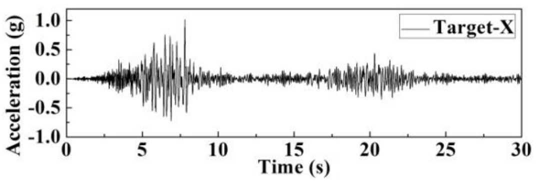
The duration of the loading in each run was 30 s. The target acceleration and the table acceleration of run 9 is shown in three directions in Figure 9. The test results presented in the following sections should only be interpreted in line with the corrected measured PGA

The rich high-frequency content was obvious on the response spectra of the input motion. Figure 10 compares the design spectra in the Chinese seismic code [11] with the measured table motion in run 9. During the high-frequency stage, the response spectra of the horizontal table motions were several times greater than the design spectra, whereas they were much lower than the design spectra for low frequency. The response spectra of the vertical table motion were similar to those of the horizontal ones.

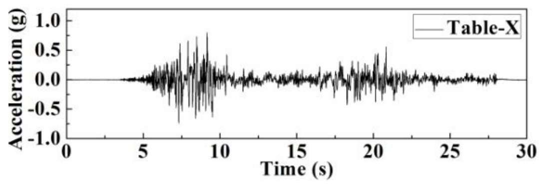
Table 3: Shake table runs and measured peak accelerations (unit: g).

Run	Target PGA-*y*	Measured PGA-*y*		Relative error
		As-recorded	Corrected*	
1	0.20	0.24	0.25	25.00%
2	0.30	0.32	0.33	10.00%
3	0.40	0.43	0.44	10.00%
4	0.50	0.55	0.53	6.00%
5	0.60	0.67	0.65	8.33%
6	0.70	0.72	0.71	1.43%
7	0.80	0.81	0.82	2.50%
8	0.90	0.94	0.92	2.22%
9	1.00	1.01	1.02	2.00%
10	1.10	1.14	1.16	5.45%

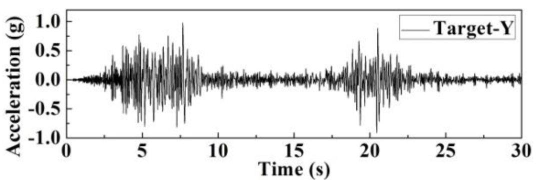
** The record is baseline-corrected and processed by a 4th order Butterworth band-pass filter with a bandwidth of 0.05~50 Hz before calculating the peak acceleration.*



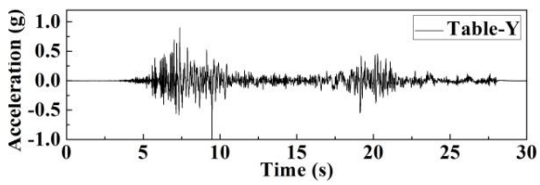
(a) Target acceleration in X direction



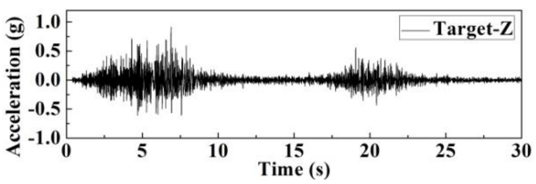
(b) Table acceleration in X direction



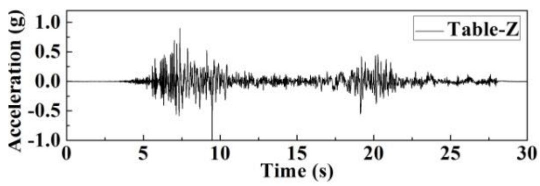
(c) Target acceleration in Y direction



(d) Table acceleration in Y direction



(e) Target acceleration in Z direction



(f) Table acceleration in Z direction

Figure 9: Comparison between the target acceleration and the table acceleration (run 9).

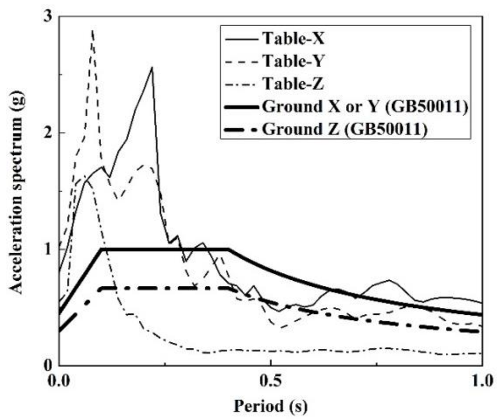


Figure 10: Response spectra of the table motions in run 9 compared with the design spectra in the Chinese seismic code.

Test Results

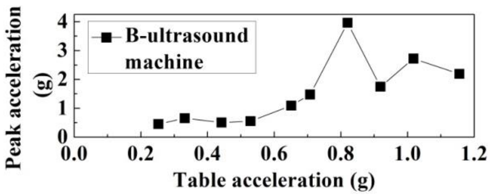
The structure itself remained almost undamaged with some minor cracks in the masonry of infilled walls (Figure 11), and the cracks appeared near windows and doors, where the infilled walls were brittle. As PGA increased, the B-ultrasound machine and the sickbed started moving randomly. The office desk, which did not have trundles also showed significant movement. The monitor on the office desk overturned after severe vibration (Figure 12). The limit of the maximum driving displacement and peak value acceleration of shaking table was as listed in Table 2. There was not enough floor displacement or floor acceleration to knock any of the furniture over (because the model was only one storey high and PGA was the peak floor acceleration for the contents).

(a) *(b)* *(c)*

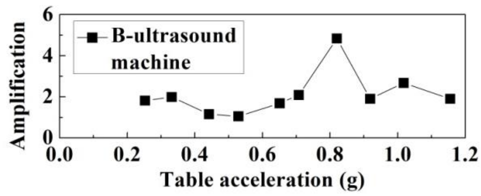
Figure 11: Cracks on the walls.

(a) *(b)*

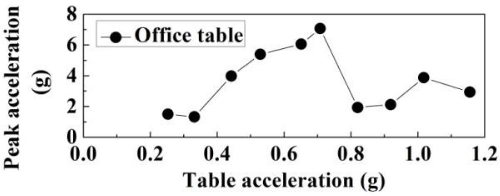
Figure 12: The B-ultrasound room after shaking.



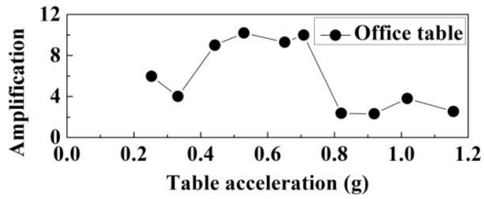
(a) Peak acceleration of the B-ultrasound machine



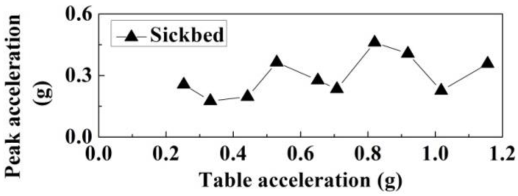
(b) Amplification of the B-ultrasound machine



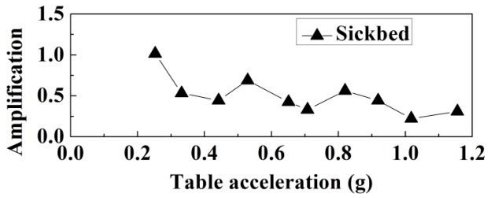
(c) Peak acceleration of the office table



(d) Amplification of the office table

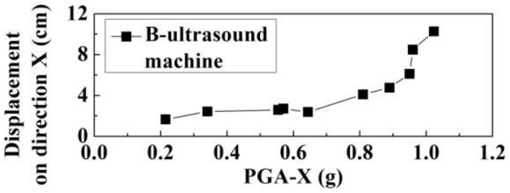


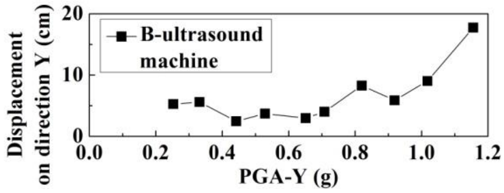
(e) Peak acceleration of the bed



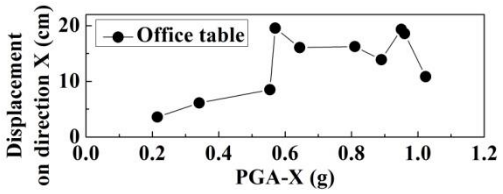
(f) Amplification of the bed

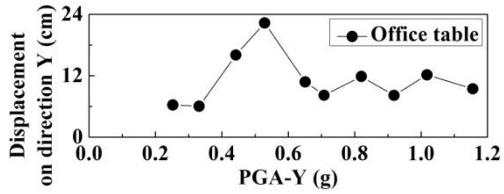
Figure 13: Peak acceleration of the room contents and their amplification factor vs. PGA.



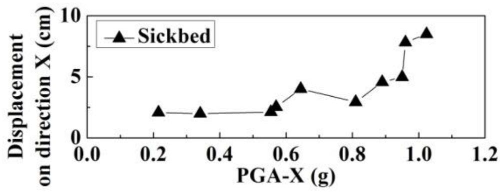


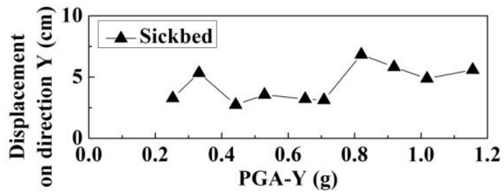
(a) The B-ultrasound machine in direction X *(b) The B-ultrasound machine in direction Y*





(c) The office table in direction X *(d) The office table in direction Y*





(d) The bed in direction X *(f) The bed in direction Y*

Figure 14: Maximum displacements of the room contents vs. PGA.

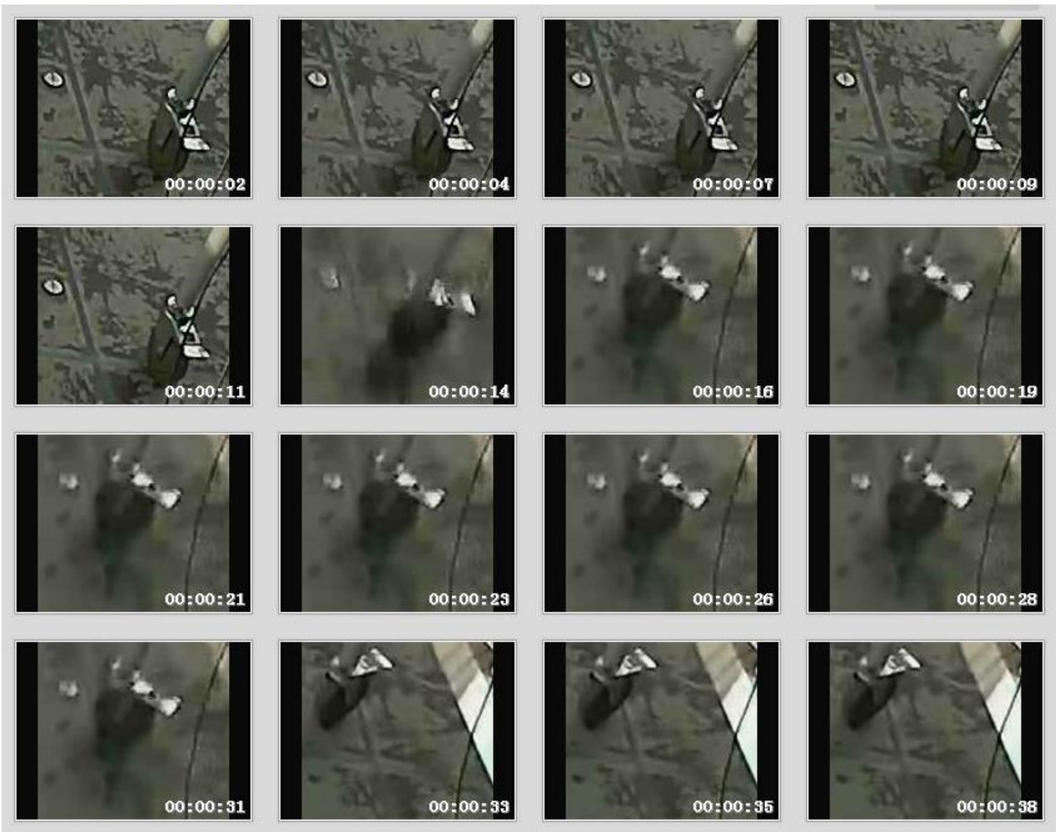


Figure 15: Snapshots from the video recordings of one trundle of sickbed.

The peak acceleration of the building contents and the amplification factor to the PGA are shown in Figure 13 and the maximum displacement is shown in Figure 14. The acceleration responses of the building contents with or without free trundles demonstrate significantly different behaviour as the PGA increased. For the office table, which did not have trundles, the peak acceleration of the building contents increased with increasing PGA. The peak acceleration of the office table decreased when the acceleration exceeded a particular value around 0.60g and had no obvious increase after 0.60g. The rule governing the displacement vs the PGA in the same direction is similar. However, the response rule of building contents with free trundles is not obvious. The response of the building contents to trundles increased gently with increased PGA and even reduced or vibrated sometimes. The coefficient of friction of the building contents without trundles was nearly ten times of that with them [12, 13]. The trundles did not rigidly connect with the main body, so they could turn freely and rapidly (Figure 15). In this way, the frictional force, which depends on the layout of trundles, plays an important role on dynamic response of the building's contents.

CONCLUSIONS

The seismic investigation of hospital facilities after the *M*w6.6 Lushan earthquake confirmed previous reports of the vulnerability to earthquake-induced damage again. Then the nonstructural damage was listed alongside structural damage. Structural and nonstructural damage in four typical hospitals are presented here. This study presents the structural damage of the hospitals and the seismic damage to architectural elements, equipment and furnishings. The hospital facilities lost partial or total functionality due to nonstructural damages, even when their structures did not suffer severe damage. However, the damage they did sustain not only led to significant economic losses but also caused interruptions to hospital services, adversely affecting the emergency response to the earthquake. A full-scale B-ultrasound model room was constructed and shaking table tests were performed. The full-scale model room was equipped with a B-ultrasound machine, a bed, a dummy representing a patient and an office desk.

The acceleration responses of the building contents with or without trundles demonstrated different behaviour. Without trundles, the peak acceleration and the peak displacement of building contents increased with increasing PGA. It decreased when the acceleration exceeded a particular value, which was here around 0.60g, but showed no obvious increase after that. With trundles, the response of building's contents as PGA increased was far gentler.

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