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Estimation of Historical Earthquake Intensities through Test on Scaled Wooden House Model

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ABSTRACT

Shake table tests on two 1:4 scaled models of an ancient Korean commoners' house made of fresh pine lumber were performed. Typical earthquake time histories recorded on soil and rock sites were used for the input motion. Natural frequency and a damping ratio of the house were identified. The PGA at collapse of the house at soil site was 0.25g, whereas the peak ground acceleration(PGA) at severe damage of the house at rock site was 0.6g. The intensity of major historical earthquake records related with house collapses was quantitatively estimated to be MM VIII.

INTRODUCTION

Several large historical earthquake records in Kyungju City area, located 35 km from the northwest of the Wolsong NPP site in the southeastern part of Korea, have raised same important issues, such as the seismic design level of NPPs and the activity of the nearby fault systems since 1982. Also, the results of the probabilistic seismic hazard analysis (PSHA) for several NPP sites have shown relatively high hazard levels and large uncertainties. The seismic hazard problem in Korea can be attributable to less reliable processing of historical and instrumental earthquake data that led to an overestimation of earthquake intensities, irrelevant consideration of incompleteness, inappropriate attenuation and so on.

The number of historical earthquake records regarding house collapses and deaths of people between the year 2 and 1905 totals fourteen. Among those, at least six events occurred in the Kyungju City area where the Yangsan Fault systems pass through. The foundation of this area is typically a soft soil with a maximum thickness of 20 m. A typical damage record of a historical earthquake is the "ground was shaken and commoners' houses collapsed and people died". The number of deaths in the largest event was approximately 100. The estimated MM intensity of these events in Kyungju City area varied from VIII to X depending on experts[1]. It is worth noting that during the 1995 Kobe earthquake the damages of wooden houses at soft soil and houses degraded due to termite or fungi were found to be much more severe than ones at rock and un-degraded houses[2]. The peak ground acceleration (PGA) of MM VIII and X ranges from 0.14g - 0.63g and 0.52g - 2.75g, respectively, depending on the empirical relationships between MM intensity and PGA.

It was identified that the commoner's house until 19th century was a three-bay-straw -roof wooden house [3]. Many differences exist between Korean and American (or European) wooden houses so there can be large differences in structural responses during earthquakes and the use of the MM intensity scale may not be directly applicable. Specifically, the wooden frames of the commoner's house showed large nonlinear inelastic behavior with a small yield capacity under lateral loading [3,4,5].

In this paper, results of a shake table tests on two 1:4 scale models of the prototype house for rock and soft soil foundation condition are described [6,7]. Models were fabricated with fresh pine lumber. The prototype house collapsed at 0.25g on a soft soil and was severely damaged at 0.6g on a rock foundation. The input PGA level at collapse or severe damage corresponds to the MM intensity VIII. The magnitude of historical earthquakes of house collapses was also estimated through nonlinear dynamic analyses of aged houses [8].

CHARACTERISTICS OF THE PROTOTYPE WOODEN HOUSE AND SCALED MODEL

The size and the materials of the ancient wooden house varied depending on the social stratum and the geographical region in Korea. The most common type of residential house in the ancient period, up to the 19^{th} century, was a three-bay-straw-roof wooden house that consisted of one kitchen, two rooms, and a porch as shown in Figure 1. The dimension of the prototype house is 7.2 m (long) x 3.6 m (wide) x 2.9 m (high).

Two types of wooden frame [3], type 1 for connecting the perimeter columns and type 2 for connecting an inner high-column and two perimeter columns in transverse direction, were used. The beam-column joint typically used at the top of the column is a tenon (Figure 2), and the joint between the cross member and the column is a dovetail. The end of each member is cut into proper shape and assembled together to form a joint, where no nail or bolt is used. Pine lumber is used for structural members.

The trunks of either the kaoliang or bush clover plastered with mud form the partition walls in the frame. Rafters with a diameter of 90 mm are placed at 300 mm intervals on the roof. Mud plaster of 50-70 mm thick and straw thatches of 300-450 mm thick are overlain on the rafters. The weight of the roof is about 170 kg/m^2. Natural stones, two or three times bigger than the column size and having a relatively flat surface, are used as cornerstones. The bottom face of the column is trimmed to contact tightly at the surface of the cornerstone and the structure is freely standing on it. The lateral load capacity and the skeleton curves under cyclic loads of each frame type were obtained from the tests on full-scale models [3,4,5].

Two 1:4 scaled models were fabricated with fresh pine lumber [6,7]. The artificial mass method was applied in the test. The mass of the roof, one half of the wall masses, and added masses were lumped on the roof. Total mass of 930 kg made of 150 mm (wide) x 600 mm (long) x 25 mm (thick) steel plates were uniformly distributed on the roof. Both ends of the rafters in the roof frame were nailed to the beams to place steel plates without increasing the stiffness of the model. Steel plates were fastened to the rafters by thin wires.

The boundary condition between the cornerstone and the bottom of the column was assumed to be a hinge and was modeled by mechanical devices specially made of ball bearings. The assumption of the hinge boundary is based on the facts that the contact surface is irregular in plane and the mass center is located at the top of the flexible frame. So rotation rather than sliding at the contact surface is more likely to happen during an earthquake. The scaled model was placed on a 10 mm thick steel plate that was tightly fastened to the shaking table. The size of the shaking table was 4 m x 4 m with 6 degrees of freedom excitation axes.

TESTS OF SCALED MODELS

Nine accelerometers and six linear variable displacement transformers (LVDT) with ±25 mm capacity were installed to measure the responses at the top of the two corner columns and one center column, as shown in Figure 3.

The Nahanni earthquake, which occurred in eastern Canada in December 1985 and was recorded at a rock site, was input to model 1 as a typical rock motion. The Imperial Valley earthquake of October 1979 in the western United States, recorded at El Centro Array No. 5, was used in model 2 to simulate the soft soil condition. The local soil characteristics of both the Kyungju City and El Centro areas are similar.

The tail parts of input time histories longer than 20 seconds were cut off in the test. It is noted that the low frequency content of the Imperial Valley earthquake is more distinct than that of the Nahanni event. Three components of earthquakes were input simultaneously. The vertical component was scaled to 2/3 of the horizontal. The PGA was increased in increments of 0.1g from 0.1g to 0.6g for model 1, the rock condition, whereas the PGA was increased from 0.05g to failure in increments of 0.05g for model 2, the soft soil condition. Random white noise was input separately for measuring the natural frequency and damping ratio at the elastic level.

TEST RESULTS

Natural Frequency and Damping Ratio

The fundamental natural frequencies of model 1 measured in the elastic range for a white noise input with a peak acceleration of 0.025g were 3.32 Hz and 3.52 Hz in longitudinal and transversal direction, respectively. Those of model 2 for the same input were 3.32 Hz and 4.29 Hz, respectively. The difference in natural frequency depends primarily on the carpenter's skill. However, the natural frequency of the prototype house is estimated, on average, as 1.66 Hz and 1.95 Hz in each direction.

The modal damping ratio of the wooden house in the elastic range was measured to be about 7% in both directions. It is noted that the equivalent viscous damping ratios of the frame system measured from the cyclic load tests for large displacements [4,5] were 27% and 13% in the longitudinal and transversal directions, respectively

Structural Responses

The acceleration and displacement responses of each model were measured for different PGA input levels. The peak responses of model 1 at the top of column A3 for rock site conditions are summarized in Table 1. Acceleration responses were filtered using a low-pass Butterworth filter. It is noted that the acceleration response in the horizontal direction is reduced significantly as compared with the input PGA as the input level is increased; however, the absolute value increases gradually as the PGA level of input increases. Acceleration and displacement responses in the longitudinal (x) direction are larger than in the transversal (y) direction because of the difference in energy content of the motion. The vertical acceleration response is slightly increased compared with the input PGA. A permanent displacement of about 0.5 mm in the longitudinal direction of model 1 was observed at a PGA of 0.6g after the test.

The maximum responses of model 2 at the top of columns A3, C2, and D1 for soft soil conditions are given in Table 2. Acceleration responses were also low-pass filtered. The trends in acceleration and displacement response were almost the same as for model 1, but model 2 collapsed in the longitudinal direction at a much lower PGA level of 0.25g. Maximum longitudinal and transverse displacements occurred at column D1 and A3, respectively. Some torsional behavior in the model was noted.

Typical response time histories in the horizontal direction of each model measured at the top of column A3 for 0.1g input acceleration are shown in Figure 4 and Figure 5. It is noted that the acceleration and displacement time histories are similar in shape in model 1. Model 1 vibrates at its fundamental frequency because it behaves mostly in the elastic range. Model 2 vibrates almost the same as the input in the beginning as shown in Figure 5, because low peaks with high frequency components are contained in the front part of the input time history. However, it vibrates at its fundamental frequency after it experiences a large displacement.

ESTIMATION OF INTENSITY OF HISTORICAL EARTHQUAKES

As described in the previous section, the prototype wooden house was judged severely damaged at PGA=0.6g at rock site, but it collapsed at PGA=0.25g at soil site. If we neglect the accumulation of damages repeated in each loading step during the tests, the aseismic capacity of the prototype house will increase. However, these were not distinguishable from the results of nonlinear dynamic analyses using the modified Double Target model [6,7]. It is noted that the parameters of the modified Double Target model were determined from test results on full-scale frame models.

The record of the largest earthquake in history is described as "commoners' houses collapsed and about 100 people died". Assuming 5 residents per house, the maximum number of houses that collapsed could have been about 20. Also, assuming that damage in a big city and nearby areas was recorded, the event would have not been great. If a large earthquake really had happened in a big city with a large population then the damage description would have been a fatal one. It is natural to presume that degraded or aged houses (i.e. 50- or 100-year old) collapsed or were damaged. This hypothesis was clarified after the Kobe earthquake in 1995. It should be noted that the tests were performed for models made from fresh pine lumber without any strength degradation and the input motions were typical ones for rock and soil site conditions.

Test results were compared with several empirical equations such as Trifunac and Brady (1975), Ambraseys (1974), Hershberger (1956), Gutenberg and Richter (1956), Murphy and O'brien (1977) in Figure 6. The empirical equations do not distinguish the soil condition. However, it can be said that MM intensity VIII comprises test results for both site conditions.

CONCLUSION

Shake table tests on two 1:4 scaled models of an ancient Korean commoners' house made of fresh pine lumber were performed. Typical earthquake time histories recorded at soil and rock sites were used for input motion. Structural characteristics were identified. The PGA of the collapse of the house at soil site was 0.25g, whereas the PGA of the severe damage of the house at rock site was 0.6g. The intensity of major historical earthquake records related with house collapses was quantitatively estimated to be MM VIII.

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Table 1. Maximum response of model 1 at the top of the A3 column for Nahanni earthquake, rock site

Input PGA level		0.1g	0.2g	0.3g	0.4g	0.5g	0.6g
Displacement response (mm)	X	1.19	2.85	3.91	6.24	7.83	9.84
	Y	1.08	3.28[*2]	5.89[*2]	4.69	6.21	7.40
	Z	-	-	-	-	-	-
Acceleration response[*1] (g)	X	0.067	0.086	0.111	0.056[*3]	0.168	0.172
	Y	0.052	0.071[*2]	0.082[*2]	0.063[*3]	0.087	0.153
	Z	0.093	0.173	0.251	0.024[*3]	0.379	0.398

*1: acceleration responses were low-pass filtered at 50 Hz

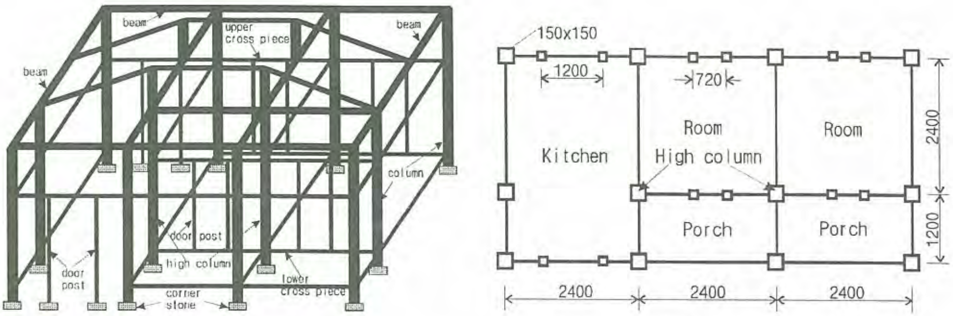
*2: accelerations were input 150-170% greater than specified level in all frequency bands.

*3: data measured are not reliable

Table 2. Maximum Response of Model 2 at the Top of Columns A3, C2, and D1 for Imperial Valley Earthquake, soil site

Input PGA level	Direction	Model Response at Top of the Column					
		Max. Acceleration (g)[*1]			Max. displacement(mm)		
		A3	C2	D1	A3	C2	D1
0.05g	X	0.038	0.043	0.052	4.28	4.20	5.13
	Y	0.036	0.029	0.035	2.33	1.59	0.80
	Z	0.041	0.045	0.040	-	-	-
0.08g	X	0.056	0.058	0.064	9.74	9.40	10.71
	Y	0.045	0.040	0.041	4.13	3.14	2.44
	Z	0.072	0.078	0.072	-	-	-
0.10g	X	0.065	0.062	0.067	14.29	13.29	14.96
	Y	0.047	0.053	0.049	4.97	4.29	2.46
	Z	0.090	0.083	0.082	-	-	-
0.15g	X	0.099	-	-	-	-	-
0.20g	X	0.146	-	-	-	-	-
0.25g	Collapse						

*1: responses were low-pass filtered at 50 Hz



(a) Perspective view (b) Plan view

Figure 1. Structure of the prototype wooden house (unit: mm)

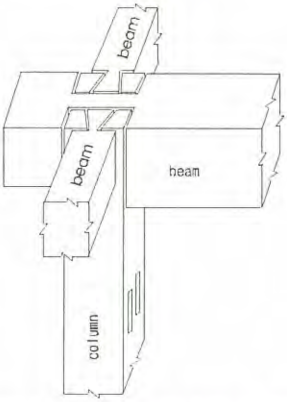
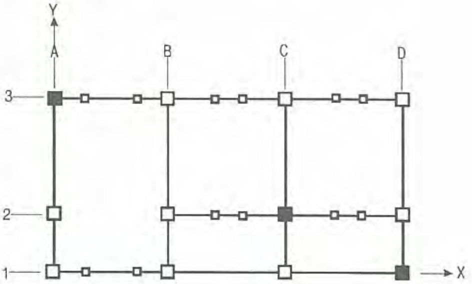
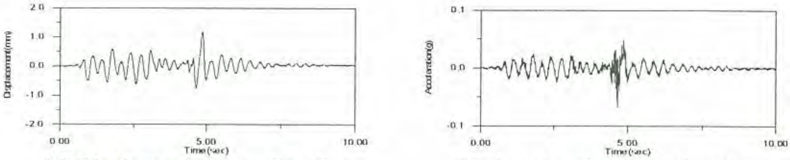


Figure 2. Perspective view of tenon joint at the top of the column (unit: mm)

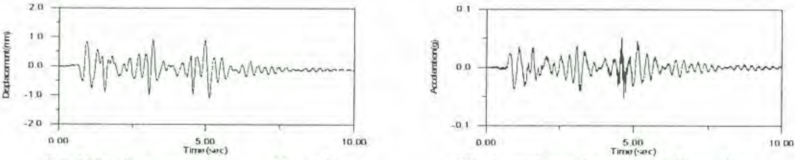


Location	LVDT	Accelerometer
A-3 Top	x,y	x,y,z
C-2 Top	x,y	x,y,z
D-1 Top	x,y	x,y,z

Figure 3. Location and type of sensors for tests

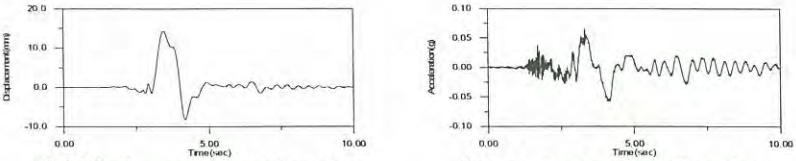


(a) Displacement in x-direction (b) Acceleration in x-direction

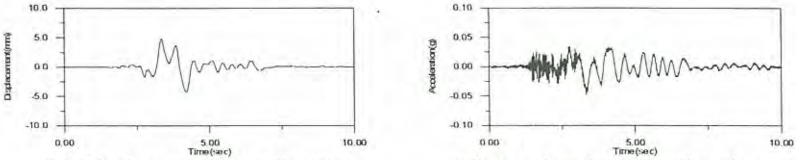


(c) Displacement in y-direction (d) Acceleration in y-direction

Figure 4. Response time history of the model 1 at the A3 column for Nahanni earthquake, input PGA=0.1g



(a) Displacement in x-direction (b) Acceleration in x-direction



(c) Displacement in y-direction (d) Acceleration in y-direction

Figure 5. Response time history of the model 2 at the column A3 for Imperial Valley earthquake, input PGA=0.1g

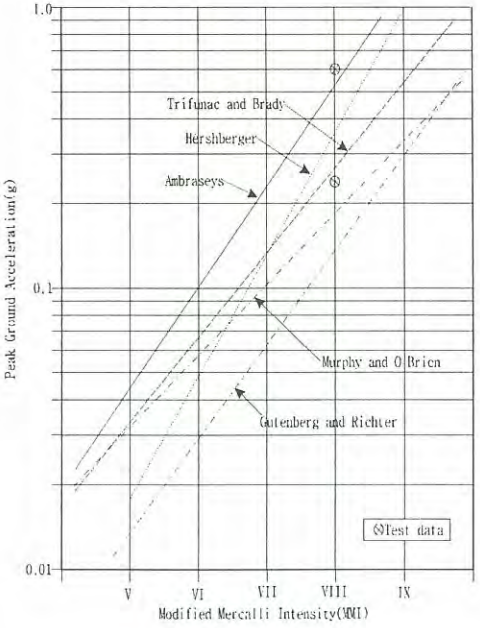


Figure 6. Acceleration versus MMI relationships