Sustainable Solutions in Structural Engineering and Construction
Edited by Chantawarangul, K., Suanpaga, W., Yazdani, S., Vimonsatit, V., and Singh, A.

ISBN: 978-0-9960437-0-0

SEISMIC COLLAPSING ANALYSIS OF THREE-STORY WOODEN HOTEL

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A 3-D collapsing-process analysis of an old Japanese-style 3-story wooden hotel under strong earthquake ground motions was carried out with three seismic intensity levels to investigate its seismic performance. Three earthquake ground motions were evaluated from three ground boring data around this wooden hotel, using the non-linear amplification characteristics of surface soil layer above the engineering base rock. As a result, this wooden hotel collapsed against a strong earthquake ground motion with JMA seismic intensity of a "6 upper" level.

Keywords: Structural engineering, Japanese-style wood-framed building, Earthquake.

1 INTRODUCTION

There are many Japanese-style 3-story wooden hotels in Japanese spa regions with lower seismic performance against strong earthquakes with a Japan Meteorological Agency (JMA) seismic intensity of "6 upper" level. Generally, seismic retrofit design for wooden houses can be determined by the seismic performance ratio, evaluated from a ratio of the necessary resistance strength of the wooden house against a strong earthquake. It is important for a structural engineer to take account of these seismic responses in the design process, because the relationship between seismic performance ratio and seismic response can be crucial for effective countermeasures.

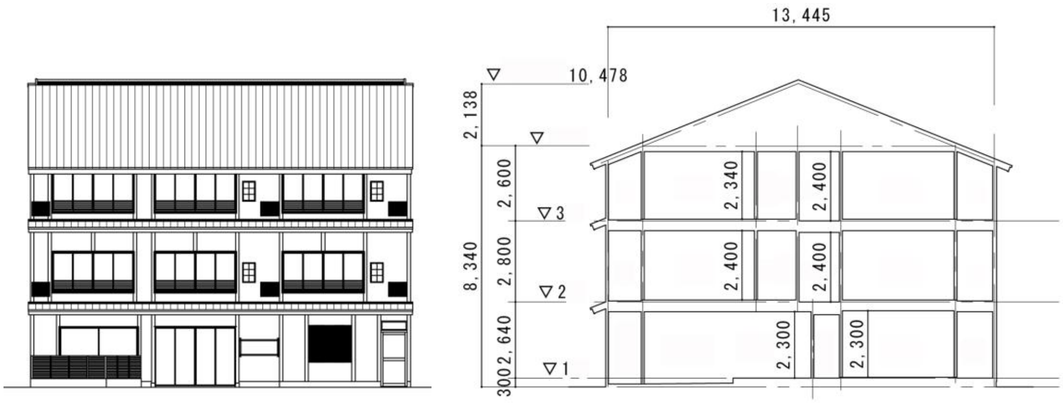
When the seismic performance behavior of Japanese-style 3-story wooden hotels built by wood frame-based building method undergoes a numerical analysis, the wooden hotel's collapsing behavior needs consideration of the non-linear properties of wooden members breaking or being dispersed. This collapsing simulation is possible by means of analysis based on the Distinct Element Method (Cundall *et al.* 1979).

To investigate the seismic performance of an old Japanese-style 3-story wooden hotel, a 3-D collapsing process analysis (Nakagawa *et al.* 2010, Nakagawa 2010, Takatani *et al.* 2012) under three strong earthquakes of JMA "5 upper", "6 lower" and "6 upper" levels was carried out. Using the non-linear amplification characteristics of surface soil layer above the engineering base rock, the three earthquake ground motions were evaluated from three ground boring data.

2 OUTLINE OF COLLAPSING PROCESS ANALYSIS

2.1 A Wooden Frame Model in Collapsing Analysis

Figure 1 shows a cross-section of a Japanese-style three-story wooden hotel, built by a traditional framed-base construction method in 1928. Total floor space is 614.87 m^2, and first, second, and third floors are 243.28 m^2, 194.77 m^2, and 176.82 m^2, respectively.



(a) Elevation (b) Cross section

Figure 1. Elevation plan of Japanese-style 3-story wooden hotel (Unit: mm).

Figure 2 indicates a frame model used in the collapsing process analysis, made to the elevation and floor plans of the three-story wooden hotel in Figure 1. Due to limited space, the details of the connection between wooden beam and pillar are omitted in this paper.

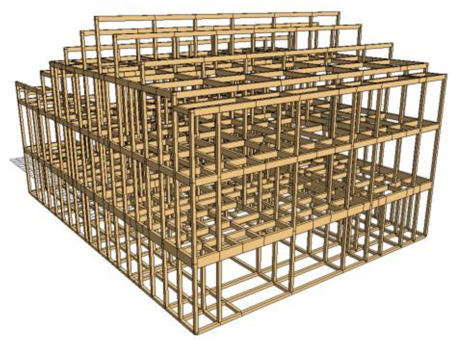


Figure 2. Analytical frame model

2.2 Input Earthquake Ground Motions

Seismic collapsing analysis was conducted by using three acceleration waves. Based on an equivalent linearizing method of "DYNEQ" program developed by Yoshida *et al.* (1996), data from three ground surface acceleration wave were calculated from three ground boring data on site. Due to the limited space, Table 1 shows the soil properties at No.3 in three boring locations. N-value means a number of blows obtained in the standard penetration test. S-wave velocity V_s can be calculated by the following empirical equation (Ohta 1978):

$$V_S = 62.48 N^{0.218} \cdot H^{0.228} \cdot F \tag{1}$$

where N is N-value, H is depth, and F is a coefficient on soil classification, i.e., 1.073 for sand, 1.0 for clay, and 1.199 for gravel. S-wave velocity of bottom base rock is assumed to be 400 m/s.

The density, ρ can be obtained by the following equation proposed by Kobayashi *et al.* (1995):

$$\rho = 0.67\sqrt{V_S / 1000} + 1.4 \tag{2}$$

Non-linear characteristics of soil material, such as a relationship between soil strain, damping ratio, and shear modulus, was evaluated from the soil classification of each soil layer, based on the research results by Koyamada (2004).

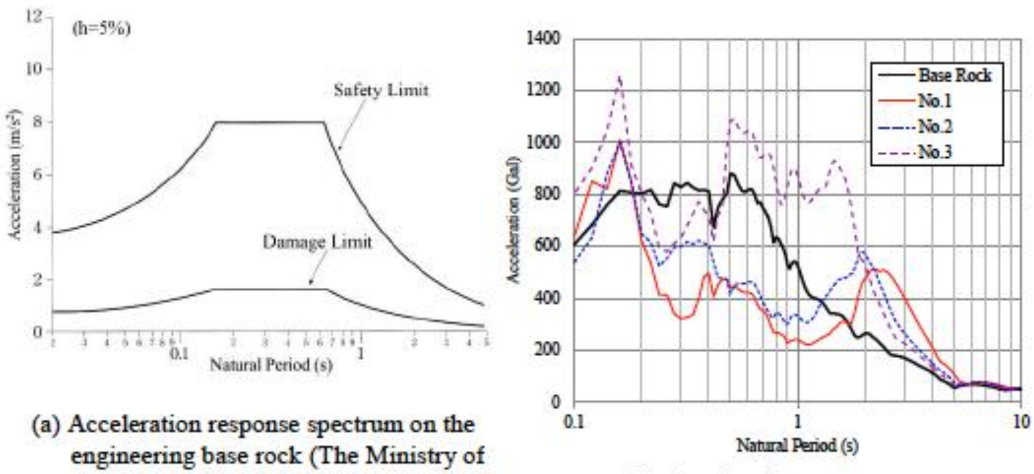
Table 1. Soil properties at No.3 boring site.

Depth (m)	N-value	S-Wave Velocity (m/s)	Density (t/m^3)	Soil Classification
1.15	39	143.4	1.65	Clay
2.15	49	173.8	1.68	Clay
3.15	6	119.9	1.63	Clay
4.15	14	153.6	1.66	Clay
5.15	11	153.1	1.66	Clay
6.15	2.57	116.2	1.63	Clay
7.15	2	113.8	1.63	Clay
8.15	2	117.2	1.63	Clay
9.15	2.57	127.2	1.64	Clay
10.15	2.57	130.2	1.64	Clay
11.15	3	137.6	1.65	Clay
12.15	3	140.3	1.65	Clay
13.15	2.57	138.1	1.65	Clay
14.15	3	145.3	1.66	Clay
15.15	3.43	151.9	1.66	Clay
16.15	3	149.7	1.66	Clay
17.15	3	151.8	1.66	Clay
18.15	3	153.7	1.66	Clay
19.15	4	165.7	1.67	Clay
20.15	4	167.6	1.67	Clay
21.15	8	197.1	1.70	Clay
22.15	3	160.9	1.67	Clay
23.15	11	215.7	1.71	Clay
24.15	5	183.4	1.69	Clay
25.15	6	192.6	1.69	Clay
26.15	6	194.3	1.70	Clay
27.15	6	196.0	1.70	Clay
28.15	10	220.9	1.71	Clay
29.15	12	231.7	1.72	Clay
30.15	39	362.0	1.80	Gravel
31.15	64.29	400	1.82	Rock

Figure 3(a) indicates the standard acceleration response spectrum on the engineering base rock, which has 8 m/s^2 in 0.16-0.64 s. Also, the acceleration spectra for both safety limit verification and damage limit used in the limit strength calculation of the building are shown in Figure 3(a).

Figure 3(b) illustrates three acceleration spectra obtained by “DYNEQ” program using three boring data. The thick solid line indicated in Figure 3(b) means a safety limit verification spectrum on the engineering base rock.

Figure 4 shows acceleration and displacement waves at three boring locations. Table 2 indicates the instrumental seismic intensity, the maximum acceleration, the maximum velocity, and the maximum displacement in three acceleration waves calculated by “DYNEQ” program. Table 3 shows the analytical cases in this paper. “Case 1” means that the acceleration wave was employed in only the X direction. “Case 3” means that the acceleration wave was done in both X and Y directions.



(a) Acceleration response spectrum on the engineering base rock (The Ministry of Construction in Japan, 2000)

(b) Acceleration response spectra

Figure 3. Acceleration response spectra of three earthquake ground motions.

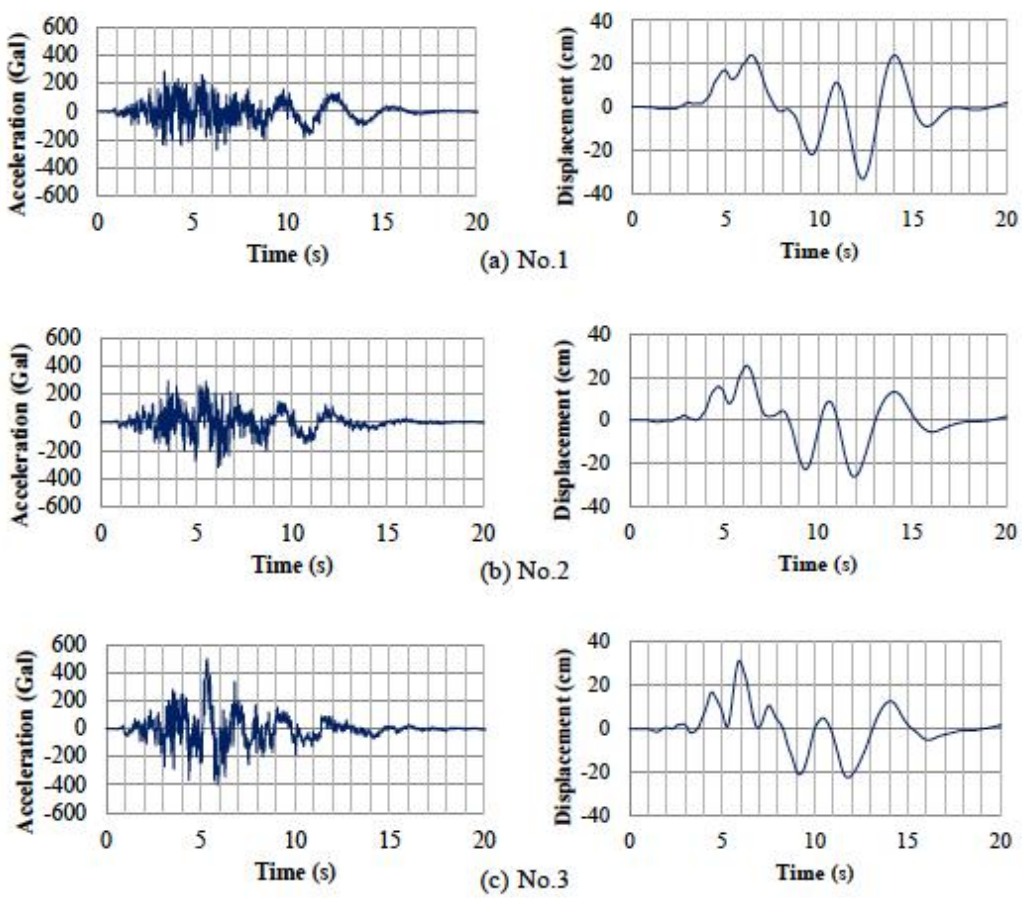


Figure 4. Acceleration and displacement waves at three ground boring locations.

Table 2. Input earthquake ground motions used in collapsing process analysis.

Earthquake Motion	Instrumental Seismic Intensity (JMA)	Peak Acceleration (Gal)	Peak Velocity (kine)	Peak Displacement (cm)
No.1	5.3 (5 upper)	273.8	59.0	33.5
No.2	5.5 (6 lower)	320.7	51.8	26.3
No.3	6.1 (6 upper)	500.8	81.9	31.4

Table 3. Collapsing analytical case.

Analytical Case Name	Input Earthquake Motion	
	X direction	Y direction
Case 1	○	×
Case 2	×	○
Case 3	○	○

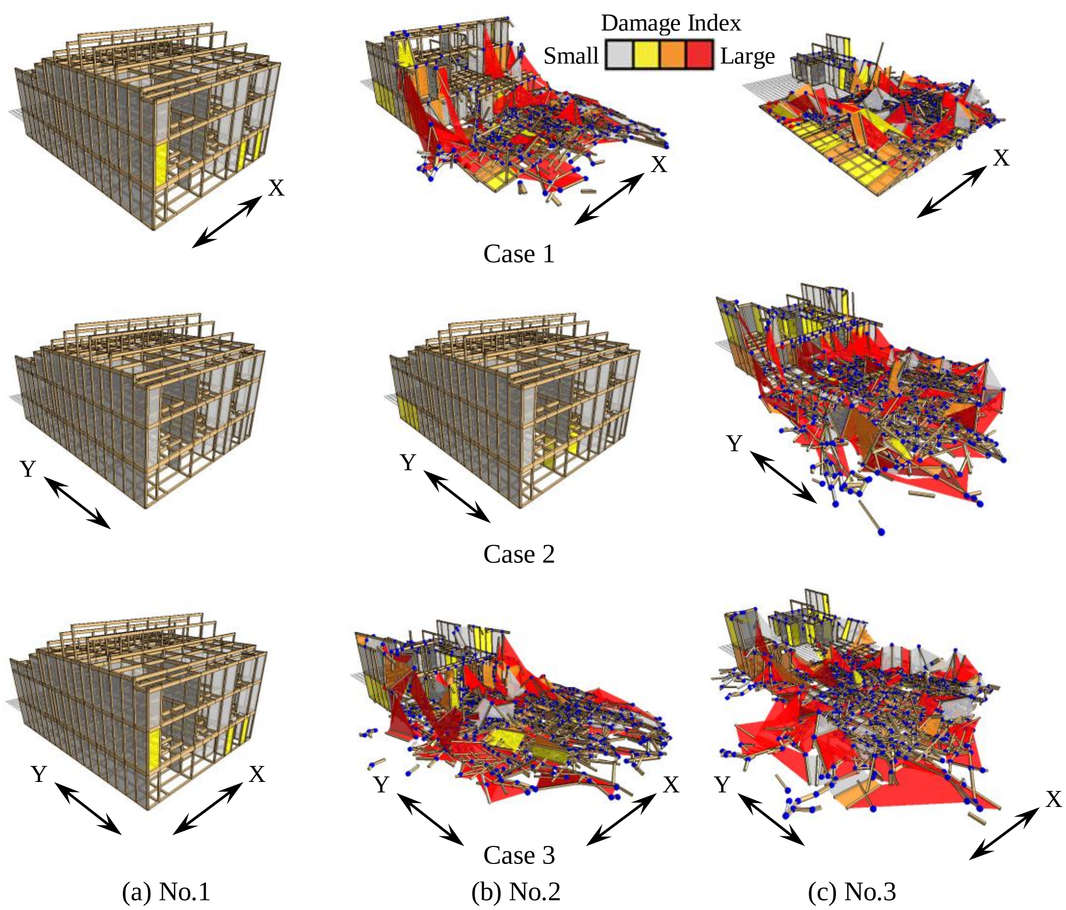


Figure 5. Collapsing states after three earthquake ground motions.

3 COLLAPSING RESULTS

Displacement wave data shown in Figure 4 are used in this collapsing process analysis. Figure 5 shows collapsing results after three earthquake ground motions indicated in Figure 4. It is noted from Figure 5(a) that this wooden hotel does not collapse in each analytical case. This is because the acceleration wave at No.1 is seismic intensity "5 upper" level, and also its peak velocity is not large. In addition, this wooden hotel has many walls in the Y direction in comparison with the X direction. According to Figure 5(b), this wooden hotel collapsed in Cases 1 and 3 when the acceleration wave at No .2 with seismic intensity "6 lower" level was used in the collapsing analysis. When the acceleration wave at No. 3 with a seismic intensity "6 upper" was used in the collapsing analysis, this wooden hotel collapsed in all three cases. This is because the earthquake motion wave at No. 3 had a maximum velocity 81.9 kine, and a maximum displacement of 31.4 cm. Consequently, it should be clear from Figure 5 that this Japanese-style 3-story wooden hotel collapses when earthquake strength is "6 upper", meaning this wooden hotel needs seismic retrofitting.

4 CONCLUSIONS

The seismic behavior of Japanese-style 3-story wooden hotels can be numerically simulated by a 3-D collapsing process analysis. Earthquake damage to Japanese-style 3-story wooden hotels greatly depends on JMA seismic intensity level. Although there is no collapsing behavior in Japanese-style 3-story wooden hotel against an earthquake of JMA "5 upper", this wooden hotel without seismic retrofit appears to suffer severe damage when the earthquake reaches "6 upper" level.

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