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Analysis of Building Response from Vertical Ground Motions

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***Abstract*—**Building structures are subjected to both horizontal and vertical ground motions during earthquakes, but only the horizontal ground motion has been extensively studied and considered in design. Most of the prevailing seismic codes assume the vertical component to be 1/2 to 2/3 of the horizontal one. In order to understand the building responses from vertical ground motions, many earthquakes records are studied in this paper. System identification methods (ARX Model) are used to analyze the strong motions and to find out the characteristics of the vertical amplification factors and the natural frequencies of buildings. Analysis results show that the vertical amplification factors for high-rise buildings and low-rise building are 1.78 and 2.52 respectively, and the average vertical amplification factor of all buildings is about 2. The relationship between the vertical natural frequency and building height was regressed to a suggested formula in this study. The result points out an important message; the taller the building is, the greater chance of resonance of vertical vibration on the building will be.

***Keywords*—**Vertical ground motion, vertical amplification factor, natural frequency, component.

I. INTRODUCTION

BUILDING structures are subjected to both horizontal and vertical ground motions during earthquakes, but only the horizontal ground motion has been extensively studied and considered in design. Most of the prevailing seismic codes assume the vertical component to be 1/2 to 2/3 of the horizontal one, and the vertical component of the ground motion was assumed as 1/2 or 2/3 of the horizontal component in Taiwan Seismic Code [1]. Howeverthe analysis of structure failure types indicated that vertical ground motion was important according to Elnashai and Papazoglou [2] (Fig. 1). Two buildings near the epicenter were collapsed during the 1999 Chi-Chi earthquake, the central column in basement was buckled by vertical ground motion shown as Fig. 2 (photo by Chi-Chung Chen), an indication of great vertical motion.

Till now, lots of researches about building performance under horizontal acceleration have been conducted. The amplification ratio of horizontal acceleration is 3 at the top of buildings by Taiwan Seismic Code, which refers to the USA Code similarly. However, the design of vertical motion in buildings is simplified, and is expressed as a function of horizontal floor motion. This implies that vertical amplification of building floors is the same as that of horizontal. Elnashai and Papazoglou [3] showed that the ratio between vertical (V) and horizontal (H) was related not only to period of building, but also the distance to epicenter. Eiji et al. [4] performed a full-scale shaking table tests to conduct a base-isolated hospital structure in order to examine the structural performance and equipment behavior under the vertical motions. The results showed that the base-isolated layer could not reduce the response of vertical vibration. The vertical response was amplified 1.5 times through the base-isolation layer and the top floor motion was amplified 2.25 times in total. In addition, the acceleration response from column to the center of slab was amplified 1.8 to 2.6 times; it showed that the vertical vibration from the ground to the top floor at the central slab could be amplified by 5 times.

In this study, the acceleration time history data of general buildings from The Central Weather Bureau in Taiwan were analyzed to find the vertical acceleration amplification relationship between the base-floor and the top-floor, and the ARX model was applied to estimate the natural frequency and in turn regressed a formula between vertical natural frequency and building height.

II. METHODOLOGY

According to the latest Taiwan Seismic Code, the formula of horizontal design force of nonstructural elements different floors was shown as:

$$F_{ph} = 0.4 S_{DS} I_p \frac{a_p}{R_{pa}} \left(1 + 2\frac{h_x}{h_n} \right) W_p \qquad (1)$$

where, F_{ph}: The minimum seismic design force of component. S_{DS}: The acceleration parameter of design spectral at short periods. I_p : The important factor of component. a_p : The amplification factor of component. R_{pa} : The response modification factor of component. W_p : The weight of structural component. h_x : The height above the base to level x. h_n : The average roof height of structure relative to the base elevation.

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Fig. 1 The failure of structure in vertical earthquake

Fig. 2 The failure of column

The maximum value of the floor amplification factor, ($1+2\frac{h_x}{h_n}$) would occur as $h_x / h_n = 1$ which was at the roof of the building, and the peak ground acceleration would be amplified 3 times.

The vertical force of nonstructural elements at different floors in (1), F_v, is expressed as 1/2 or 2/3 of F_{ph}, depends on if the building is near-fault or not.

In this study, 20 buildings lower than 50 m were selected to analyze the amplification factor of vertical floor motion, and the building information was shown in Table I.

The PGA record of their vertical earthquake motion, exceeding 25 gal from 1999 to 2014, was selected as the analysis data, and 88 sets in total were applied to analyze in this study.

The free field data were selected as input data, and the roof signal of building was taken as output. The output signal peak was divided by input peak in order to obtain the acceleration amplification factor at the top floor.

TABLE I
INFORMATION OF BUILDING STATION

Station code	Material	Height(m)	Stories
CHYBA0	RC	30.36	8F
CHYBA3	RC	20.00	5F
CHYBA4	RC	24.36	6F
CHYBA5	RC	22.95	6F
CHYBA8	RC	7.55	2F
HWABA0	RC	14.20	4F
HWABA2	RC	24.50	5F
ILABA2	RC	14.40	4F
TCUBA0	RC	32.18	8F
TCUBA6	RC	45.60	14F
TCUBAA	RC	30.40	8F
TTNBA0	RC	14.38	3F
TTNBA1	RC	21.65	6F
CHYBA7	RC	75.00	23F
KAUBA0	SRC	221.50	50F
TAPBA1	S	103.85	30F
TAPBA2	S	54.42	12F
TAPBA2	S	54.42	12F
TAPBAG	S	503.50	101F
HWABA5	SRC Base-isolated	45.10	11F

MATLAB is the operating platform, the free field signal in vertical direction (input) and the top floor vertical motion (output) was applied in MATLAB to build ARX conversion model in the frequency domain. According to the frequency conversion function formula, the vertical natural frequency of building could be obtained by simulating a curve with the least squares method. In addition, the SAC model was built in SAP2000 to verify the applicability of system identification in this study [5]. A test model referenced to the FEMA354, whose structure system was built in steel moment resisting frame structures (SMRF), was used to test the analysis algorism. The computer model also complies with the design requirements of gravity, wind and seismic forces in the existing regulations of the USA Code. The structural models were based on the Boston Local Code (BOCA, 1993) which were parted as three floors (three floors above ground), nine floors (nine floors above ground floor) and 20 floors (20 floors on the ground floor) respectively, and were shown in Fig. 3.

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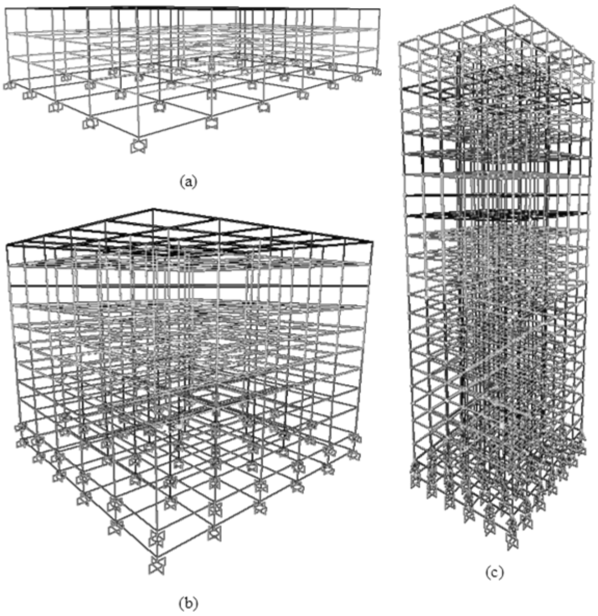

Fig. 3 Boston model (a) 3F (b) 9F (c) 20F

According to the maximum value of modal participating mass ratios in vertical direction, the vertical natural frequency estimated of 3F is 10.85 Hz, 9F is 5.63 Hz, and 20F is 3.95 Hz. To verify their validity, earthquake response was used to calculate their transfer function for comparison. The time history of station (TCU068 and TCUBAA) from Chi-Chi earthquake was chosen as the input. The model was excited only in the vertical direction to obtain the acceleration of roof as the output signal by dynamic history analysis. The result of system identification was shown as Table II.

In Table II, the tolerance between actual natural frequency of computer model and natural frequency of program calculation was under 2%, which means that the method was a good indication effect in this study.

TABLE II
VERIFICATION RESULT OF VERTICAL NATURAL FREQUENCY IN BOSTON MODEL

TCU068

Boston model	Modal Analysis Frequency (Hz)	The frequency in identification Frequency (Hz)	Correlation coefficient (%)	Tolerance (%)
20F	3.95	3.96	0.82	0.32
9F	5.64	5.58	0.85	0.91
3F	10.85	10.67	0.91	1.66

TCUBAA

Boston model	Modal Analysis Frequency (Hz)	The frequency in identification Frequency (Hz)	Correlation coefficient (%)	Tolerance (%)
20F	3.95	3.95	0.82	0.05
9F	5.64	5.59	0.91	0.87
3F	10.85	10.71	0.93	1.29

III. FLOOR RESPONSE OF VERTICAL VIBRATION

The floor amplification factor is the ratio between peak response in each floor and peak ground acceleration. According to the aseismic coefficient of nonstructural components of present design code in Taiwan, the vertical floor amplification formula was shown as:

$$\frac{A_x}{A_g} = 1 + 2\frac{h_x}{h_n} \tag{2}$$

In (2), A_g is the vertical peak ground acceleration, h_n is the average roof height of structure relative to the base elevation, A_x is the vertical peak floor acceleration, and h_x is the height from the base to Level x. 88 seismic records were selected to estimate the floor acceleration amplification by dividing the peak acceleration (A_x) of the output signal by the peak acceleration of the input signal (A_g).

The relationship between floor ratio in different buildings and vertical floor amplification is shown as Fig. 4. The regression result shows that the vertical acceleration amplification factor in different height is 2.04 times, with a standard deviation 0.67. This building height below 50 m is 1.78 times, with a standard deviation 0.58, and the height exceeding 50 m is 2.52 times, with a standard deviation 0.56. The regression formula of floor amplification factor is shown as [6]:

1. The suggested formula of vertical amplification factor in different height:

$$\frac{A_x}{A_g} = 1 + 1.04\frac{h_x}{h_n} \tag{3}$$

2. The suggested formula of vertical amplification factor for low-rise with height below 50 m:

$$\frac{A_x}{A_g} = 1 + 0.78\frac{h_x}{h_n} \tag{4}$$

3. The suggested formula of vertical amplification factor for high-rise with height exceeding 50 m:

$$\frac{A_x}{A_g} = 1 + 1.52\frac{h_x}{h_n} \tag{5}$$

Because of the little data in vertical direction at middle floors in Taiwan, earthquake records in New Zealand collected in GeoNet were applied to analyze the middle floor amplification factor, and two sets of earthquake data in one building were analyzed in this study. The site of the building was in Christchurch and is reinforced concrete construction, and it had one basement and six floors which have 16 strong motion systems in each floor [7].

The relationship of amplification factor in different earthquake data was shown in Figs. 5 and 6 [8]. The vertical axis represented the top floor of the building to the basement

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floor, and the lateral axis is the floor amplification of each floor peak acceleration relative to base floor peak acceleration.

According to Figs. 5 and 6, the relationship of vibration response along building height can be considered linear. In addition, the amplification at the top floor of the building in the figure was 1.96 and 1.80, the average was 1.88 which was close to 1.78, the floor vertical amplification of low-rise calculated by (4).

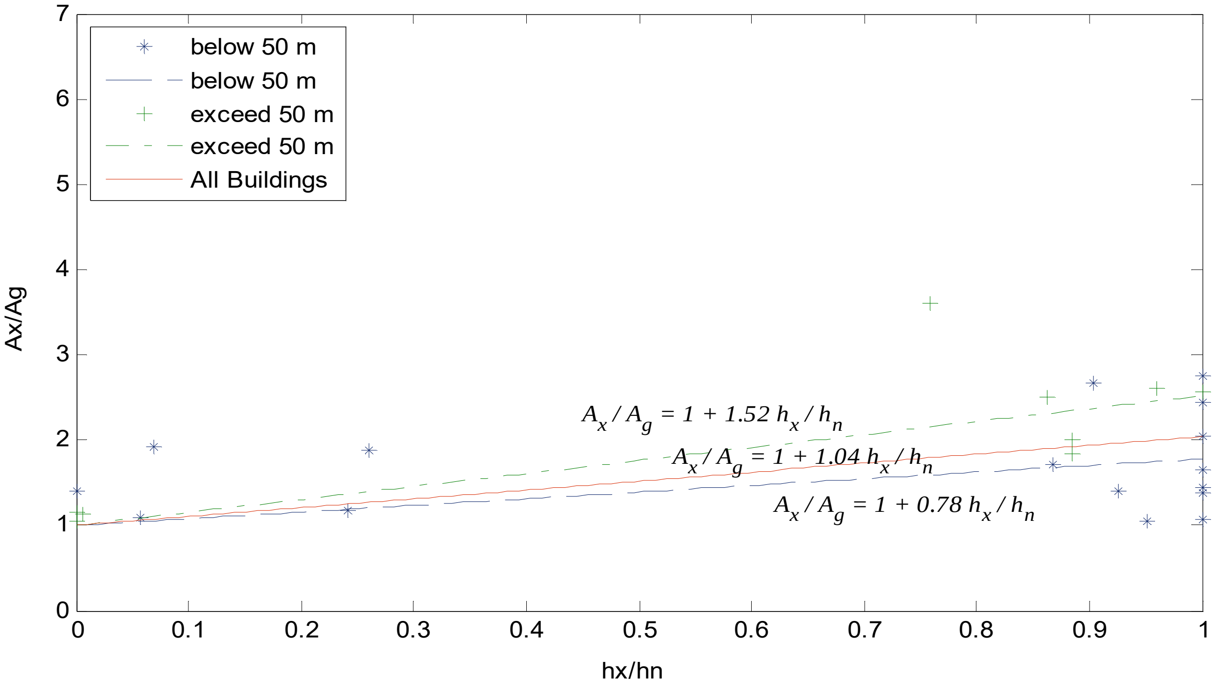


Fig. 4 Floor amplification factor of vertical acceleration

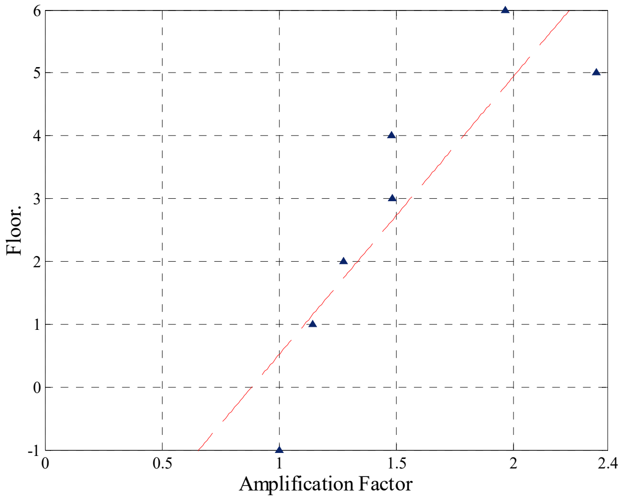


Fig. 5 The relationship of floor and amplification factor in data (1)

IV. THE FREQUENCY RESPONSE FUNCTION OF VERTICAL VIBRATION

To analyze the natural frequency in vertical direction, the ARX model was applied to estimate the natural frequency of the conversion function between the input signal and the output signal. Considering a better recognition result of ARX model with a relating small noise/signal, the strong seismic motion segment was selected as the input and output signal for each earthquake record. In addition, the vibration record at roof was estimated by FFT spectrum in order to compare the ARX model curve and FFT figure that could verify the rationality.

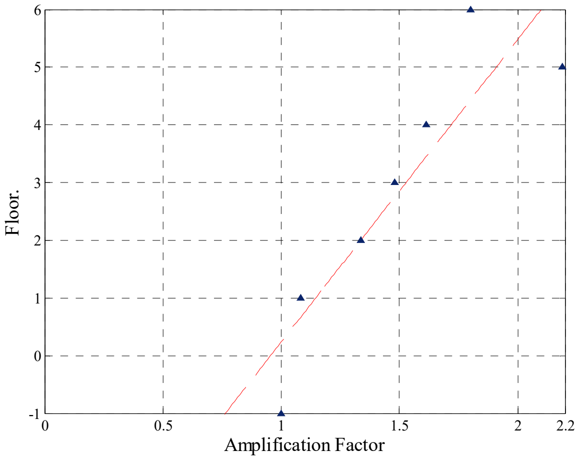
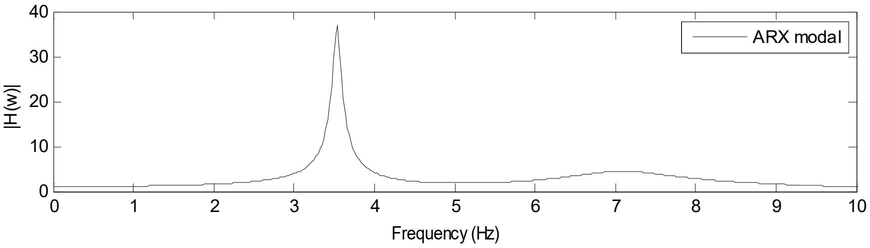
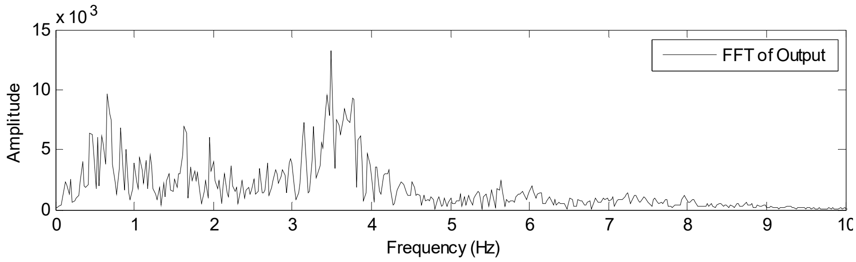


Fig. 6 The relationship of floor and amplification factor in data (2)

Take the TAPBA1 as an example, the ARX of free field input signal and top floor output signal was shown in Fig. 7, and the identification result of natural frequency is 3.6 Hz. In addition, the FFT of top floor output signal was shown in Fig. 7 (b) where the frequency distribution could be clearly found at the frequency 3.6 Hz with most obvious peak. Different buildings' first vertical natural frequencies were identified and plotted against their building heights in Fig. 8.



(a)



(b)

Fig. 7 The signal of input and output (a) ARX model curve (b) FFT output of top floor

Fig. 8 shows that the vertical natural frequency decreased, while the building height increased. A regression formula between vertical natural frequency and building height can be shown as follows:

$$f_v = 163.74 h_n^{-0.778} \tag{6}$$

In (6), f_v is the vertical natural frequency, and the h_n is the average roof height of structure relative to the base elevation.

Fig. 9 shows the vertical natural frequency and top floor vertical amplification of identification in each building. Although the distributed trend of data was not obvious, the top floor vertical amplification was higher with a lower natural frequency, especially for the building whose natural frequency is below 10 Hz.

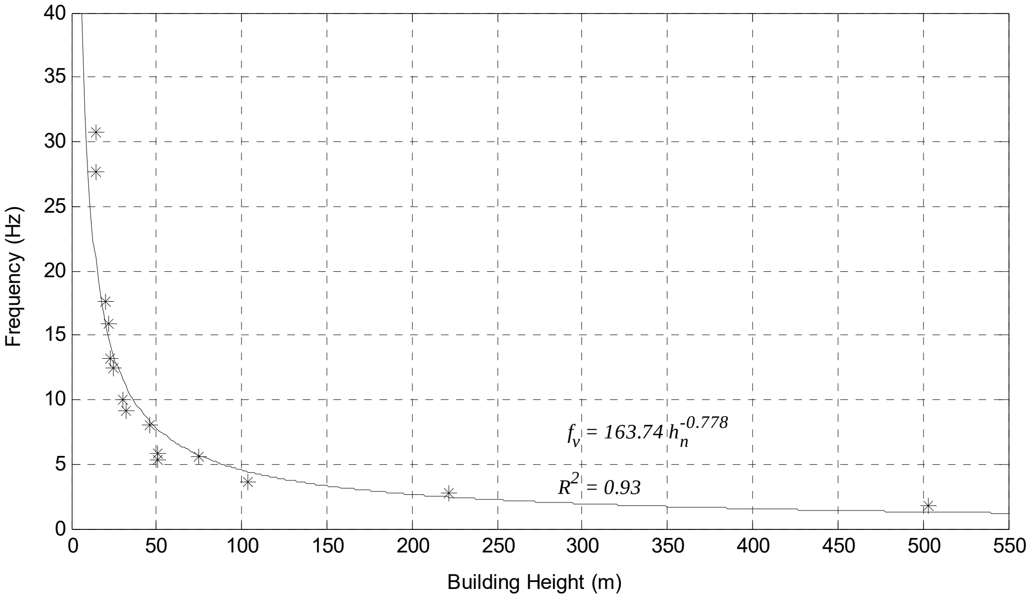


Fig. 8 Natural frequency of vertical

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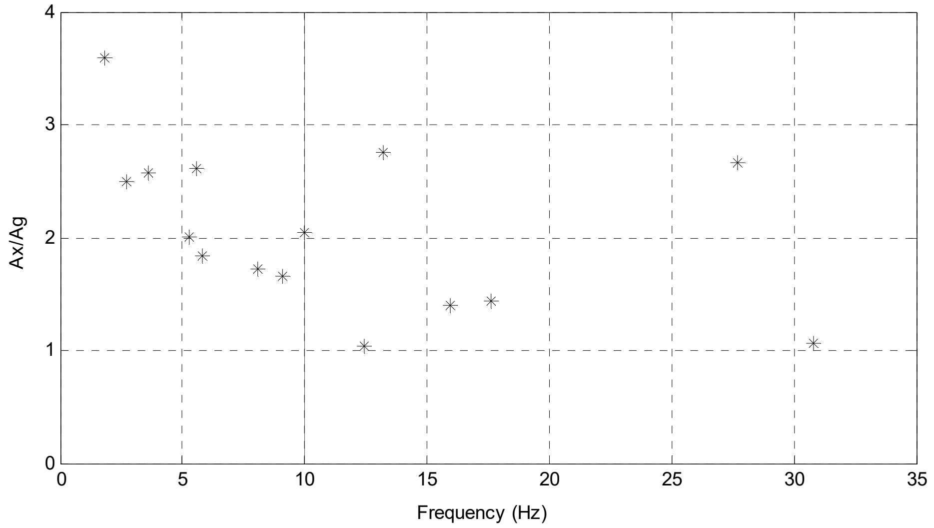

Fig. 9 The relationship between vertical natural frequency and top floor amplification factor

V. CONCLUSIONS

In this study, 20 buildings lower than 50 m were selected to analyze the amplification factor of vertical floor motion, and the vertical natural frequency of building was estimated by MATLAB to analysis the relationship of vertical frequency and building height. The conclusion of this study was arranged as below:

(1) The vertical amplification factor of building floor height: The regression result shows that the vertical acceleration amplification factor in different height is 2.04 times. The low-building of which height below 50m is 1.78 times, and the high-building of which height exceed 50m is 2.52 times.

(2) The regression formula of floor amplification factor could be proposed as follow: The suggestive formula of vertical amplification factor in different height:

$$A_x / A_g = 1 + 1.04(h_x / h_n) \cdot$$

(3) The building vertical natural frequency: The vertical natural frequency decreased while the building height increased, and a regression formula between vertical natural frequency and building height could be expressed as follows: $f_v = 163.74 h_n^{-0.778}$ which could be a reference to the future research.

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REFERENCES

[1] Taiwan Construction and Planning Agency, *Seismic Design Specifications and Commentary of Buildings*, 2011.
[2] Elnasha, A. S. and Papazoglou A. J., *Analytical and field evidence of the damaging effect of vertical earthquake ground motion*, Earthquake Engineering & Structural Dynamics, 25(10), 1109-1137, 1996.
[3] Elnashai, A. S. and Papazoglou A. J., “Procedure and spectra for analysis of RC structures subjected to strong vertical earthquake loads”, Journal of Earthquake Engineering, 1(1), 121-155, 1997.
[4] Eiji, S., Sachi, F., Atsuo, K., and Masayoshi, N., *Full-scale shaking table for examination of safety and functionality of base-isolated medical facilities*, Earthquake Engineering & Structures Dynamics, 40(13), 1435-1453, 2011.
[5] Kuo, Fung-Wen, “Vertical Earthquake Response Analysis of General and Base-isolated Buildings”, National Cheng Kung University Department of Architecture, Taiwan, 2013.
[6] Chang, Yu-Shan, “Vertical Buildings Response Characteristics from Earthquake Ground Motion Analysis”, Master thesis, National Cheng Kung University, Department of Architecture, 2015.
[7] GeoNet,http://info.geonet.org.nz/display/appdata/Structural+Array+Data
[8] Tu, Chao-Yu, “A Study on Vertical Floor Amplification Factor and Resonant Amplification Factor of General Buildings”, Master thesis, National Cheng Kung University Department of Architecture, Taiwan, 2015.