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SEISMIC CAPACITY EVALUATION OF EQUIPMENT IN A MODERN HOSPITAL AT SOUTHERN TAIWAN

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ABSTRACT

A/C equipment's seismic capacity in a modern hospital is evaluated. Three different specifications each has different amplification factors to assess the design lateral forces in buildings are discussed. Combining these factors, three standards are established to represent different levels of consideration based on the current Taiwanese code. Three groups of A/C equipment are evaluated against these standards. Actual lateral force these equipment will experience in a major earthquake is predicted from the empirical magnification factors derived from the 1989 Loma Prieta earthquake records. After comparing actual lateral force to the specification values, some problems in current Taiwanese equipment design practice to resist earthquake forces are discovered. Equipment located on the higher floors of a building will experience larger force than the present code describes. Anchor bolt strength to tie down the equipment are also checked.

KEYWORDS

Hospital; A/C equipment; Floor magnification factor; Equipment magnification factor; Anchor bolts.

INTRODUCTION

For the last 30 years, Taiwan has been exempt from any major earthquake. Last major inland earthquake, occurred in 1964, was registered magnitude 7.0 located in southwestern Taiwan. According to seismological research reports, the thirty-year strong earthquake recurrence period is near the end of its cycle and an earthquake of magnitude 6.5 or greater in southwestern Taiwan can be expected in the near future.

This paper is part of the results of a hospital safety evaluation program carried out at NCKU. The program intends to evaluate hospitals in southwestern Taiwan their strength against earthquake. The focus of this paper is the non-structural elements' seismic capacity in a modern hospital whose structural elements were designed to be earthquake-resistant. The emphasis is laid on the A/C equipment's strength against earthquake. The expected PGA of the investigation site is equated to 0.28g which accounts for the largest design PGA in southwestern Taiwan (Sheu et al.,1993).

DESCRIPTION OF THE HOSPITAL AND ITS EQUIPMENT

The hospital is a 12-story RC structure with two basement floors. It was designed with a base shear of 13.7% of total weight and a ductile moment-resisting space frame system with shear walls was adopted. A previous investigation with micro tremor found the fundamental period of the structure in both horizontal directions were both 0.8 second close to its designed fundamental period of 0.9 second.

A/C equipment under investigation can be divided into three groups, Pumps, Ground-Supported (GS) fans, and Ceiling-Suspended (CS) fans. All these equipment are supported by isolation springs in the vertical direction in order to prevent the operational high frequency vibration from been transmitted to the structure. Isolation springs reduce the fundamental frequency of a machine system in the vertical direction. It also reduces a system's frequency in the lateral direction. Because of the reduction in lateral frequency, some of the equipment are susceptible to have amplified response during an earthquake owing to the resonance effect with the residing buildings' low fundamental frequency. If the supporting anchor bolts were not strong enough to resist this dynamic motion, damage or failure of the equipment may occur and hamper functions of a hospital after a strong earthquake.

There are 16 types of pumps in this hospital and they are located on the B1 floor. Base of each pump is attached to an isolation plat which is supported from below by springs that sit on the concrete floor. There is no anchor bolts to tie the concrete floor and the springs. Basic information of the pumps are listed in Table 1. All of the twelve types of GS fans are located on the fifth floor. Most of the fans are supported by springs at four corners. Some have six and even eight isolation springs. These springs are then fixed to the concrete floor by anchor bolts. All of the ten types of CS fans are located in B1 floor with supporting points at bottom of the first floor slab. All of them are supported from four corners with isolation springs. Table 2 and 3 list the basic information of these fans.

EQUIPMENT DESIGN SPECIFICATIONS FOR EARTHQUAKE FORCE

In this study, equipment safety during earthquakes is found by comparing estimated lateral force to lateral force from three design standards. These standards each adopts particular parameters that represent different level of consideration for design against earthquake motion. Before the discussion of these standards, three relevant codes where these parameters from are discussed first.

Earthquake force for equipment design specification in Taiwan mostly follow the 1983 UBC provision. It is represented by equation (1).

$$F_p = ZICW \tag{1}$$

US DOD (TriService) issued its own design specification for equipment based on the following equation.

$$F_p = ZICA_pW \tag{2}$$

Japanese equipment specification (BCJ, 1984) uses equation below for the design force.

$$F_p = ZIk_0k_1k_2W \tag{3}$$

In these equations, there are zoning factor(Z), important factor(I), and coefficient of earthquake force (C, K_0) in common. However, in equation (2) and (3) there are equipment amplification factor (k_1, A_p) to account for amplified vibration caused by the closeness of the fundamental frequencies of the equipment and the building. In equation (3), a particular parameter (k_1) to include the floor amplification at different building elevation is adopted in the Japanese code. The reasoning is that amplified motion on the higher floors will make a difference on the response of the equipment attached to that floor compared to that at the lower floor. Therefore, the inclusion of such a factor seems more reasonable for design engineers. A brief description of the equipment amplification factor and the floor amplification factor are presented below:

Equipment Amplification Factor(Ep)

Japanese Code. This factor is calculated as following:

(a) When the natural frequency of the equipment (f_e) is unknown: $E_p=2.0$

(b) When f_e is known :

(i) $f_e \leq 15$ Hz. E_p is a function of the ratio R, which is calculated by dividing the natural period of the equipment to that of the building (T_s).

$$E_p = \begin{cases} 1.0 & R \leq 0.3 \\ 1.0 + \frac{R-0.3}{0.6} & 0.3 < R \leq 0.9 \\ 2.0 & 0.9 < R \leq 1.5 \\ 2.0 - \frac{R-1.5}{0.5} & 1.5 < R \leq 2.0 \\ 1.0 & 2.0 < R \end{cases}$$

(ii)$f_e \geq 15$ Hz: $E_p=1.0$ (4)

TriService Code. Ep is calculated differently as below:

(a) When fe is smaller than 17 Hz,

(i) $T_s \leq 0.5$ sec

$$E_p = \begin{cases} 1.0 & R \leq 0.1 \\ 1.0 + 4\left(\frac{R-0.1}{0.7}\right) & 0.1 < R \leq 0.8 \\ 5.0 & 0.8 < R \leq 1.2 \\ 5.0 - \left(\frac{R-1.2}{0.8}\right) & 1.2 < R \leq 2.0 \\ 1.0 & 2.0 < R \end{cases}$$

(ii) T_s > 0.5 sec

$$E_p = \begin{cases} k' & R \leq 1.2 \\ k' - (k'-1)\left(\frac{R-1.2}{0.8}\right) & 1.2 < R \leq 2.0 \\ 1.0 & 2.0 < R \end{cases} \qquad (5)$$

$$k' = \begin{cases} 5.0 & T_s = 0.51 \\ 4.75 & T_s = 0.75 \\ 4.0 & T_s = 1.0 \\ 3.3 & T_s = 2.0 \\ 2.7 & T_s = 3.0 \end{cases}$$

(b)When f_e is greater than 17 Hz, $E_p=1.0$

Empirical records. The equipment amplification factor was investigated by Chiou at NCKU (Chiou,1994). Chiou analyzed the 1989 Loma Prieta earthquake records in ten buildings. The response spectrum of these records were calculated to represent the amplified motion of equipment inside each building. An empirical formula was proposed to account for equipment amplification due to equipment and building resonance as following:

$$E_p = \begin{cases} 1.0 & R \le 0.3 \\ 2.0 & 0.3 < R \le 1.5 \\ 2.0 - \frac{R-1.5}{0.5} & 1.5 < R \le 2.0 \\ 1.0 & 2.0 < R \end{cases} \tag{6}$$

Floor Amplification Factor (Sp)

Japanese code. The floor amplification factor (S_p) is related to the height of the building (H), elevation of the investigated floor (h), and the top floor amplification factor (A_s).

$$S_p = \begin{cases} 1 + (A_s - 1)\frac{h}{H} & \text{:Second floor and above} \\ 1.0 & \text{:First floor and below} \end{cases} \tag{7}$$

$$A_s = \begin{cases} \frac{10}{3} & T_s \le 0.6 \\ \frac{10}{3} - \frac{2}{3}\left(\frac{T_s}{0.6} - 1\right)^2 & 0.6 < T_s \le 1.2 \\ \frac{3.2}{T_s} & 1.2 < T_s \end{cases} \tag{8}$$

Empirical records. Floor amplification factor was investigated at NCKU by Tseng (Tseng, 1994). Tseng compared time history records from the 1989 Loma Prieta earthquake in twenty buildings of different height. Statistical approach were used to analyzed the peak acceleration amplification between the top floor and the ground. It was found that the top floor amplification factor is not related to a building's fundamental period but rather exhibit a pattern of Gaussian distribution. Therefore, Tseng proposed a formula for As based on standard deviation numbers assigned to different equipment as :

$$A_s = \begin{cases} 5.3 & \text{:Two Standard Deviations} \\ 4.1 & \text{:One Standard Deviation} \end{cases} \tag{9}$$

Tseng also found that the linear distribution of Sp along the building height at different elevation generally in comply with the findings from earthquake time history records. Therefore, Tseng suggested using equation (7) to calculate the floor amplification factor but use equation (9) for the top floor amplification factor.

Three standards, based on the Taiwanese code, accommodate parameters discussed above are described below:

#1:Taiwanese specification.(Z=1.0, C=0.9, I=1.5)
#2:Standard #1 multiplied by the Ep from equation (4) and Sp from equation (7).
#3:Standard #1 multiplied by the Ep from equation (5).

These standards represent the current Taiwanese code, the Taiwanese code with Japanese consideration for Ep and Sp, and the Taiwanese code that includes TriService's consideration for Ep.

EQUIPMENT STRENGTH ANALYSIS

To evaluate the safety of an equipment, the actual earthquake force an equipment will experiences is first compared to the standards to check if it is adequately designed for. The actual earthquake force is determined from the multiplication of factors derived from the empirical records as shown in equation (10).

$$F_A = 0.28 \times E_p \times S_p \times W \tag{10}$$

In determining Ep, a 25% reduction from the vertical spring stiffness is selected for the lateral spring stiffness (ASHRAE,1993) to calculate the lateral frequency of the spring-isolated equipment . To calculate the floor amplification factor, a top floor amplification factor of 5.3 is assumed.

The strength of anchor bolts are also checked. To evaluate the strength of anchor bolts, the design method proposed by HVACR (Carlson, et al., 1992) is adopted. HVACR assumes an equipment will act as a single DOF system. By adopting the equilibrium of force and moment, the effective shear(Veff) and effective tension (Teff) on anchor bolts can be calculated. The allowable shear strength(Vall) and tensile strength (Tall) of anchor bolts can be obtained from the original design manual. Safety of anchor bolts are determined from equation (11):

$$\frac{T_{eff}}{T_{all}} + \frac{V_{eff}}{V_{all}} = \begin{cases} <1 & :safe \\ \geq 1 & :unsafe \end{cases} \tag{11}$$

RESULTS

In Table 1, F_A for pumps is compared to earthquake force from three standards. F_A's, calculated from the empirical data, are smaller than those from all three standards. Therefore, the design force from various standards is higher than what could actually expected in southwestern Taiwan. However, because all pumps are not anchored to the concrete floor, it is still under a great risk of damage in a major earthquake.

In Table 2, for GS fans, many F_A value are slightly larger than standard #1 values . If F_A's are compared to #2 and #3, it can be seen that #2 values are slightly higher than F_A's, and #3 values are a lot higher than F_A's. The reason for this is due to the fact that GS fans are located on the fifth floor and the higher floor resulted in larger Sp. Also, the closeness of fundamental periods between equipment and the hospital created a large Ep for both standards. The last column in Table 2 is the stress ratio of anchor bolts. It is shown that stress ratios are smaller than 1.0 which means adequate capacity is reserved in these bolts.

Table 3 shows that CS fans' F_A are smaller than values in the three standards. The stress ratios of their anchor bolt strength are also small.

CONCLUSIONS

All three groups of A/C equipment's seismic capacity are checked. It's found that GS fans located on the fifth floor may experience larger earthquake force than current Taiwanese code expected. However, because of their bolt strength are adequate, anchor bolts can hold up the large lateral force. Standard #2 have adequately enveloped this magnified lateral force while standard #3 have over enveloped the response. Also discovered is that pumps at the basement are not anchored although code specified design force in adequate. This poses as a threat to the continuing operation of these pumps after a major earthquake. CS fans are found to have adequate strength against a major earthquake in soutthwestern Taiwan.

REFERENCES

ASHRAE (1993), 1993 Fundamental Handbook (SI), ASHRAE, 7.11-7.13.
The Building Center of Japan (1994), Seismic Design for Building Equipment, Japan.
Carlson, J.A. and Staehlin, W. (1992), Seismic Restraint Design for HVAC Equipment, ATC-29, 439-454.
Chiou, Y.Y. (1994), A Study on System Identification of Hospital Buildings and Equipment, Master Thesis, NCKU, Taiwan.
Sheu, M.S., J.S. Chang and G. C. Yao (1993), School Building Evaluation in Tainan City, NCKU, Taiwan.
Tseng, M.Y. (1994), Investigation of Seismic Specification for Nonstructural Elements in Buildings, Master Thesis, NCKU, Taiwan.

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Table 1. Pump information and their earthquake strength comparison

Type	Design Disp. (in)	Weight (lb)	Hori. Freq. (Hz)	F_A (lb)	Standard #1 (lb)	Standard #2 (lb)	Standard #3 (lb)
vsvc 6*8*9-4/3	0.63	2977	3.40	830	4018	4018	16075
vsvc 10*12*11	0.73	4395	3.18	1226	5932	5932	23732
vsvc 8*10*13B	0.74	5073	3.14	1414	6848	6848	27394
vsvc 12*14*17-1/2	0.75	9103	3.14	2539	12288	12288	49156
1510 1-1/4 AC	0.56	775	3.62	216	1046	1046	4185
1510 2BC	0.65	1313	3.36	365	1772	1772	7090
1510 2-1/2BB	0.66	1343	3.29	374	812	1812	7251
1510 2E	0.58	1555	3.57	433	2098	2098	8396
1510 4E	0.55	1824	3.65	508	2462	2462	9848
1510 4E	0.68	2271	3.33	633	3065	3065	12262
1510 4BC	0.69	1850	3.26	516	2498	2498	9990
1510 3G	0.58	1944	3.57	542	2624	2624	10497
1510 5E	0.68	2277	3.29	635	3074	3074	12295
1510 5BC	0.58	2730	3.57	762	3685	3685	14741
1510 5G	0.68	3203	3.29	893	4323	4323	17296
1510 5G	0.69	3260	3.26	909	4400	4400	17603
1510 5G	0.72	3371	3.2	940	4550	4550	18202
1510 5G	0.79	3691	3.06	1030	4982	4982	19931
1510 5G	0.62	3775	3.44	1053	5096	5096	20385
1510 6E	0.73	3442	3.18	960	4646	4646	18586
1510 6G	0.68	4088	3.27	1140	5518	5518	22075
1510 6G	0.78	4704	3.07	1312	6350	6350	25401

Table 2. GS fans information and their earthquake strength comparison

Types	Design Disp. (in)	T_{all} (lb)	V_{all} (lb)	Weight (lb)	Hori. Freq. (Hz)	F_A (lb)	Stand. #1 (lb)	Stand. #2 (lb)	Stand. #3 (lb)	Stress Ratio
SAF-A-2 # I	0.56	1540	1320	210	3.63	156	283	485	1134	0.09
SAF-A-2 # II	0.73	1540	1320	210	3.18	156	283	485	1134	0.09
SAF-A-2 # III	0.73	3410	3960	210	3.18	156	283	485	1134	0.02
SAF-A-2 # IV	0.56	1540	1320	210	3.63	156	283	485	1134	0.09
SAF-A-2-1/2#	0.72	1540	1320	269	3.20	199	363	624	1452	0.11
SAF-A-3 #	0.96	3410	3960	379	2.77	562	511	910	2046	0.08
SAF-A-4 #	1.6	3410	3960	544	2.15	807	734	1508	2937	0.11
SAF-A-5 # I	2.04	5060	6820	815	1.90	1210	1100	2450	4400	0.10
SAF-A-5 # II	1.73	5060	6820	815	2.06	1210	1100	2314	4400	0.10
SAF-A-5 # III	1.94	1540	1320	815	1.95	1210	1100	2389	4400	0.28
SAF-A-5 # IV	1.61	3410	3960	815	2.14	1210	1100	2276	4400	0.24
SAF-A-5-1/2 # I	0.33	5060	6820	1044	5.78	775	1409	2410	5638	0.09
SAF-A-5-1/2 # II	2.22	5060	6820	1044	1.82	1549	1409	3205	5638	0.14
SAF-A-5-1/2 # III	2.05	3410	3960	1044	1.90	1549	1409	3132	5638	0.16
SAF-A-6 #	2.64	5060	6820	1512	1.67	2244	2041	4886	8164	0.20
SAF-A-7 # I	2.71	5060	6820	2040	1.65	3028	2753	6686	11016	0.27
SAF-A-7 # II	2.71	5060	6820	2040	1.65	3028	2753	6403	11016	0.27
SAF-A-7 # III	2.38	5060	6820	2040	1.76	3028	2753	6640	11016	0.41
SAF-A-7 # IV	2.69	5060	6820	2040	1.65	3028	2753	7465	11016	0.23
SAF-A-8 # I	2.93	5060	6820	2200	1.56	3265	2970	7465	11880	0.29
SAF-A-8 # II	2.93	5060	6820	2200	1.56	3265	2970	7160	11880	0.29
SAF-A-8 # III	2.56	5060	6820	2200	1.66	3265	2970	6551	11880	0.22
SAF-A-8 # IV	1.95	5060	6820	2200	1.91	3265	2970	7279	11880	0.22
SAF-A-10 #	3.32	5060	6820	4180	1.48	6202	5642	14666	22571	0.56
SAF-B-8 # I	2.47	5060	6820	2166	1.72	3214	2924	6850	11696	0.27
SAF-B-8 # II	2.46	5060	6820	2166	1.73	3214	2924	6850	11696	0.16
SAF-B-8 #	0.33	5060	6820	3960	5.42	2938	5346	9141	21384	0.26

Table 3. CS fans information and their earthquake strength comparison

Type	Design Disp. (in)	T_{all} (lb)	V_{all} (lb)	Weight (lb)	Hori. Freq. (Hz)	F_A (lb)	Stand. #1 (lb)	Stand. #2 (lb)	Stand. #3 (lb)	Stress Ratio
SAF-A-2 #	0.37	1540	1320	139	4.46	39	188	188	750	0.11
SS-2-1/2 #	1.16	1540	1320	231	2.52	129	311	342	1246	0.18
SS-4-1/2 #	0.79	1540	1320	814	3.05	227	1099	1099	4395	0.32
SS-5 #	0.49	3410	3960	990	3.87	276	1336	1336	5345	0.15
BSF-1 #	0.49	3410	3960	55	3.87	15	74	74	296	0.01
BSF-1-1/4 # I	0.59	5060	6820	66	3.52	18	89	89	356	0.01
BSF-1-1/4 # II	0.33	5060	6820	66	4.72	18	89	89	356	0.01
BSF-1-1/2 #	0.39	1540	1320	77	4.34	21	104	104	415	0.03
BSF-1-3/4 # I	0.55	3410	3960	110	3.65	31	148	148	594	0.02
BSF-1-3/4 # II	0.33	5060	6820	110	5.03	31	148	148	594	0.01
BSF-1-1/2 # I	0.56	5060	6820	209	3.62	58	281	281	1128	0.02
BSF-1-1/2 # II	0.39	5060	6820	209	4.34	58	281	281	1128	0.02
BSF-1-1/2 # III	0.3	5060	6820	209	4.95	58	281	281	1128	0.02
BSF-3 #	0.43	5060	6820	297	4.13	83	400	400	1604	0.03