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# SEISMIC REHABILITATION OBJECTIVES WITH EVALUATION AND DESIGN PROGRAM FOR MEDICAL EQUIPMENT IN HOSPITALS

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**ABSTRACT:** Based on the experiences learned from recent earthquakes, it is recognized that the earthquake resisting capacity of the responsibility hospitals with acute services in Taiwan should be upgraded. These hospitals assigned to provide emergency services after major earthquakes should remain functional for their engineering structures, medical facilities, electricity and water supply, and information services. In order to facilitate the governmental political issue and practical engineering services regarding the seismic upgrading of hospitals, the objective of this paper is to determine the seismic rehabilitation objectives of essential medical equipment and nonstructural components in responsibility hospitals, and further, to propose the seismic evaluation and strengthening guidelines. Owing to the onerous works required to improve the seismic performance of various nonstructural components, a simplified program is established using MS Excel software to execute the seismic evaluation and retrofit design for individual medical equipment. Users are asked to fill in the blanks with hospital information and the parameters of selected equipment, then, the program will identify the performance objective for each equipment, and further, it will determine whether the equipment should be retrofitted or not. In addition, the preliminarily designed of post-installed anchor bolts for seismic retrofit against the specified seismic demands can be checked automatically by the program.

## 1. Introduction

The most important issue of a designated responsibility hospital with acute services is to maintain its emergency medical function all day long. However, from the experiences of the recent earthquakes, not only the hospital building structures but also the inside medical equipment (e.g. medicine cabinets and X-ray machines) were damaged seriously, and hence it resulted in significant shortage of emergency medical capacities of hospitals. It implies that the earthquake resisting capacity of the designated responsibility hospitals for emergency treatment should be upgraded to remain functional for the engineering structures, medical facilities, electricity and water supply, and information services after major earthquakes.

Currently, most of the Ministry of Health and Welfare (MOHW) hospitals in Taiwan have completed the simplified evaluation of seismic capacity of building structures and the electrical and mechanical systems, some MOHW hospitals have finished the detailed seismic evaluation of building structures, but the specific seismic capacity of medical equipment and piping systems has not been considered. Therefore, in order to facilitate the governmental political issuing and practical engineering services regarding the seismic upgrading of hospitals, a 3-year project with the objective to develop a draft of "Seismic Evaluation and Strengthening Guidelines for Hospital Buildings" was organized by NCREE. As proposed, this guideline will consist of three major parts: (1) the upgrading strategy for seismic performance of hospitals, including the classification of building structures and nonstructural components of hospitals, and the associated seismic rehabilitation objectives; (2) the seismic evaluation and strengthening guidelines for hospital building structures, and (3) the seismic evaluation and strengthening guidelines for nonstructural components and systems (NSCS) in hospitals.

Furthermore, a program was established by MS Excel software to execute the seismic evaluation and preliminary retrofit design for individual medical equipment. The framework of the program and the detail algorithm of each step will be described in this paper. In addition, the program can evaluate the seismic performance of anchor bolts according to the criteria specified by ACI code. In order not to underestimate the seismic demands on the worst bolt, the demands are calculated first using generic equations on the basis of rigid body assumption, and then adjusted by the modification coefficients which were determined statistically by numerical analyses for the structures of real equipment.

## 2. Rehabilitation Objectives and Evaluation Criteria for NSCS in Hospitals

In general, as shown in Fig.1, the space in a hospital can be classified by human occupied area and non-human occupied area, or essential care area (including critical medical space and emergency exit access) and general area. For the nonstructural components and systems (NSCS) in a hospital, the essential care areas and the supporting mechanical and electrical systems will be identified first according to the SB1953 (2001) and the Hospital Safety Index developed by WHO. Then, inside the identified essential care areas, the architectural components for performance level of life safety and the critical medical equipment with higher seismic vulnerability will be chosen from criterion stated in ASCE7-05 (2005) and the survey questionnaire answered by head nurses and facility managers.

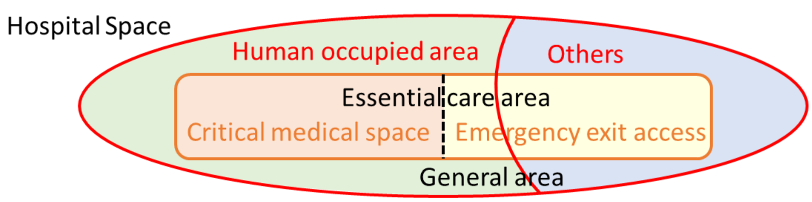


**Fig. 1 – The classification of space in a hospital**

The rehabilitation objective will be defined for the hospital to meet the specified rehabilitation goals. Each goal shall consist of a target performance level and an earthquake hazard level. There are three earthquake hazard levels EQL-1, EQL-2 and EQL-3 to be considered for the seismic evaluation of hospitals. Herein, EQL-1 is the frequently occurring small earthquake, EQL-2 is the design basis earthquake (DBE) with a return period of 475 years (10% probability of exceedance within 50 years), and EQL-3 is the maximum considered earthquake (MCE) with a hazard of 2%/50 years. The seismic demands (e.g. EPA) for the three earthquake hazard levels can be determined as specified by the Seismic Design Specifications and Commentary of Buildings (2011) in Taiwan.

Similar to SB1953, the target nonstructural performance level of a hospital shall be selected from 5 discrete performance levels NPL1, NPL2, NPL3, NPL4 and NPL5, and the description of each nonstructural performance level is listed in Table 1 Therefore, each nonstructural component can be tagged based on its particular characteristic and contribution in a hospital to meet the target performance level. The NSCS required to satisfy the performance level of NPL2 are tagged as NPL2, the additional NSCS required to satisfy the NPL3 are tagged as NPL3, and the more additional NSCS required to satisfy NPL4 are tagged as NPL4. In addition, the NSCS required to satisfy the performance level of NPL5, i.e.

the electric and mechanical components used to support the components tagged by NPL3 to keep function without any interruption after strong earthquakes, are tagged as NPL5.

**Table 1 – Nonstructural performance levels of a hospital**

| Performance Level | Description |
|---|---|
| **NPL5** | **Operational for essential care areas** - The building meets the criteria for NPL3, and further, on-site supplies of water and holding tanks for wastewater, sufficient for emergency operations in essential care areas without any interruption, are integrated into the building plumbing systems. An on-site emergency system is incorporated into the building electrical system for critical care areas. Additionally, the system shall provide for radiological service and an onsite fuel supply of acute care operation. |
| **NPL4** | **Immediate Occupancy for human occupied areas** - The building meets the criteria for NPL3, and further, all architectural, mechanical, electrical systems, components and equipment, and hospital equipment in human occupied areas meet the bracing and anchorage requirements |
| **NPL3** | **Immediate Occupancy for essential care areas -** The building meets the criteria for NPL2, and further, the critical components and equipment in essential care areas meet the bracing and anchorage requirements.<br>critical care areas: including clinical laboratory service spaces, pharmaceutical service spaces, radiological service spaces, and central and sterile supply areas.<br>critical components: including elevator, communications systems, piping systems and tanks and vessel related to medical service; medical equipment; and potential falling or overturning architecture components. |
| **NPL2** | **Life Safety** - the equipment related to emergency exit access are braced or anchored (e.g. communications systems, emergency power supply, bulk medical gas systems, fire alarm systems; and emergency lighting equipment and signs in the means of egress) |
| **NPL1** | Keep the existing building with the same performance, the equipment and systems may not meet the bracing and anchorage requirements. |

Based on the specified Seismic Category (I=1.0, 1.25 or 1.5) and the designated acute level (severe, moderate, or general) of an interested hospital, the rehabilitation objective of the NSCS can be determined by the performance matrix as shown in Table 2. It can be found by Table 2(a) for non-designated responsibility hospitals (I=1.25) that the nonstructural performance level is expected to be up to NPL4 under earthquake hazard level of EQL-1, NPL3 under EQL-2 (DBE) and NPL2 under EQL-3 (MCE), respectively, and the nonstructural performance level of NPL5 is not necessary for non-designated responsibility hospitals. In addition, the performance matrix also indicates that the NSCS tagged by NPL2 for a non-designated responsibility hospital should be designed for seismic retrofit under the earthquake hazard level of EQL-3 (MCE), the ones tagged by NPL3 should be designed by EQL-2 (DBE), and the ones tagged by NPL4 should be designed by EQL-1. For 'moderate', and 'general' designated responsibility hospitals (I=1.5), it is found from Table 2(a) that the associated rehabilitation objective is the same as that for non-designated responsibility hospitals (I=1.25) except that the performance level of NPL5 should be satisfied. It means that the NSCS tagged by NPL5 should be designed for seismic retrofit under the earthquake hazard level of EQL-2 (DBE), the same as that for components tagged by NPL3. Similarly, it can be found by Table 2(b) for university hospital (medical center) and 'severe' designated responsibility hospitals (I=1.5) that the nonstructural performance level is expected to be up to NPL4 under earthquake hazard levels of EQL-1 and EQL-2 (DBE), and NPL3 under EQL-3 (MCE), respectively. Furthermore, the NSCS tagged by NPL5 should be designed for seismic retrofit under the earthquake hazard level of EQL-3 (MCE), the same as that for components tagged by NPL3.

For NSCS in a hospital, each component should be identified and tagged by NPL2, NPL3, NPL4 or NPL5 due to its particular characteristic and contribution in the hospital to meet the target performance level. The seismic capacity of brace or anchorage system of the identified components shall be determined, and then compared with the seismic demands determined under the specified earthquake hazard levels to check the rehabilitation objective as define by Table 2 is satisfied or not.

**Table 2 – Nonstructural performance matrix**

| Earthquake Hazard Level | (a) For non-designated responsibility hospital (I=1.25) and 'moderate', and 'general' designated responsibility hospitals (I=1.5) | | | | (b) For university hospital (medical center) and 'severe' designated responsibility hospitals (I=1.5) | | | |
|---|---|---|---|---|---|---|---|---|
| | NPL2 | NPL3 | NPL4 | NPL5* | NPL2 | NPL3 | NPL4 | NPL5* |
| EQL-1 | ○ | ○ | ◎ | ○ | ○ | ○ | ○ | ○ |
| EQL-2 (DBE) | ○ | ◎ | | ◎ | ○ | ○ | ◎ | ○ |
| EQL-3 (MCE) | ◎ | | | | ◎ | ◎ | | ◎ |

* NPL5 is specified for designated responsibility hospitals only

## 3. Seismic Evaluation and Retrofit for NSCS

Referred to FEMA 356 (2000), this guideline will set forth requirements for the seismic rehabilitation of existing architectural, mechanical and electrical components and systems, and medical equipment that are permanently installed in, or are an integral part of, a building system. It will provide the general requirements for condition assessment, component evaluation, rehabilitation objectives, and structural-nonstructural interaction. In addition, the nonstructural components are classified into acceleration and deformation sensitive components, and the associated procedures for determining seismic forces and deformations on nonstructural components are specified. Furthermore, the general rehabilitation methods will be identified, and the seismic behavior, evaluation and acceptance criteria for all NSCS in a hospital.

In this study, a simplified evaluation form was established using MS Excel software to determine the seismic performance of any selected nonstructural items in the essential care areas. Users can get the evaluation results by filling in the characteristic parameters of the selected NSCS. The installation for items identified as 'seismic evaluation required' should be considered under the seismic effect. Fig.2 shows the identified NSCS to be installed under seismic consideration.

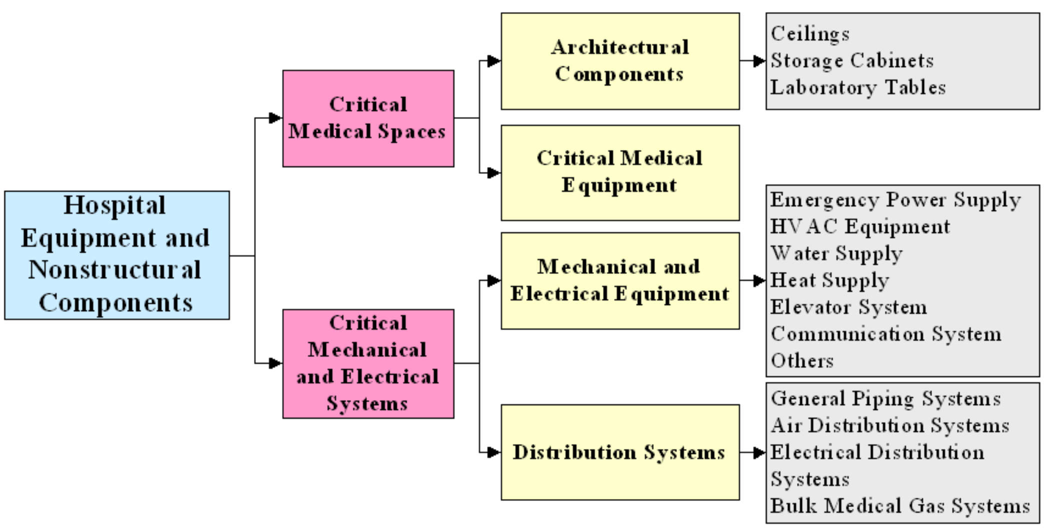


**Fig. 2 – Identified nonstructural items to be installed under seismic consideration**

In general, the installation types for nonstructural items are considered to meet the operational requirement. For seismic consideration, it is required to improve the seismic capacity of installation devices for NSCS, and meanwhile not obstruct the functionality of such nonstructural components and medical equipment. Typically, all medical equipment can be classified into three categories according to its type of attachment, namely, freestanding items (e.g. safety cabinet), wheel movable items (e.g.

medical trolley, micro-selectron, pharmaceutical refrigerator, mass infuser, hyperbaric oxygen capsule, dialysis machine), and desktop items (e.g. gamma counter). As summarized in Table 3, Z-shape stoppers and some auxiliary non-destructive seismic restraint devices, such as brakes and adhesive belts (such as Thumb Lock), were proposed and designed for equipment according to its daily use.

Based on the Seismic Design Code for Buildings in Taiwan and other references, the seismic demand on attachments of nonstructural components and medical equipment can be calculated automatically by MS Excel software. In addition, a simplified seismic design form for post-installed anchorage was presented according to the appendix D of ACI 318-02 (2002). Based on the determined design parameters (e.g. number of anchors at each support, anchor size, and embedded depth), the attachments of equipment can be designed to satisfy the specified seismic demands. The detail of the simplified seismic evaluation and retrofit design programs will be narrated in following paragraphs.

**Table 3. Proposed seismic restraint devices for the medical equipment**

| Medical Equipment | Bearing | seismic restraint devices A | seismic restraint devices B |
|---|---|---|---|
| safety cabinet | adjustable glides | top/bottom stoppers | bottom stoppers |
| pharmaceutical refrigerator | iron casters | against the wall / Thumb Lock | against the wall |
| medical trolley supporting defibrillator | rubber casters | diagonal braking trolley/ defibrillator restrained by Thumb Lock | diagonal braking trolley / defibrillator restrained by plastic clasps and cable |
| micro-selectron | medical equipment casters | against the wall / Thumb Lock | Braking casters |
| mass infuser | hooded ball casters | Thumb Lock | alternative devices (metal clasps and cable) |
| dialysis machine | hooded ball casters | Thumb Lock | alternative devices (metal clasps and cable) |
| gamma counter | rubber glides | Thumb Lock | angles and rubber pads |

## 4. Experiment Study on Anchorage Capacity

In order to verify the application of proposed simplified evaluation forms and recommended seismic restraints, some critical and vulnerable medical equipment items were chosen for shaking table tests. Because of the extremely high price of medical equipment, it was modeled by square pipe and steel plate for the shaking table test, except medical trolley, mass infuser and electrical stimulator. According to the in situ survey, the size, weight and support types of test specimens were actually modeled from the prototype of medical equipment. The modeled specimens for some selected medical equipment are illustrated in Fig.3.

(a)micro-selectron

(b)safety cabinet

**Fig. 3 – Experimental specimen for the selected medical equipment for shaking table tests**

For the equipment items without seismic restraint devices, most responses in shaking table tests were quite consistent with the response identified by the simplified evaluation form. Based on the test results, it can be observed that seismic restraint devices efficiently decreased displacement responses and possibilities of overturning or bumping with other items. However, restraint devices would inevitably increase the acceleration responses of equipment items. In order to reduce impact force and to avoid resonance of internal components in medical equipment, using ductile restraint devices or adding energy-dissipating devices (such as rubber pads) are suggested. In addition, the fundamental frequencies of medical equipment with restraint become generally higher than those without any restraint. Besides, damage of the adhesive layer between restraint devices and equipment, and anchors into partition walls, appeared under larger earthquakes. Hence, the pull-out strength of anchors in partition walls, and the adhesive strength of non-destructive devices, will be the next research subjects for seismic design of medical equipment.

# 5. Seismic Evaluation and Retrofit Design Program for NSCS in Hospitals

## 5.1. Framework and Sheets in the Program

Fig.4 shows the framework and flowchart of the program. Users will fill in the blanks with hospital information and equipment parameters in two separated sheets of MS Excel software. For components to be retrofitted by anchor bolts, users will fill in the additional sheet about anchor bolt information. Fig.5 shows the sheet of 'hospital' which should be filled in first, it consists of the classification and location of the interested hospital, seismic parameters according to seismic design code, and height of each floor in the hospital.  Then, the second sheet to be filled in is the sheet of 'equipment' as shown in Fig.6. The sheet consists of the information of selected component (e.g., name, sort, location, weight, height), and one column for one equipment. The program will identify the performance objective for each equipment, and further, it will determine whether the equipment should be retrofitted or not. In addition, the preliminarily designed of post-installed anchor bolts for seismic retrofit against the specified seismic demands can be checked automatically by the program using the sheet of 'anchor bolt' as shown in Fig.7.

## 5.2. Determination Algorithm in the Program

As mentioned before, each component can be identified and tagged by NPL2, NPL3, NPL4 or NPL5 due to its particular characteristic and contribution in the hospital to meet the target performance level. Even for the same type of NSCS, the identified performance levels may be different if they are located at or serve for different areas. In the proposed MS Excel software, the target nonstructural performance level NPL2, NPL3 or NPL4 can be identified for each NSCS by its location, type, sort, and category. Fig.8 shows the identification algorithm. On the other hand, the associated earthquake hazard level can be determined according to the nonstructural performance matrix (Table 2) to meet the performance objective. The process to determine the associated earthquake hazard level is shown in Fig.9.

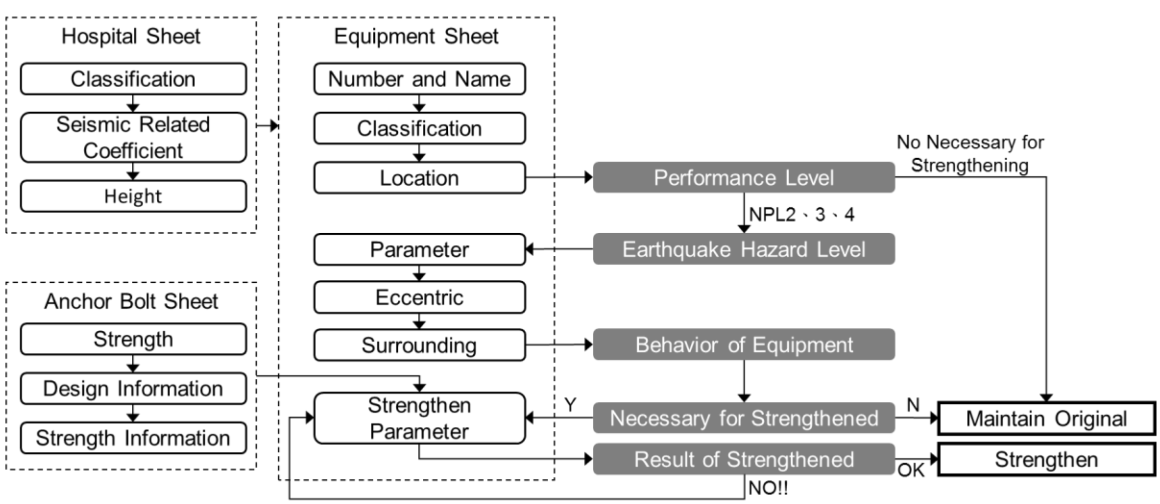


**Fig. 4 – Framework and flowchart of the program**

| | |
|---|---|
| **Hospital Accreditation：** | Medical Center |
| **Emergency Responsibility Hospitals：** | General Designated Responsibility Hospitals |
| **Coefficient in seismic code of Taiwan** | |
| Site： | Near Fault |
| DBE Coefficient of Horizontal Design Spectrum Acceleration-factor ($S_S^D$)： | 0.8 |
| DBE Nea-Fault Factor(Na)： | 1.42 |
| DBE Coefficient of Fa： | 1 |
| MCE Coefficient of Horizontal Design Spectrum Acceleration-factor ($S_S^M$)： | 1 |
| MCE Nea-Fault Factor(Na)： | 1.32 |
| MCE Coefficient of Fa： | 1 |
| **Floor** | **Height of Each Floor(cm)** |
| RF | 5450 |
| 15F | |
| 14F | |
| 13F | |
| 12F | 5050 |
| 11F | 4650 |
| 10F | 4250 |
| 9F | 3950 |
| 8F | 3450 |
| 7F | 3050 |
| 6F | 2650 |
| 5F | 2100 |
| 4F | 1580 |
| 3F | 1050 |
| 2F | 540 |
| 1F | 0 |

**Fig. 5 – The sheet of 'hospital'**

| | | |
|---|---|---|
| **Number and Name** | | |
| Number: | | Normal Supply System-001 |
| Name: | | Water Chiller Unit |
| **Classification** | | |
| Types: | MENU | Mechanical Equipment |
| Sorts: | MENU | HVAC System Component |
| Categories: | MENU | Vibration isolated |
| **Location** | | |
| Location: | MENU | Others Human Occupied |
| Floor: | Number (R for Roof,-1~-5 for Basement) | R |
| **Parameter** | | |
| Weight ($W_p$)： | kgf | 2000 |
| Supporting Structural Component | MENU | Floor |
| Dimension: | Length of X-Axies ($L_x$) m | 2.26 |
| | Length of Y-Axies (Ly) m | 2.15 |
| | Heught (Container Included) (h) m | 2.40 |
| Distance between top to floor: | (Container Included) m | 2.22 |
| **Eccentric** | | |
| X-Axis Eccentric： | (Filled with Y or N) | Y |
| X-Axis Distance between the Edge to the Center of Gravity： | (Blank Space for Non-Eccentric or Uncertain) ($L_{xG}$) m | 1.00 |
| Y-Axis Eccentric： | (Filled with Y or N) | Y |
| Y-Axis Distance between the Edge to the Center of Gravity： | (Blank Space for Non-Eccentric or Uncertain) ($L_{yG}$) m | 1.00 |
| Z-Axis Eccentric： | (Filled with Y or N) | N |
| Z-Axis Distance between the Edge to the Center of Gravity： | (Blank Space for Non-Eccentric or Uncertain) ($h_G$) m | |
| **Surrounding** | | |
| Connection with Structure : | MENU | Non-Fixed |
| Material of Floor Surface : | MENU | Rubber |
| Material of floor : | MENU | Concrete |
| Lean on the Wall : | MENU | Independent |
| Seismic Evaluation Required | | Y |
| Performance Level | | NPL4 |
| Earthquake Hazard Level | | DBE |
| Seismic Response of Equipment | | Sliding |
| **Necessary for Strengthening** | | **Y** |
| **Bolt Strenrthening** | (Blank Space for No Necessary Strenrthen) | |
| Number of bolts on X-Axies : | | 4 |
| Number of bolts on Y-Axies: | | 4 |
| Type or Size: | MENU | Hilti-M10 |
| Depth in concrete: | in | 4.00 |
| Anchorage on Concrete or Other Material : | MENU | |
| Strength of Base Material : | psi | 2800 |
| **Result** | | **OK** |

**Fig. 6 –The sheet of 'equipment'**

| | | | | | |
|---|---|---|---|---|---|
| Strength of Anchor Bolt | (psi) | | | | |
| | $f_{ya}$ | 92800 | | | |
| | $f_{uta}$ | 116000 | | | |
| Design Information of Anchor Bolt | Data | $d_o$ | he(min) | Ase | Np |
| | Item Number | in | in | in^2 | lb |
| | Hilti-M8 | 0.47 | 2.36 | 0.057 | 2810 |
| | Hilti-M10 | 0.59 | 2.76 | 0.090 | 4496 |
| | Hilti-M12 | 0.71 | 3.15 | 0.131 | |
| | Hilti-M16 | 0.94 | 3.94 | 0.243 | |
| Design Strength (Design Strength of Anchor Bolt in Different Base - Provided by Factory) | ϕ Tn (psi) | Strength of Concrete | | | |
| | Item Number | 2500 | 3000 | 4000 | 6000 |
| | Hilti-M8 | 1825 | 2000 | 2310 | 2830 |
| | Hilti-M10 | 2920 | 3200 | 3695 | 4525 |
| | Hilti-M12 | 4360 | 4775 | 5515 | 6755 |
| | Hilti-M16 | 6095 | 6675 | 7705 | 9440 |
| | ϕ Vn (psi) | Strength of Concrete | | | |
| | Item Number | 2500 | 3000 | 4000 | 6000 |
| | Hilti-M8 | 2160 | 2365 | 2730 | 3345 |
| | Hilti-M10 | 7685 | 8420 | 9720 | 11905 |
| | Hilti-M12 | 9390 | 10285 | 11880 | 14550 |
| | Hilti-M16 | 13125 | 14375 | 16600 | 20330 |

**Fig. 7 – The sheet of 'anchor bolt'**

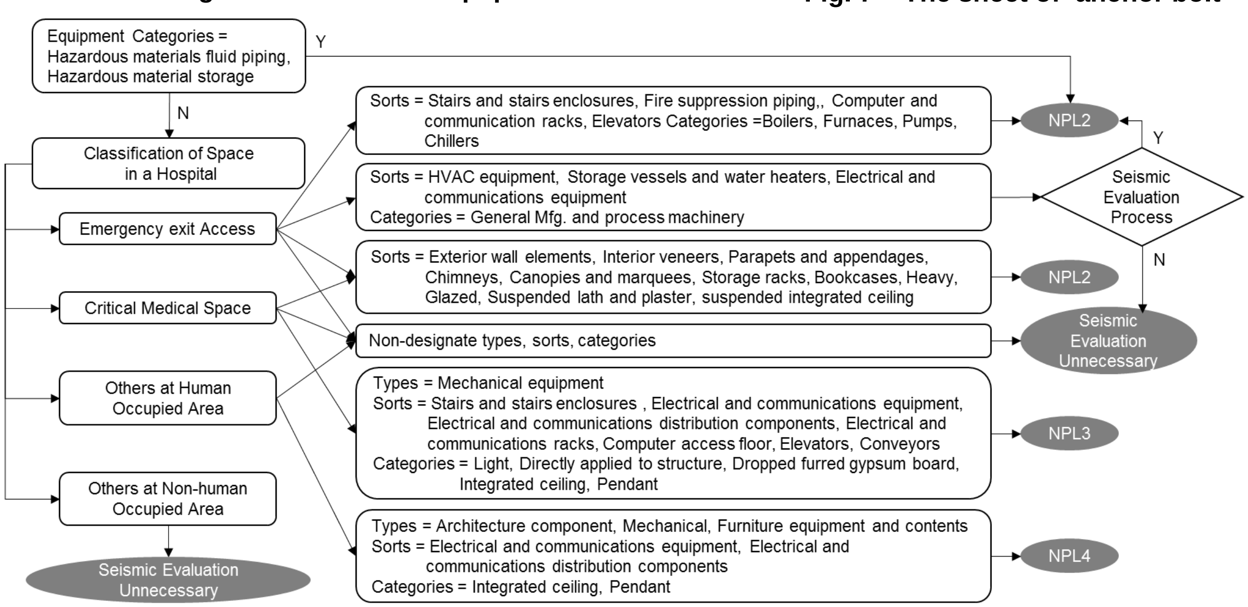


**Fig. 8 – Process to determine performance level**

Seismic response of equipment can be determined by (Ishiyama,1982)

$$A > \mu g \Rightarrow Sliding \quad (1)$$

$$B/H < A/g \Rightarrow Rocking \quad (2)$$

$$V > 10 \times B^{*}/\sqrt{H} \Rightarrow Overturning \quad (3)$$

where $A$ and $V$ are the peak floor acceleration and velocity, respectively. The process to determine seismic response is shown in Fig.10. The steps for strengthening will be followed-up for the components which are determined as 'sliding' or 'overturning'.

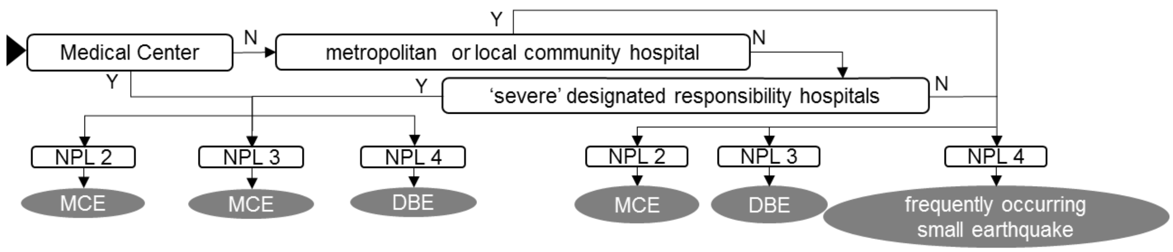


**Fig. 9 – Process to determine earthquake hazard level**

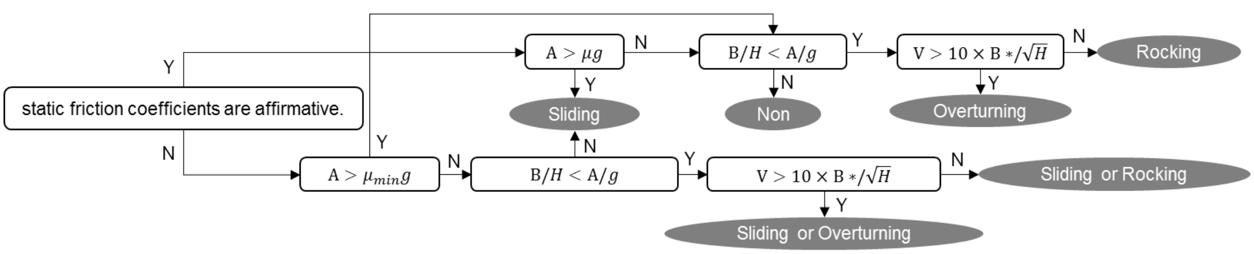


**Fig. 10 – Process to determine seismic response**

## 6. Seismic Evaluation Criteria for Anchor Bolts

### 6.1. Seismic Demand for Rigid Equipment

In general, based on the rigid body assumption, Eq.4 and Eq.5 are adopted to calculate the tension and shear demands $T_{ua}$ and $V_{ua}$ exerted on one anchor bolt (referred to Fig.11).

$$T_{ua} = \left[F_{ph} \times h_G - \left(W_p - F_{pv}\right) \times l_G\right] / \left(L \times n_t\right) \quad (4)$$

$$V_{ua} = F_{ph} / n \quad (5)$$

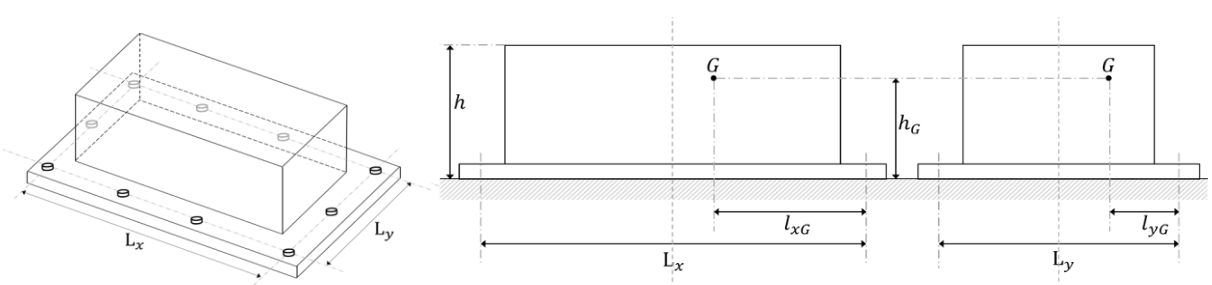


**Fig. 11 – Notes for rigid rectangular equipment**

Herein, $n$ is the total number of bolts and $n_t$ is the number of bolts along one side. The dead load ($W_p$) and seismic force ($F_{ph}$ and $F_{pv}$) are combined to determine the tension force. For shear demand $V_{ua}$, it is determined by the average of horizontal seismic force.

## 6.2. Modification Coefficients for Real Equipment

As mentioned before, Eq.4 and Eq.5 are defined under rigid equipment assumption without considering the response of equipment structure. In addition, it is noted that only one component of horizontal seismic force is considered in the simplified equation, and the maximum values determined from seismic force in x- or y-direction will be used for design. Therefore, in order not to underestimate the seismic demands on the worst bolt, the tension and shear demands in the proposed program are defined by

$$T_{ua} = 0.9 \times \phi_{TW} \times T_W + \phi_{TE} \times T_E \quad (6)$$

$$V_{ua} = \phi_{VE} \times V_E \quad (7)$$

where, $T_W$ and $T_E$ are the calculated tension forces caused by dead load and seismic loads under rigid body assumption, respectively. $V_E$ is the shear force caused by seismic load under rigid body assumption. The generic equations to calculate $T_W$, $T_E$ and $V_E$ are defined by

$$T_W = \min\left(\frac{W_p \times \min(l_{xG}, L_x - l_{xG})}{L_x \times n_y}, \frac{W_p \times \min(l_{yG}, L_y - l_{yG})}{L_y \times n_x}\right) \quad (8)$$

$$T_E = \max\left(T_{QX} + 0.3 \times T_{QY} + T_{QZ}\ ,\ 0.3 \times T_{QX} + T_{QY} + T_{QZ}\right) \quad (9)$$

$$V_E = \sqrt{\left(\frac{F_{ph}}{n}\right)^2 + \left(\frac{0.3 \times F_{ph}}{n}\right)^2} \quad (10)$$

where $T_{QX}$, $T_{QY}$, and $T_{QZ}$ are the tension demands caused by seismic force $F_{ph}$ in x-, y-directions, and $F_{pv}$ in z-direction, respectively, and they are defined by

$$T_{QX} = \frac{F_{ph} h_G}{L_x n_y}, \quad T_{QY} = \frac{F_{ph} h_G}{L_y n_x}, \quad T_{QZ} = \max\left(\frac{F_{pv} \times \max(l_{xG}, L_x - l_{xG})}{L_x \times n_y}, \frac{F_{pv} \times \max(l_{yG}, L_y - l_{yG})}{L_y \times n_x}\right) \quad (11)$$

where $n$ is the total number of bolts, and $n_x$ or $n_y$ is the number of bolts located on one side along x- or y-direction, respectively. It is noted that the loading combination 0.9D+1E is adopted to determine the tension demand for an anchor bolt. In addition, 100-30 rule is adopted to consider the effect caused by two horizontal directions, i.e., 100% of the effect in one direction is combined with 30% of the effect in the other orthogonal direction. The seismic base shear $V_E$ is defined by the vector sum of the two horizontal components following the 100-30 rule.

In order to determine the modification coefficients $\phi_{TW}$, $\phi_{TE}$ and $\phi_{VE}$, the finite element software SAP2000 was adopted to determine the reaction forces at the supporting points of a real equipment. The equipment is modeled by a frame-type structure with multi-supports. For an equipment with specific aspect ratio, eccentricity, distribution of anchor bolts, the tension forces caused by dead load and seismic load exerted on each bolt can be determined. Then, the seismic demands of the worst bolt were compared with the values determined by generic equations (Eq.8 to Eq.11), and hence, the associated modification coefficients can be determined for the specific case.  Based on the scenario of equipment with different aspect ratio, eccentricity, distribution of anchor bolts, the modification coefficients $\phi_{TW}$, $\phi_{TE}$ and $\phi_{VE}$ can be determined statistically. Table 4 illustrates the values of modification coefficients $\phi_{TE}$, similar formats are defined for $\phi_{TW}$ and $\phi_{VE}$. The tables of values of modification coefficients $\phi_{TW}$, $\phi_{TE}$ and $\phi_{VE}$ have been well defined already in the proposed evaluation and design program, and the program will determine the values of modification coefficients by the parameters as filled in by users in the sheet of ‘equipment’ (Fig.6). Then, the actual demand for the worst bolt can be determined by Eq.6 and Eq.7.

**Table 4. Values of modification coefficients $\phi_{TE}$**

| $\phi_{TE}$ | Eccentricity - none | Eccentricity – in single x- or y- axis | | Eccentricity - in both x- and y- axes | |
|---|---|---|---|---|---|
| | | $\log(x/y)<0$ | $\log(x/y)\geq 0$ | $\log(x/y)<0$ | $\log(x/y)\geq 0$ |
| $n_x < n_y$ | 1.0 | 1.4 | 1.0 | 1.5 | 1.3 |
| $n_x = n_y$ | | 1.2 | | 1.3 | |
| $n_x > n_y$ | | 1.3 | 1.0 | 1.3 | 1.5 |

### 6.3. Acceptance Criteria for Anchor Bolts

Designs of anchorage in concrete is in compliance with the Appendix D of ACI 318 code. The acceptance criteria is defined by

$$\left(\frac{T_{ua}}{\phi T_n}\right)^{1.5} + \left(\frac{V_{ua}}{\phi V_n}\right)^{1.5} \leq 1.0 \tag{12}$$

The capacity of anchor bolt $\phi T_n$ and $\phi V_n$ would be evaluated in the sheet of ‘anchor bolt’, and the tension and shear demands $T_{ua}$ and $V_{ua}$ are calculated by Eq.6 and Eq.7. For which satisfying Eq.12, the blank ‘Result’ in Fig. 3 will reply ‘OK’, otherwise it will reply ‘NO!!’. For those not satisfying the acceptance criteria, users should modify the design of anchor bolt (e.g. bolt diameter, embedded length, etc.) or other restraint conditions such that the ‘Result’ will reply ‘OK’.

## 7. Conclusion

In order to facilitate the governmental political issuing and practical engineering services regarding the seismic upgrading of hospitals, a 3-year project to develop the “Seismic Evaluation and Strengthening Guidelines for Hospital Buildings” was organized by NCREE. The seismic rehabilitation objectives of NSCS in a hospital and the evaluation criteria were defined and introduced in this paper. The evaluation process proposed in the guideline may be more complex than common evaluation, however, an MS Excel program is established such that users can execute the seismic evaluation and retrofit design for individual medical equipment more easily and conveniently. More studies are on the way including the development of seismic evaluation and design program for the equipment attached on the wall or ceiling, and for those strengthened by z-shape stopper or welding.

## 8. References


ACI Committee 318, ACI 318-02, “Building Code Requirements for Structural Concrete and Commentary”, American Concrete Institute, 2002.

ASCE Standard, ASCE/SEI 7-05, Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, 2005.

FEMA 356, Prestandard and Commentary for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency, Washington, D.C, 2000.

Ishiyama Y., (1982). “Motions of Rigid Bodies and Criteria for overturning by earthquake excitations”, Earthquake Engineering and Structural Dynamic, 10, pp.635-650.

J.F. Chai et al., (2013), Seismic Evaluation and Strengthening Guidelines for Hospital Buildings, Taipei: National Center for Research on Earthquake Engineering, NCREE-13-037, 2013.

Seismic Design Specifications and Commentary of Buildings, Construction and Planning Agency Ministry of the Interior (CPAMI), 2011.