

SEISMIC REHABILITATION OBJECTIVES AND A SIMPLIFIED SEISMIC EVALUATION AND DESIGN PROGRAMME FOR MEDICAL EQUIPMENT IN HOSPITALS

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ABSTRACT

From the experience gained from recent earthquakes, it has been recognized that the earthquake resisting capacity of so-called responsibility hospitals for acute services in Taiwan should be upgraded. These hospitals, which have been tasked with the provision of emergency services after major earthquakes, should remain functional with regard to their structures, medical facilities, electricity and water supply, and information services. In order to facilitate the issuing of governmental policies 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 seismic evaluation and strengthening guidelines. Owing to the onerous work required to improve the seismic performance of various nonstructural components, a simplified programme is established using Microsoft Excel software to execute a preliminary seismic evaluation and retrofit design for individual pieces of medical equipment. Users are asked to fill in blanks with hospital information and the parameters of selected equipment and then the programme identifies the performance objective of each piece of equipment. It also determines whether the equipment should be retrofitted or not. In addition, preliminary designs of post-installation anchor bolts for seismic retrofitting against specified seismic demands can be checked automatically by the programme.

INTRODUCTION

The most important issue for a designated responsibility hospital (a hospital assigned by government and with responsibility to provide emergency treatment) for acute services is to maintain its emergency medical function continuously. However, during recent earthquakes, not only the hospital building structures but also the medical equipment inside (e.g. medicine cabinets and X-ray machines) were seriously damaged, which resulted in a significantly limited emergency medical capacity of hospitals. This implies that the earthquake-resistance capacity of the designated responsibility hospitals for emergency treatment should be upgraded to remain functional with regard to their 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 simplified evaluations of the seismic capacity of their building structures and some have finished detailed seismic evaluation of such. However, due to lack of information about evaluation methods for nonstructural components and equipment, the electrical and mechanical systems were only roughly visually inspected and the seismic capacity of the medical equipment and piping systems has still not been considered. Therefore, in order to facilitate the governmental policies and practical engineering services regarding the seismic upgrading of hospitals, a 3-year project with the objective of developing a draft of "Seismic Evaluation and Strengthening Guidelines for Hospital Buildings" [1] was organized by the National Center for Research on Earthquake Engineering (NCREE). As proposed,

this guideline will consist of three major parts: (1) an upgrading strategy for the seismic performance of hospitals, including the classification of building structures and nonstructural components of hospitals, and associated seismic rehabilitation objectives; (2) seismic evaluation and strengthening guidelines for hospital building structures; and (3) seismic evaluation and strengthening guidelines for nonstructural components and systems (NSCS) in hospitals.

Furthermore, a programme was established using Microsoft Excel software to execute the seismic evaluation and preliminary retrofit design for individual medical equipment. The framework of the programme and the detailed algorithm for each step will be described in this paper. In addition, the programme can evaluate the seismic performance of anchor bolts according to the criteria specified by the ACI code [2]. In order not to underestimate the most critical seismic demand on the bolts, the demands are calculated first using generic equations based on the assumption that the structure of the equipment behaves as a rigid body, and they are then adjusted by modification coefficients that are determined statistically from the numerical analysis results of finite element models.

REHABILITATION OBJECTIVES AND EVALUATION CRITERIA FOR NSCS IN HOSPITALS

In general, the space in a hospital can be classified as either a human-occupied area or non-human occupied area, or as either an essential care area (including critical medical space and the means of egress) or a general area, as shown in Figure 1. For NSCS in a hospital, the essential care areas and the supporting

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mechanical and electrical systems are identified first according to the SB1953 (2001) and the Hospital Safety Index developed by the WHO. Then, inside the identified essential care areas, the architectural components that could reduce the life-safety performance of hospitals and the critical medical equipment with higher seismic vulnerabilities are chosen from criteria stated in ASCE7-05 [3] and a survey questionnaire answered by head nurses and facility managers.

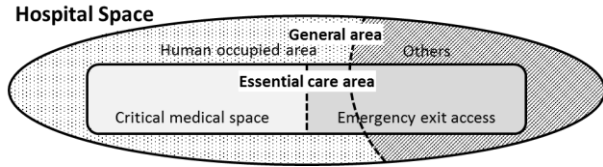


Figure 1: The classification of space in a hospital.

The rehabilitation objective consists 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 represents a frequently occurring small earthquake, EQL-2 represents the design basis earthquake (DBE) with a return period of 475 years (10% probability of exceedance within 50 years) and EQL-3 represents the maximum considered earthquake (MCE) having a 2% probability of exceedance in 50 years. The seismic demands (e.g., Effective Peak Acceleration) of the three earthquake hazard levels can be determined as specified by the Seismic Design Specifications and Commentary of Buildings [4] in Taiwan.

Similar to SB1953, the target nonstructural performance level of a hospital is selected from five discrete performance levels NPL1, NPL2, NPL3, NPL4 and NPL5, and descriptions of each nonstructural performance level are listed in Table 1. Therefore, each nonstructural component can be tagged based on its particular characteristics and contribution toward meeting 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 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 electrical and mechanical components used to support the components tagged with NPL3 to keep functioning without any interruption after strong earthquakes, are tagged as NPL5.

Based on the specified seismic category ($I = 1.0, 1.25$ or 1.5) and the designated acute level (severe, moderate or general) of a hospital of interest, the rehabilitation objective of the NSCS can be determined by the performance matrix as shown in Table 2. It can be found from Table 2 for non-designated responsibility hospitals ($I=1.25$) that the nonstructural performance level is expected to be up to NPL4 under an earthquake hazard level of EQL-1, NPL3 under EQL-2 (DBE) and NPL2 under EQL-3 (MCE), 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 with NPL2 for a non-designated responsibility hospital should be designed for seismic retrofiting under the earthquake hazard level of EQL-3 (MCE), the ones tagged with NPL3 should be designed for EQL-2 (DBE), and the ones tagged with NPL4 should be designed for EQL-1. For ‘moderate’ and ‘general’ designated responsibility hospitals ($I=1.5$), it seems from Table 2 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. This means that the NSCS tagged with NPL5 should be designed for seismic retrofiting under the earthquake hazard level of EQL-2 (DBE), the same as that for components tagged with NPL3. Similarly, it can be found in Table 2 for university hospitals (medical centres) and ‘severe’ designated responsibility hospitals ($I=1.5$) that the nonstructural performance level is expected to be up to NPL4 under earthquake hazard level of EQL-2 (DBE) and NPL3 under EQL-3 (MCE). Furthermore, the NSCS tagged by NPL5 should be designed for seismic retrofiting under the earthquake hazard level of EQL-3 (MCE), the same as that for components tagged with NPL3.

Table 1: Nonstructural performance levels of a hospital

Performance Level	Description
NPL1	The existing building remains at its existing condition and the equipment and systems may not meet the bracing and anchorage requirements.
NPL2	Life safety - The equipment related to storage of toxic or radioactive material, heavy and above head-height equipment, and equipment for emergency exit access is 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*).
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. Critical care areas: includes clinical laboratory service spaces, pharmaceutical service spaces, radiological service spaces, and central and sterile supply areas. Critical components: includes elevators, communications systems, piping systems and tanks, and vessels related to medical service, medical equipment, and potential falling or overturning of architectural components.
NPL4	Immediate occupancy for human occupied areas - The building meets the criteria for NPL3, and furthermore, all architectural, mechanical and electrical systems, components and equipment, and hospital equipment in human-occupied areas meet the bracing and anchorage requirements.
NPL5	Operational for essential care areas - The building meets the criteria for NPL3, and furthermore, 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’s electrical system for critical care areas. Additionally, the system shall provide radiological services and an onsite fuel supply for acute care operation.

*The SB1953 concerns access items related to life safety only.

Table 2: Nonstructural rehabilitation objective

Earthquake Hazard Level	For non-designated responsibility hospital (I=1.25) or 'moderate', or 'general' designated responsibility hospitals (I=1.5).				For university hospitals (medical centres) or '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.

*○:Under this earthquake hazard level, the equipment still remains secure.

◎:This earthquake hazard level would be the main decision level.

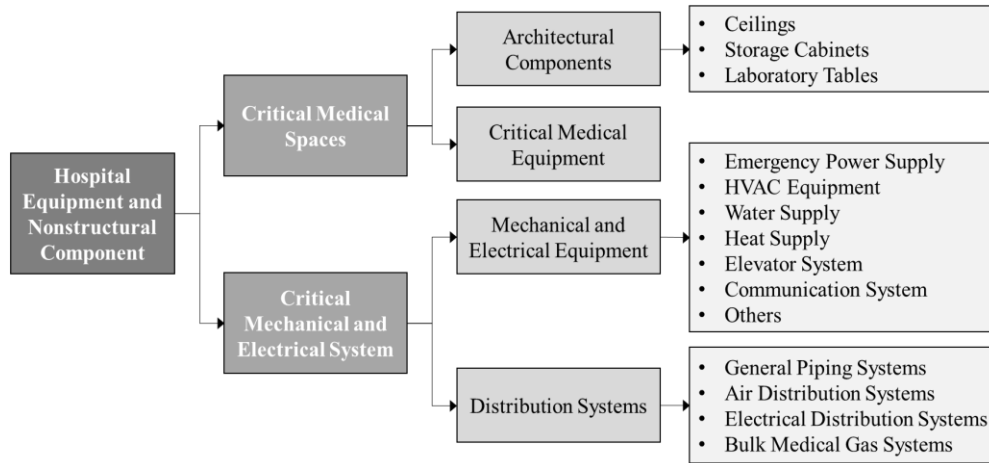


Figure 2: Identified nonstructural items to be installed under seismic consideration.

For NSCS in a hospital, each component of interest should be identified and tagged with NPL2, NPL3, NPL4 or NPL5 according to its particular characteristics and contribution toward meeting the target performance level. The seismic capacity of the brace or anchorage systems for NSCS should be designed and then the improved performance of NSCS with the seismic demands should be determined under the specified earthquake hazard levels to check that the rehabilitation objective, as defined in Table 2, is satisfied or not.

SEISMIC EVALUATION AND RETROFIT OF NSCS

The FEMA 356 [5] guideline sets forth requirements for the seismic rehabilitation of existing architectural, mechanical and electrical components and systems that are permanently installed in, or are an integral part of, a building system, and medical equipment. It provides 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 of nonstructural components and acceptance criteria are specified. Furthermore, the general rehabilitation methods are identified for the NSCS in a hospital.

In this study, a simplified evaluation form was established using Excel software to determine the seismic performance of any selected nonstructural items in essential care areas. Users can obtain the evaluation results by filling in the characteristic parameters of the selected NSCS. A further detailed evaluation for an item identified as ‘seismic evaluation required’ according to its vulnerability or importance should be

considered under the seismic effect. Figure 2 shows the identified NSCS to be installed according to seismic considerations.

In general, the installation types for nonstructural items are originally considered to meet the operational requirements. For seismic considerations, it is necessary to improve the seismic capacity of installation devices for NSCS and not obstruct the original 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 cabinets), wheel-movable items (e.g., medical trolleys, micro-selectrons, pharmaceutical refrigerators, mass infusers, hyperbaric oxygen capsules and dialysis machines) and desktop items (e.g., gamma counters). As summarized in Table 3, Z-shape stoppers and some auxiliary non-destructive seismic restraint devices, such as braking casters and adhesive belts (such as Thumb Locks), 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 demands for attachment of nonstructural components and medical equipment can be calculated automatically using Excel software. In addition, a simplified seismic design form for a post-installed anchorage was presented according to Appendix D of ACI 318-02 [2]. By adjusting the design parameters (e.g., the number of anchors at each support, anchor size and embedded depth), the equipment attachments can be designed to satisfy the specified seismic demands. The details of the simplified seismic evaluation and retrofit design programmes will be explained in the following paragraphs.

Table 3: Proposed seismic restraint devices for 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 cables
Micro-selectron	Medical equipment casters	Against the wall / Thumb Lock	Braking casters
Mass infuser	Hooded ball casters	Thumb Lock	Alternative devices (metal clasps and cables)
Dialysis machine	Hooded ball casters	Thumb Lock	Alternative devices (metal clasps and cables)
Gamma counter	Rubber glides	Thumb Lock	Angles and rubber pads

EXPERIMENTAL STUDY ON ANCHORAGE CAPACITY

In order to verify the application of the 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 prices of the medical equipment, the equipment was modelled with square pipes and steel plates for the shaking table tests, except for the medical trolley, mass infuser and electrical stimulator. According to the in-situ survey, the size, weight and support types of the test specimens were actually modelled from prototypes of the medical equipment. The modelled specimens for some selected medical equipment are illustrated in Figure 3.



(a) micro-selectron



(b) safety cabinet

Figure 3: Experimental specimen for the selected medical equipment for shaking table tests.

For the equipment items without seismic restraint devices, most responses to the 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 the seismic restraint devices efficiently decreased displacement responses and the possibility of overturning or bumping other items. However, restraint devices would inevitably increase the acceleration responses of equipment. In order to reduce impact forces and to avoid resonance of internal components in medical equipment, the use of ductile restraint devices or energy-dissipation devices (such as rubber pads) is suggested. In addition, the fundamental frequencies of medical equipment with restraints generally become higher than those without any restraints. Furthermore, damage to the adhesive layer between the restraint devices and equipment, and also at the anchors into the partition walls, appeared during larger earthquakes. Hence, the pull-out strength of the anchors into the partition walls and the adhesive strength of non-destructive devices, will be the next subjects of research for the seismic design of medical equipment.

SEISMIC EVALUATION AND RETROFIT DESIGN PROGRAMME FOR NSCS IN HOSPITALS

Framework and Sheets in the Programme

Figure 4 shows the framework and flowchart of the programme. For the purpose of seismic evaluation, two separate Excel spreadsheets, 'hospital' and 'equipment', need to be filled in by users with hospital information and equipment parameters. An additional sheet is also used for the seismic design of components retrofitted with anchor bolts. Figure 5 shows 'hospital' spreadsheet which should be filled in first. The sheet consists of the classification and location of the hospital of interest, seismic parameters according to the Seismic Design Code [4] and the heights of each floor in the hospital. Then, the second spreadsheet to be filled in is the 'equipment' spreadsheet as shown in Figure 6. The sheet consists of the information of the selected component (e.g., name, sort, location, weight, height) and there is one column for one piece of equipment. Equipment can be classified into three different levels, namely types, sorts and categories, the details of which be found in Ref.[1]. After users fill in the above information, the programme identifies the performance objective of each piece of equipment, and furthermore, determines whether the equipment should be retrofitted or not. In addition, the preliminary design of post-installed anchor bolts for seismic retrofitting against the specified seismic demands can be checked automatically by the programme using the 'anchor bolt' spreadsheet, as shown in Figure 7.

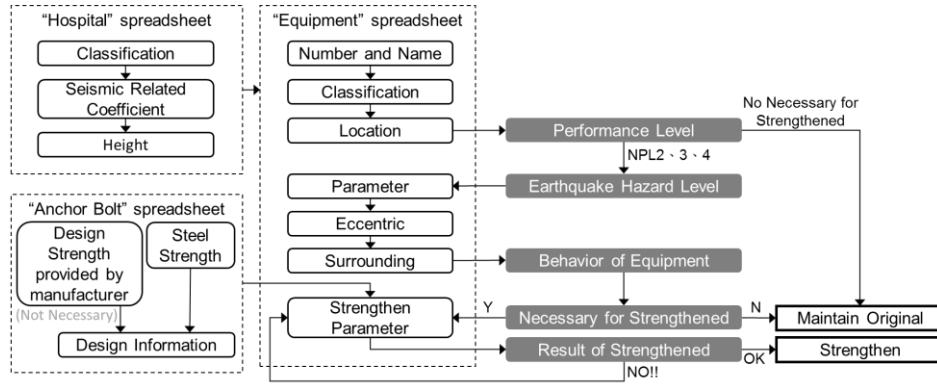


Figure 4: Framework and flowchart of the programme.

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_d):	kgf	2000
Supporting Structural Component	MENU	Floor
Dimension:	Length of X-Axes (L_x) m	2.26
	Length of Y-Axes (L_y) m	2.15
	Height (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_{xc}) 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_{yc}) 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_c) 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 Strengthening		
	(Blank Space for No Necessary Strengthen)	
Number of bolts on X-Axes:		4
Number of bolts on Y-Axes:		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

Figure 6: 'Equipment' spreadsheet.

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_a^D) :	0.8
DBE Near-Fault Factor(N_a) :	1.42
DBE Coefficient of F_a :	1
MCE Coefficient of Horizontal Design Spectrum Acceleration-factor (S_a^M) :	1
MCE Near-Fault Factor(N_a) :	1.32
MCE Coefficient of F_a :	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

Figure 5: 'Hospital' Spreadsheet.

Steel Strength of Anchor Bolt	(psi)				
	f_{ya}	92800			
	f_{uta}	116000			
Design Information of Anchor Bolt	Data	d_b	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 Manufacturer)	ϕT_n (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
ϕV_n (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	

Figure 7: 'Anchor bolt' spreadsheet.

Determination Algorithm in the Programme

As mentioned before, each component can be identified and tagged as NPL2, NPL3, NPL4 or NPL5 according to its particular characteristics and contribution towards meeting 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 different areas. In the proposed Excel software, the target nonstructural performance levels NPL2, NPL3 or NPL4 can be identified for each NSCS by its location, type, sort and category. Figure 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 Figure 9.

The evaluation of the seismic response of the equipment is based on Ishiyama's theory [6].

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

$$B/h < A/g \Rightarrow \text{Rocking} \quad (2)$$

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

where μ is the static friction coefficient between bottom side of equipment and floor surface, g is gravitational acceleration, A and V are the peak floor acceleration and velocity, respectively. B and h are shown in Figure 10, B^* can be

calculated as 2B if the other side leans against the wall [7]. The process to determine seismic response is shown in Figure 11. The steps for strengthening will be followed by the components determined to be 'sliding' or 'overturning'.

SEISMIC EVALUATION CRITERIA FOR ANCHOR BOLTS

Seismic Demand on the Rigid Equipment

In general and 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} , respectively) that act on one anchor bolt.

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

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

Herein, n is the total number of bolts and n_t is the number of bolts along one side. Other symbols are shown in Figure 10. 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 assumed that the horizontal seismic force is equally borne by all bolts.

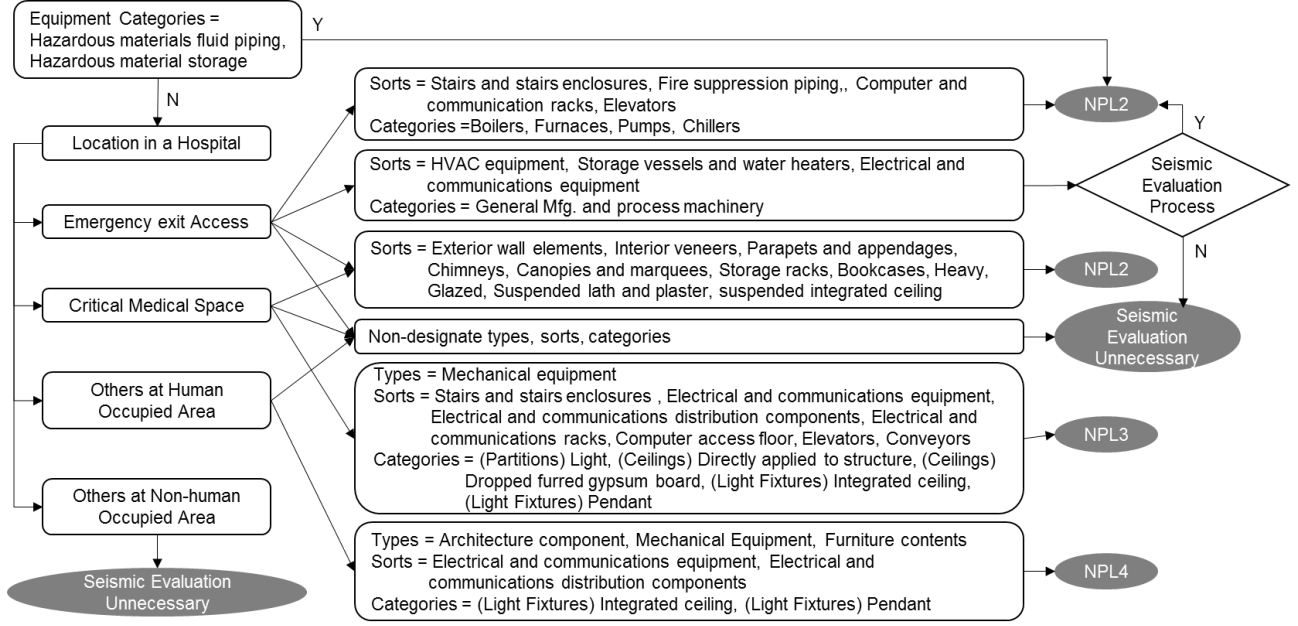


Figure 8: Process to determine performance level.

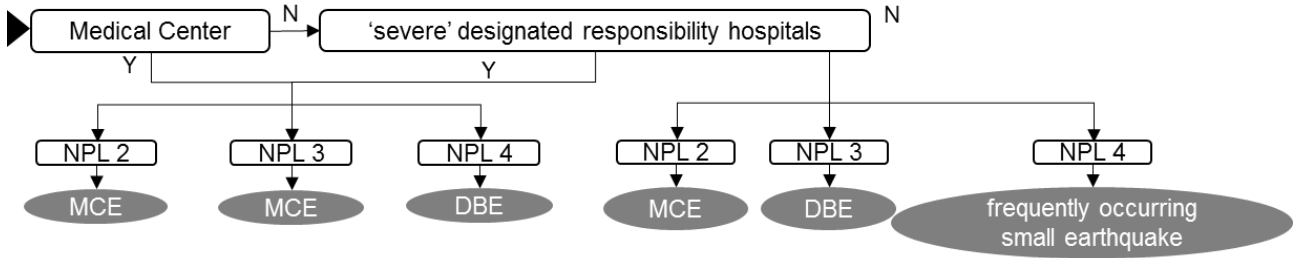


Figure 9: Process to determine earthquake hazard level.

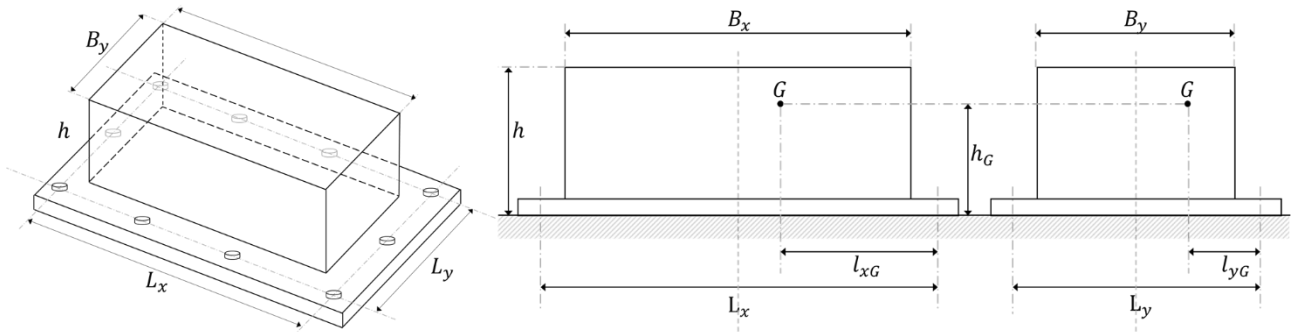


Figure 10: Notes for rigid rectangular equipment.

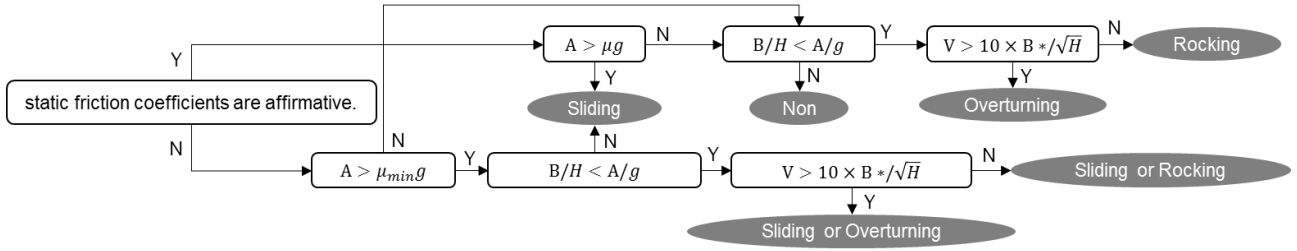


Figure 11: Process to determine seismic response.

Modification Coefficients for Real Equipment

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

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

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

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

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

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

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

where T_{QX} , T_{QY} , and T_{QZ} are the tension demands caused by a seismic force F_{ph} in the x- and y-directions (Eq.11 to Eq.13), and F_{pv} in the z-direction, respectively and they are defined by:

$$T_{QX} = \frac{F_{ph} \times h_G}{L_x \times n_y} \quad (11)$$

$$T_{QY} = \frac{F_{ph} \times h_G}{L_y \times n_x} \quad (12)$$

$$T_{QZ} = F_{ph} \times \max \left(\frac{\max(l_{xG}, L_x - l_{xG})}{L_x \times n_y}, \frac{\max(l_{yG}, L_y - l_{yG})}{L_y \times n_x} \right) \quad (13)$$

where n is the total number of bolts, and n_x and n_y are the number of bolts located on one side along the x- and y-directions, respectively. It is noted that the loading combination 0.9D+1E is adopted to determine the tension demand for an anchor bolt. In addition, the 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.

Coefficients for Modification

In order to determine the modification coefficients ϕ_{TW} , ϕ_{TE} , and ϕ_{VE} , the finite element software SAP2000 was adopted to determine the reaction forces at the supporting points of real equipment. As shown in Figure 12, the model prototype was a cube constructed of beam elements. Seismic force was applied to each joint according to the mass distribution. The parameters included aspect ratio, bolt-installation location and eccentricity. Since the parameters affect each other, all parameters should be considered simultaneously to calculate the results. In this study, only some conditions in each parameter were selected for analysis. For example, the aspect ratio 1:10 was considered as a critical situation. To be conservative, the meaning of "eccentricity" was simulated in $l_G/(L - l_G) = 1/3$ as a critical situation. Three eccentric conditions were identified: None, Single-axis and Double-axes. Figure 13 shows variables along the x- and the y-axes in the Single-axis eccentric condition, where the x-axis is the aspect ratio, y-axis is bolt-installed in different distribution (numbers and side).

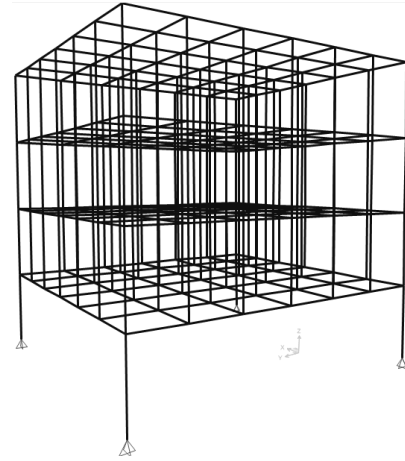


Figure 12: The prototype for analysis in SAP2000.

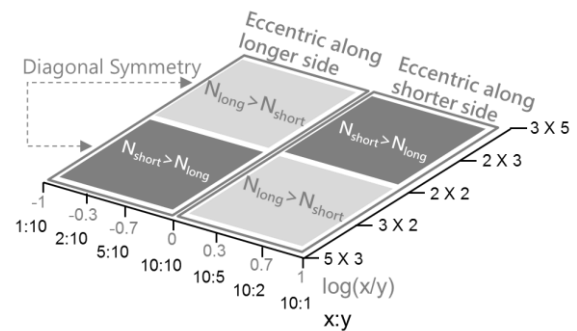


Figure 13: A coordinate system for different parameters.

Table 4: Values of modification coefficients ϕ_{TW}

ϕ_{TW}	Eccentricity - none	Eccentricity – in single x- or y- axis		Eccentricity - in both x- and y- axes	
$n_x < n_y$		$\text{Log}(x/y) \leq 0$	$0 < \text{Log}(x/y)$	$\text{Log}(x/y) \leq 0.3$	$0.3 < \text{Log}(x/y)$
	0.5	0.2	-0.1	-0.2	-0.5
$n_x = n_y$	1.0	1.0		0.3	
$n_x > n_y$		$\text{Log}(x/y) \leq 0.3$	$0.3 < \text{Log}(x/y)$	$\text{Log}(x/y) < -0.3$	$-0.3 \leq \text{Log}(x/y)$
	0.5	0.4	0.1	-0.5	-0.2

Table 5: Values of modification coefficients ϕ_{TE}

ϕ_{TE}	Eccentricity - none	Eccentricity – in single x- or y- axis		Eccentricity - in both x- and y- axes	
$n_x < n_y$	1.0	$\log(x/y) < -0.3$	$-0.3 \leq \log(x/y)$	$\log(x/y) < -0.3$	$-0.3 \leq \log(x/y)$
		1.4	1.0	1.5	1.3
$n_x = n_y$		1.2		1.3	
$n_x > n_y$		$\log(x/y) < -0.3$	$-0.3 \leq \log(x/y)$	$\log(x/y) \leq 0.3$	$0.3 < \log(x/y)$
		1.3	1.0	1.3	1.5

Table 6: Values of modification coefficients ϕ_{VE}

ϕ_{VE}	Eccentricity - none		Eccentricity – in single x- or y- axis		Eccentricity - in both x- and y- axes	
$n_x < n_y$	$\text{Log}(x/y) \leq 0$	$0 < \text{Log}(x/y)$	$\log(x/y) < 0.3$	$0.3 \leq \text{Log}(x/y)$	$\log(x/y) < 0$	$0 \leq \log(x/y)$
	1.1	1.4	1.9	1.4	2.0	1.7
$n_x = n_y$	1.0		1.5		1.5	
$n_x > n_y$	$\text{Log}(x/y) < 0$	$0 \leq \text{Log}(x/y)$	$\log(x/y) < 0.3$	$0.3 \leq \text{Log}(x/y)$	$\log(x/y) \leq 0$	$0 < \log(x/y)$
	1.4	1.1	1.6	1.1	1.7	2.0

The equipment is modelled by a frame-type structure with multi-supports. For a piece of equipment with a specific aspect ratio, eccentricity and distribution of anchor bolts, the tension forces caused by dead load and seismic load exerted on each bolt can be determined. Then, the most critical seismic demands of the bolt can be 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. As shown in Tables 4 to 6 and based on the scenario involving equipment with different aspect ratios, the eccentricity, distribution of anchor bolts and the modification coefficients ϕ_{TW} , ϕ_{TE} , and ϕ_{VE} can be determined statistically. The most critical demand for a bolt can then be determined by Eq. 6 and Eq. 7.

The tables of the values of the modification coefficients ϕ_{TW} , ϕ_{TE} , and ϕ_{VE} have been well defined already in the proposed evaluation and design programme. The programme can automatically determine the values of modification coefficients and the most critical demand on a bolt from the parameters as filled in by users in the ‘equipment’ spreadsheet (Figure 6).

Acceptance Criteria for Anchor Bolts

In this study, the seismic design of the anchorage in concrete was in compliance with Appendix D of the ACI 318 code [2]. The acceptance criteria is defined by:

$$\left(\frac{T_{ua}}{\phi T_n}\right)^{1.5} + \left(\frac{V_{ua}}{\phi V_n}\right)^{1.5} \leq 1.0 \quad (13)$$

The capacity of anchor bolts ϕT_n and ϕV_n is evaluated in the ‘anchor bolt’ spreadsheet, and the tension and shear demands, T_{ua} and V_{ua} respectively, are calculated by Eq. 6 and Eq. 7. For those satisfying Eq. 13, the blank ‘Result’ in Figure 3 replies ‘OK’, otherwise it replies ‘NO!!’. For those not satisfying the acceptance criteria, users should modify the design of the

anchor bolt (e.g., bolt diameter, embedded length, etc.) such that the ‘Result’ returns ‘OK’, or else other seismic restraint devices will be recommended.

CONCLUSIONS

In order to facilitate the issuing of governmental policies 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” [1] was organized by the National Center for Research on Earthquake Engineering (NCREE). The seismic rehabilitation objectives of nonstructural components and systems in a hospital and associated evaluation criteria were defined and introduced in this paper. The evaluation process proposed in the guideline may be more complex than the common evaluation; however, a Microsoft Excel programme was established with which users can execute the seismic evaluation and retrofit design for individual items of medical equipment more easily and conveniently. More studies are underway, including the development of a seismic evaluation and design programme for equipment attached to a wall or ceiling and for those strengthened by z-shape stoppers or welding.

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