LOSS ANALYSIS OF MEDICAL FUNCTIONALITY DUE TO HOSPITAL'S EARTHQUAKE-INDUCED DAMAGES

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ABSTRACT :

In recent years the concept of Performance-based design and assessment requires the performance targets being expressed in a more direct way so that users can understand the seismic risk easily. For a hospital, medical functionality (MF) is the most concerned performance target after an earthquake. This study focuses on the loss analysis of MF due to damages of nonstructural components (NSCs). First, damage levels of MF are defined into four levels from the viewpoint of casualty triage. Then, the impacts on loss of medical functionality by damages of NSCs are investigated based on a questionnaire survey on the 2004 Mid Niigata prefecture earthquake, Japan. Furthermore, a supplementary questionnaire survey is conducted to assess the influence of clutter by using the AHP method, which is a conventional method for analyzing decision- making problems. The results of loss analysis in this study can be connected to seismic fragilities of critical NSCs, so that given a seismic intensity, such as PGA, the performance of post-earthquake medical functionality can be provided to hospitals and concerned authorities.

KEYWORDS: hospital, performance-based assessment, medical functionality, nonstructure

1. INTRODUCTION

In the field of earthquake engineering, conventionally the performance targets of a building are expressed in engineering parameters, such as interstory drift angle. In recent years the concept of Performance-based design and assessment furthermore requires the performance targets being expressed in terms of 3D: dollars, deaths, and downtime, so that users can understand the seismic risk easily. For a hospital responsible for emergency medical service, medical functionality (MF) is the most concerned performance target after an earthquake. As earthquake damage experience of hospitals indicates that building structures generally could sustain sever excitations but medical service is still stopped or reduced due to damages of nonstructural components (NSCs), such as falling ceiling panels and stop of water supply. Therefore, this study focuses on the loss analysis of MF due to damages of critical NSCs. The results of the proposed loss analysis in this study can be connected to seismic fragilities of NSCs, so that given a seismic intensity, such as PGA, the performance of post-earthquake medical functionality can be provided to hospitals and concerned authorities.

2. DEFINITIONS OF DAMAGE LEVELS FOR MEDICAL FUNCTIONALITIES AND RELATED NONSTRUCTURAL DAMAGES

2.1. Damage Levels of Medical Functionalities

How to express the damage levels of medical functionality is a problem. Although many seismic damage surveys on hospitals have been conducted [William et al. 1994, Nakayama et al. 1996], loss of medical functionality was not described in a systematic way yet. The medical functionality discussed in this study focuses on the emergency medical service after an earthquake. When a great earthquake occurs, hospitals encounter an unusual situation that lots of injuries come to the hospital in a short time. With limited medical staffs, to take care of the great amount of injuries and to deliver medical service with the best efficiency, disaster medicine that deals with the problems of massive casualties in a short period due to a disastrous event such as fire and terror attack has a critical concept: triage. Triage of casualties by the severity of injury is adopted as a necessary measure. Following the concept of triage, in this study medical functionalities are defined into four levels: (1) Surgery operation, (2) Treatment of severe trauma, (3) Treatment of moderate trauma, and (4) Treatment of mild trauma. Figure 1 shows a tag for casualty triage, in which the defined MF damage levels 1 and 2 correspond to the priority I, level 3 to priority II and levels 4 to priority III while the priority 0 represents the patient is death of arrival. This definition method provides a practical approach for discussing post-earthquake medical functionality more specifically.

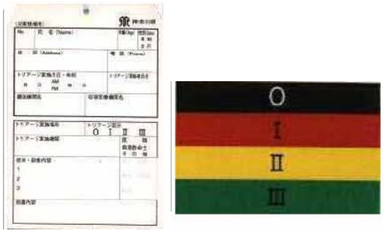

Figure 1 Tag for casualty triage in disaster medicine

2.2. Damage Levels of Nonstructural Components Inducing Medical Functionality Damage

Three types of critical NSC damage are considered in the questionnaire: (1) Falling ceiling panels is safety type; (2) Loss of water or power supply is functional type; (3) Clutter situation is obstacle type. Falling ceiling panels in medical rooms may enforce to stop of operation for safety concerns; loss of water and power supply resulting from lifeline stop and damaged internal backup systems makes medical instruments inoperable; clutter situations in critical medical rooms could disrupt the related medical services.

In the questionnaire for the survey introduced in Chapter 3, the damage of falling ceiling panels is defined into four levels: no, partial, half falling, and falling of almost all ceiling panels. For loss of water or power supply, the situations of supply by lifeline and internal backup systems are inquired, respectively. For clutter situations, they are divided into five levels: no, partial, half, complete clutter, and complete clutter with piled up objects. The five levels represent about 0, 20, 50, 80% clutter floor area, and more than 80% clutter floor area with piled up objects, respectively. Totally eight critical medical rooms are investigated: laboratory, emergency room, radiology room, operating room, central supply room, dialysis room, pharmacy, and ICU unit. The clutter levels in these medical rooms are not necessarily the same. Under the assumption that each of these medical rooms is required for emergency medical service, the most serious situation is adopted to represent the clutter level of the entire critical medical rooms.

3. QUESTIONNAIRE SURVEY ON THE 2004 MID NIIGATA PREFECTURE EARTHQUAKE

3.1. Outline of Questionnaire Survey

The questionnaire survey was conducted on hospitals for the 2004 Mid Niigata prefecture earthquake. The earthquake induced strong ground motion up to the JMA (Japan Meteorological Agency) seismic intensity 7, which is as large as that recorded in the 1995 Hanshin-Awaji (Kobe) earthquake. For most of the observed motions, the predominant period was as short as 0.5 second or less, thus the cases of severe structural damage were few although the values of seismic intensity and acceleration were large. A total of 140 questionnaire sheets were sent according to a list of hospitals provided by the Bureau of hospital administration of Niigata prefecture. Although 50%, about 70 hospitals, of the questionnaires were responded, only 29 of them had operating rooms. Finally, 28 hospitals that suffered structural damage less than moderate level are used in the following analyses.

The questionnaire consists of three parts. The first part questions, answered by engineering and administrative personnel, are about structural damage and water and power supply. The second part questions, answered by medical staffs, are about maintainable medical functionality, falling ceiling panels, clutter levels, and malfunction of medical instruments. In the third part, medical staffs are asked to make decisions on the maintainable medical functionality in a "future" earthquake event under the impact of damages of NSCs.

3.2. Survey Results of Relationship Between Medical Functionality Damages and Nonstructural Damages

Among the selected 28 hospitals, ceiling panels with damage level of partial falling were observed in only three hospitals and did not cause an evacuation of the room for safety concerns. Accordingly, this study focuses on the impacts of functional and obstacle type damages, and groups the data into four categories as shown in Table 3.1. However, in this survey no hospitals suffered the loss of water and power supply because all the hospitals that experienced lifeline stop switched immediately to their internal backup systems until the lifeline restoration. Hence, the damage of water and power supplies are classified based on supply by lifeline or by internal backup systems. This alternative classification method can investigate the influence of water and power supply by internal backup systems. As for clutter situations, to ensure an adequate number of samples in the category, the damages are divided from the level of complete clutter. This is based on medical experts' opinions that a medical room is difficult to use in this situation after an earthquake.

Table 3.1 Classification of surveyed hospitals by lifeline supply situation and clutter levels

	L_0	L_1
C_0	18	5
C_1	0	5

(L_0: lifeline OK, L_1: lifeline stopped but supply by internal backup systems,
C_0: clutter level < complete, C_1: clutter level ≥ complete)

The survey results of the damage levels of medical functionality influenced by damages of NSCs are shown in Figures 2~5. In the figures, the abscissa denotes the levels of medical functionality, as indicated in Table 3.2, and the ordinate is the probability of maintaining a certain level medical functionality. Discussions on the relationships between medical functionality and nonstructural damages are as below.

(1) Figure 2 shows the results of category L_0C_0 and L_1C_0 to compare the influence of water and power supply by lifeline and internal backup systems. Under normal operation of backup systems, the probabilities of maintaining surgery operation (MF1) and treatment of severe trauma (MF2) are as high as 0.8, and no large reduction of medical functionality is observed.
(2) In Figure 3, the staffs' decision results for a future earthquake are adopted to show the influence of loss of water and power supply. The figure shows that loss of water and power supplies have approximate impacts on medical functionality, and surgery operation (MF1) and treatment of severe trauma (MF2) are disabled under loss of water or power supply. It is because operation of medical instruments is necessary for higher-level medical services, and the operation of medical instruments is interrupted or extremely reduced under loss of water and power supply.
(3) Comparisons of influence due to different clutter levels (Figure 4) are based on the data of category L_1C_0 and L_1C_1 because no data are grouped into the category L_0C_1. Meanwhile, since no large reduction of medical functionality is observed in the category of L_1C_0, as introduced in Figure 2, it is assumed that the differences in medical functionality of L_1C_1 and L_1C_0 categories mainly result from clutter. It is observed that medical functionality reduces drastically at the clutter level greater or equal to complete. The probabilities of maintaining surgery operation (MF1) and treatment of severe and moderate trauma (MF2, 3) reduce to 0.2, 0.4, and 0.6, respectively. It is because higher-level medical services depend much on normal operation of critical medical rooms, and serious clutter hindering medical rooms results in loss of those services. In the figure the results of medical staffs' decision for a future earthquake are also shown. However, the decision results are extremely conservative compared with the survey results, especially for the higher-level medical services. The large discrepancy is considered to result from small sample number and inquiring method. In the next chapter, a supplementary survey using a conventional method for decision-making problems is conducted to analyze medical staffs' decisions under different clutter levels.

Table 3.2 Abbreviations of medical functionalities

Level	Description
MF1	Surgery operation OK
MF2	Treatment of severe trauma OK
MF3	Treatment of moderate trauma OK
MF4	Treatment of mild trauma OK

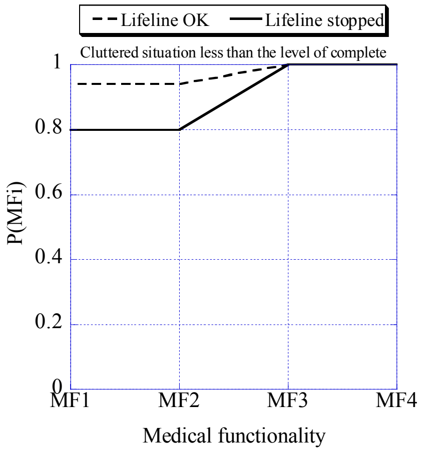

Figure 2 Influence of water and power supply by lifeline and internal backup systems

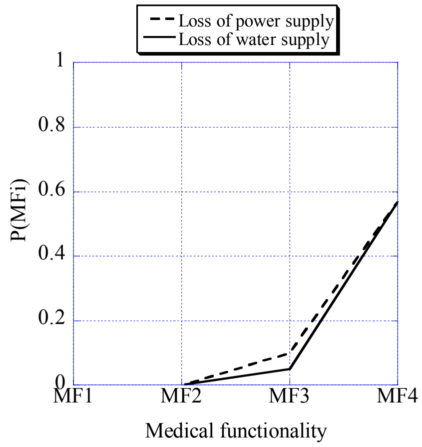

Figure 3 Influence of loss of water and power supply based on staff's decisions

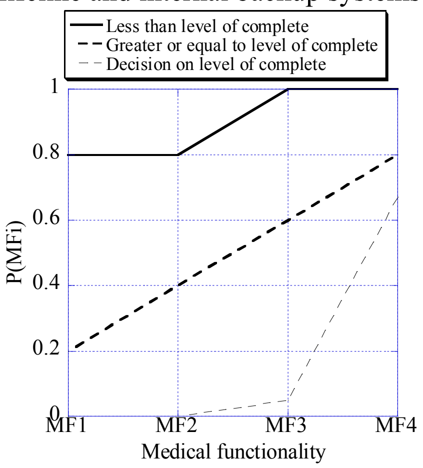

Figure 4 Influence of clutter level based on survey results and staff's decisions

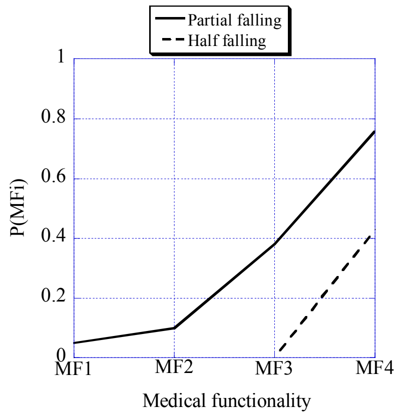

Figure 5 Influence of falling ceiling panels based on staff's decisions

(4) In Figure 5, the staffs' decision results for a future earthquake are adopted to show the influence of falling ceiling panels. It is observed that at the level of partial falling, the higher-level medical services are extremely reduced, as the probabilities of maintaining surgery operation and treatment of severe trauma are less than 0.1. It is because higher-level medical services depend much on normal operation of medical rooms, and once falling ceiling panels occur, operation of the rooms is generally stopped for safety concerns.

From the aforementioned survey results, it is found that the influence of loss of water and power supply is absolute for higher-level medical functionality, which means the probability of maintaining surgery operation and treatment of severe trauma is reduced to zero (Figure 3), as medical instruments are inoperable without water or power. The influence of falling ceiling panels is also approximately absolute on surgery operation and treatment of severe trauma (Figure 5), as operation of medical rooms is enforced to stop due to the safety concern. On the other hand, the influence of clutter is not absolute, which means the probability of maintaining the medical services is not reduced to zero (Figure 4). It is because under the clutter situations, whether to terminate operation of the medical room is judged by medical staffs. In this chapter's analysis, clutter levels are divided into only two groups by the complete level. In the next chapter, to investigate the influence of different clutter levels, a supplementary survey is conducted to investigate medical staffs' judgments using a conventional analysis method for decision-making problems.

4. INFLUENCE OF INTERIOR CLUTTER ON CONTINUOUS OPERATION OF MEDICAL ROOMS

When encountering clutter situations after an earthquake, medical staffs judge whether to terminate or continue operation of the room synthetically, based on their professional experiences and the limit of manpower and time to deal with the situation. A supplementary questionnaire survey is conducted on medical staffs, and their judgments are analyzed using the Analytic Hierarchy Process (AHP) method, which is a conventional method for analyzing decision- making problem [Saaty 1996].

4.1. Outline of Questionnaire Survey

The questionnaire sheets were posted to six hospitals responsible for emergency medical service. A total of 42 sheets were responded from four hospitals. In the questionnaire sheet, four clutter levels are defined as introduced in 2.2: partial, half, complete clutter, and complete clutter with piled up objects. A predominant characteristic of this survey is that the clutter situations are demonstrated with real photos taken in the past earthquakes (Figure 6), instead of literal descriptions. Therefore, the damage situation is expressed more precisely and the judgments of medical staffs can be more reliable. The photos used here show the clutter occurring in pharmacies and laboratories. In the sheet, the terms of clutter levels are replaced by A~D, respectively, to avoid the influence of literal descriptions. Medical staffs are asked to compare the influence of two clutter levels on the operation of medical room by each question, hence a total of six questions are listed in the questionnaire sheet. Figure 7 shows an example of the responded questionnaire sheet.

In comparison of influence of two clutter levels, a 7-rank scale is adopted (Figure 7). The judgments of "absolute larger influence", "considerably larger influence", "somewhat larger influence", and "equal influence" are represented by values of 7, 5, 3, and 1 in the following analyses. While these values are not shown to the medical staffs in the questionnaire sheet.

4.2. Analysis results of clutter levels on continuous operation of medical rooms

In the analysis using the AHP method, first a pairwise comparison matrix is constructed for each responded questionnaire. The dimension of the matrix is 4×4 because four clutter levels are defined. In the matrix, the element of *i*th row and *j*th column represents the comparison between level *i* and level *j*. Hence, the diagonal elements are 1. Table 4.1 demonstrates the construction of pairwise comparison matrix for the example shown in Figure 7. The judgment is that the influence of clutter level of complete (represented by C) is considerably larger than that of level of partial (represented by A), so that the element denoting C to A (row C, column A) is 5, and the element denoting A to C (row A, column C) is 1/5, reciprocal of 5. Next, the largest eigenvalue λ_{max} of the matrix is calculated, and the consistency of the respondent's judgment is verified using the consistency index (*C.I.*) calculated by Eqn. 4.1 [Tone 1986].

$$C.I. = \frac{\lambda_{max} - n}{n-1}, \quad n\text{: the number of total eigenvalues} \qquad (4.1)$$

(a) Partial clutter (c) Complete clutter

(b) Half clutter (d) Complete clutter with piled up objects

Figure 6 Photos of clutter levels shown in the questionnaire sheet

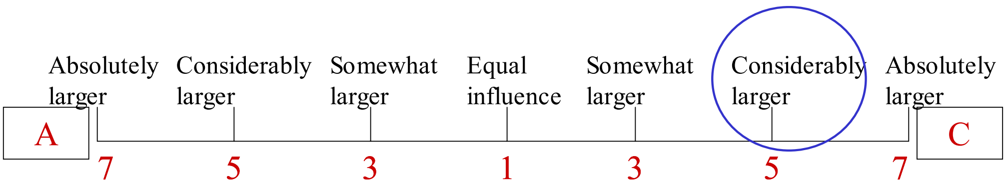

Figure 7 Example of the responded questionnaire sheet

Table 4.1 Construction of pairwise comparison matrix

	A	B	C	D
A	1	k_{12}	1/5	k_{14}
B	$1/k_{12}$	1	k_{23}	k_{24}
C	5	$1/k_{23}$	1	k_{34}
D	$1/k_{14}$	$1/k_{24}$	$1/k_{34}$	1

The index *C.I.* represents the consistency of the judgments, and the value less than 0.2, which means good consistency, is required [Tone 1986]. As a result, totally 31 matrices with *C.I.* less than 0.2 are adopted in the following analyses. Then, to obtain the pairwise comparison matrix representing general judgments, the elements k_{ij} of the matrix are calculated as the geometric average of the corresponding elements $k_{ij}^{(p)}$ in the 31 matrices (Eqn. 4.2).

$$k_{ij} = \sqrt[m]{\prod_{p=1}^{m} k_{ij}^{(p)}} \quad , \ m\text{: the number of matrices with } C.I. \text{ less than } 0.2 \qquad (4.2)$$

Finally, by calculating the eigenvector of the largest eigenvalue for the matrix representing general judgments, the weight of influence is obtained from each element of the eigenvector. For clutter levels of partial, half, complete clutter, and complete clutter with piled up objects, the obtained weights of influence are 0.06, 0.12, 0.26, and 0.57, respectively (the left side ordinate of Figure 8). It is observed that the weight of influence is about double that of the previous clutter level. The weights of influence obtained from the elements of eigenvector represent relative values. However, absolute values that indicate probabilities of maintaining or stopping use of medical rooms are required in the loss evaluation. At the clutter level of complete with piled up objects, it is reasonable to set the probability of operation stop as 1, which means under the situation operation of the room stops absolutely. Suppose the probability of operation stop at the clutter level is proportional to the weight of influence, so that for the clutter levels of partial, half, and complete clutter, the probabilities of operation stop are 0.1, 0.21, and 0.45, respectively (the right side ordinate of Figure 8).

Furthermore, Figure 9 shows the results of different professional staffs' judgments. The results of pharmacists and laboratory technicians are similar and close to the average result. In contrast, the results of doctors and nurses are higher, 0.35 and 0.69 at the clutter level of half and complete, respectively. The judgments by doctors and nurses are more conservative. Therefore, operating room and emergency room, where the doctors and nurses work in, have a higher probability of operation stop compared with pharmacy, laboratory and radiology room, where pharmacists and laboratory technicians work in.

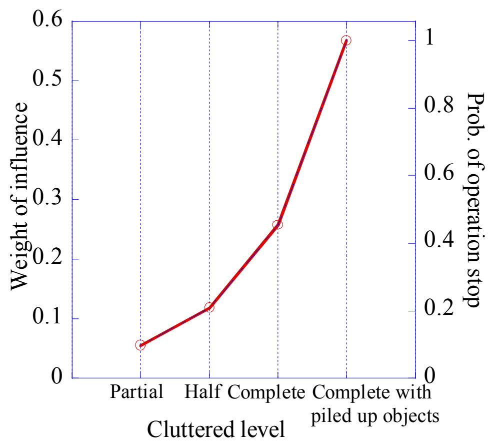

Figure 8 Weight of influence and probability of operation stop at different clutter levels

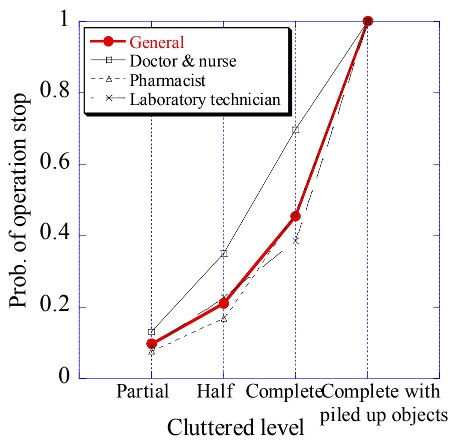

Figure 9 Comparison of probability of operation stop by different medical professions

These analysis results are compared with the survey results introduced in Chapter 3. Based on medical staff's general judgments, at the clutter level of complete the probability of terminating operation of the room is 0.45, i.e. probability of 0.55 to maintain the operation. As described in Chapter 3, the operation stop of critical medical rooms interrupts higher-level medical services. In the survey results, at the clutter level of complete, the probability to maintain treatment of moderate trauma, representing the threshold of higher-level medical services, is 0.6. Therefore, a well agreement is observed between the analysis and survey results. Next, operating and emergency rooms are the medical rooms highly related to surgery operation (MF1) and treatment of severe trauma (MF2), hence, the analysis results of doctors and nurses are compared with the probability of maintaining MF1 and MF2 in the survey results. In the analysis results of doctors and nurses' judgments, at the clutter level of complete the probability of terminating operation of the room is 0.69, i.e. probability of 0.31 for maintaining the operation. In the survey results, at the clutter level of complete, the probabilities for maintaining surgery operation and treatment of severe trauma are 0.2 and 0.4, respectively. Thus, the analysis results also show a satisfactory agreement with the survey results.

The influences of nonstructural damages on medical functionality are expressed in influence factors in Table 4.2, based on the survey and the analysis results: ceiling panels with damage of partial falling for safety type (Figure 5), loss of water and power supply for functional type (Figure 3) and clutter situations for obstacle type

(Figure 9). The terms of I_S, I_F, and I_C represent, respectively, the influence factors of the safety, functional types, and clutter situations, which are obstacle type.

Table 4.2 Medical functionality influence factors of different types of damages of nonstructural components

Influence factor	I_S	I_F
Stop of surgery operation and treatment of severe trauma	1.0	1.0
Stop of treatment of moderate trauma	0.6	1.0

I_C

Cluttered ratio	20%	50%	80%	≥80%
Stop of surgery operation and treatment of severe trauma	0.13	0.35	0.69	1.0
Stop of treatment of moderate trauma	0.10	0.21	0.45	1.0

5. CONCLUSIONS

This study focuses on the loss analysis of medical functionality due to damages of nonstructural components. Damage levels of medical functionality are first defined into four levels from the viewpoint of casualty triage. Then, the impacts on loss of medical functionality by nonstructural damages are investigated based on a questionnaire survey on the 2004 Mid Niigata prefecture earthquake, Japan. Furthermore, a supplementary questionnaire survey is conducted to assess the influence of clutter levels by using the AHP method. The major conclusions are summarized as follows:
(1) Loss of water and power supply absolutely interrupts higher-level medical functionalities, including surgery operation and treatment of severe trauma.
(2) Falling ceiling panels, even at the level of partial, disable surgery operation and treatment of severe trauma.
(3) For the clutter level of complete, the analysis results of medical staff's judgments show well agreement with the survey results of higher-level medical functionalities.

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