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Case Study: Rapid Seismic Assessment of Existing Hospitals in Karachi †

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Abstract: Hospitals are considered to be safe havens as they have to remain functional during an earthquake or any other natural calamity. However, in past, the performance of the hospitals in high seismic regions is seen to be poor, raising the intensity of life lost in such calamities. To prevent disruption in functionality or any damage to the infrastructure of the hospital, it is mandatory to perform pre and post-earthquake assessments and evaluate the integrity of structural as well as functional aspects of the hospital. This research paper outlines a modified Rapid Visual Screening (RVS) procedure with FE analytical method similar to ASCE41-17. The developed procedure is a three-tier process that is tested on three major hospital buildings in the city of Karachi, a metropolitan city known as the financial hub of Pakistan. The developed procedure begins with the RVS process that considers the structural elements and their vulnerability either at full structure or at the element level. This process then further combines with the evaluation of Demand-Capacity Ratios (DCR) for the entire structure to obtain a physical model with the vulnerabilities that need further non-linear evaluation or physical interventions are developed.

Keywords: seismic evaluation; hospitals; Rapid Visual Screening (RVS); Finite Element Analysis; Disaster Prevention

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1. Introduction

It is widely accepted that hospitals and other health facilities should be prepared to deal with any crisis as masses tend to rush to these facilities in wake of disasters. Generally, this is true, but some events in the past have demonstrated that the behavior of hospital buildings is like any other and is subject to damage and collapse, in such a case a hospital would not be able to function in a most critical situation. Hospitals have been observed to have performed poorly in wake of earthquakes as accounted by Jain et al. [1]. Similarly, During the devastating earthquake dated 8 October 2005 shocked Pakistan's Northern area with a magnitude of Mw = 7.6 in the early morning, affecting an area of approximately 30,000 km^2. The destruction that was observed in an aftermath of the Earthquake was extensive [2]

According to the EERI reconnaissance report around 574 medical facilities were either affected partially or fully put out of commission which constitutes 70% of facilities in the area [2]. Among the hospitals affected were hospitals Combined Military Hospital (CMH) Muzaffarabad which completely collapsed shown in Figure 1 and another hospital Ayub Medical College in Abbottabad which was evaluated incorrectly, nonstructural damage was categorized as structural damage, and patients were put in the front yard. This disrupted the operations of the hospitals significantly in a critical situation this was caused due to the fact there was no post-seismic evaluation technique present at the time [3].

(**a**) (**b**)

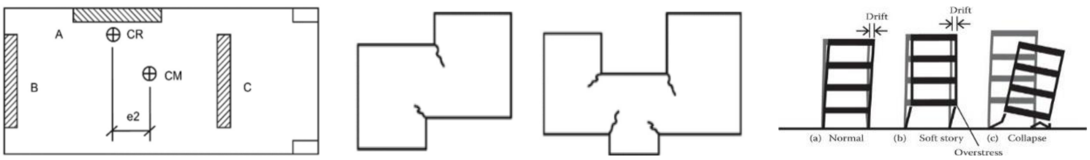
Figure 1. Damage to Combined Military Hospital (CMH) in Muzaffarabad (**a**) Front View (**b**) Back View [3].

Karachi plays a significant role in Pakistan's economy, as it constitutes around 20% of Pakistan's economy and industrial sector contributions are around 30% of the whole of Pakistan. 95% of Pakistan's international trade is handled by the two ports located in Karachi i.e., Karachi Port and Port Qasim [4].

Karachi is located Southwest of Pakistan and is vulnerable to both Earthquakes and tsunamis. Bilham et al. have presented the historical data of the earthquakes as well as a potential overview of earthquake sources near Karachi. Bilham et al. indicated that there are four major faults near Karachi and several destructive Earthquakes and tsunamis have occurred in the past. Despite that, a more troubling conclusion was made by Bilham et al. that Karachi's seismic hazard is much like Los Angles, in addition to that the only difference that makes conditions even extreme is the proximity to the subduction zones which are not present in Los Angeles [5].

When it comes to providing healthcare there is a shortage of health facilities for the rapidly increasing population of Karachi. Currently, there are only 33 hospitals, 271 health centers, and 152 dispensaries. It is estimated to be around 15,000 beds, among which 9000 are tertiary and teaching hospitals apart from those around 6000 are present in secondary and primary care facilities. If we calculate the ratio of beds to people it comes out to be 1 to 1700 in the tertiary category of health facilities and 1 to 1020 for all other public health facilities. Apart from the public sector, it can be estimated that there are 6600 beds in the private sector distributed over a total of 356 large and small hospitals [6].

Based on the above sentiments, the current state of the health care system located in Karachi is already deficient; therefore, it becomes imperative to conduct the Rapid Seismic Assessment of hospitals in the Karachi region. Otherwise, if not taken into account it could have disastrous outcome if the health care system collapse during a strong event of an earthquake. This study particularly focuses on the structural assessment of health care facilities. Identification of structural irregularity such as plan, vertical, torsional, etc shown in Figure 2.



(**a**) (**b**) (**c**)

Figure 2. Plan and Vertical Irregularities. (**a**) Torsional Irregularity [7] (**b**) Re-entrant Corner [7] (**c**) Soft Story [8].

2. Methodology

The seismic evaluation of hospitals is an extensive process as compared to other buildings as a building may be of the same dimension as a hospital but the number of components in a hospital is very intricate as compared to residential or commercial facilities. Therefore, hospitals need to be accessed accordingly. Furthermore, the hospital must remain in a functional state structurally as well as based on functionality. The components that are not structural are termed as non-structural components and play an equivalent role. These non-structural components are great hazards inside and in the surrounding of the facility as falling objects and equipment can cause injuries, deaths, functional hindrance, and economic loss for the health facility. In various cases, hospitals have been not able to function properly even after a week of the event.

Various methods exist to assess medical facilities but they differ from one another in the expense, precision, and level of complexity that is observed in performing the assessment. The proven techniques are ASCE 41 [7], FEMA P-154 [9], ATC-40 [10], WHO [11], and PAHO [12], which not only provide the desired earthquake resistance but also reduce the cost incurred in terms of life and monetary factors following an Earthquake. The seismic assessment is performed in a systematic procedure the structure is assessed in four stages. The four stages in the assessment are presented in Figure 3.

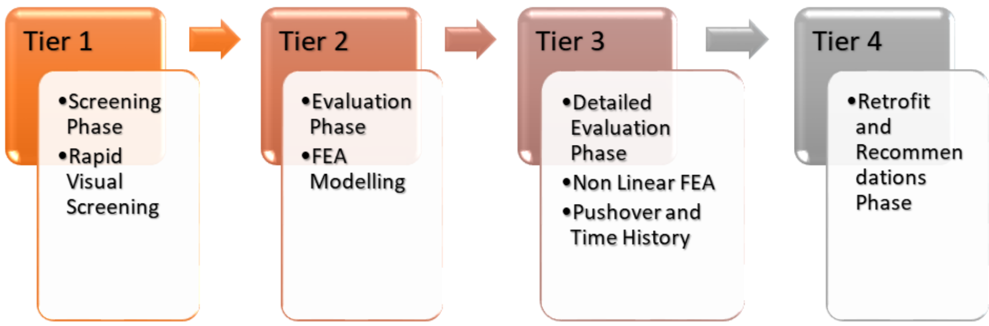


Figure 3. Seismic Evaluation Procedure.

This study is limited to Tier 1 and Tier 2 phases. A modified approach to the tier-1 RVS procedure was applied to the structures. The procedure was made incorporating ASCE-41 [7], FEMA-154 [9], ATC-40 [10], WHO [11], WHO/EURO [13], and Nepal Guidelines [14] and was then modified for Pakistan.

3. Case Study Buildings

3.1. General Features

The general features of the three selected hospital buildings presented in this study are given below in Table 1. The structural systems of buildings 1 and 2 are concrete framed systems consisting of concrete slabs, beams, columns, shear walls, and foundation, while the third building consists of a concrete flat slab with edge beams supported by RC shear walls and columns. The raft-type foundation is provided as a foundation for all the structures.

Table 1. General Features.

	Building # 1	Building # 2	Building # 3
Year of Construction	2020	2004	2019
# of Stories	08	08	16
Basement	01	01	02
Area	4762.95 m^2	1038.19 m^2	3467.85 m^2
Typical Story Height	4.2672 m	3.5676 m	4 m
Total Height	32.6136 m	30.1752 m	77.62 m

3.2. Material Properties

The design compressive strengths for the buildings selected are presented below in Table 2. The strengths of building 2 and 3 are based on actual data. While the strengths of building 3 are taken as general construction practice. The yield strength of the steel rebar is 60 ksi for all the buildings.

Table 2. Design Compressive Strength.

	Building # 1	Building # 2	Building # 3
	MPa	MPa	MPa
Beams	25.85	22.75	27.58
Slabs	25.85	22.75	27.58
Columns	32.578	27.58	27.58
Shear Walls	32.578	27.58	27.58
Foundation	32.578	27.58	27.58

3.3. Site and Hazard Information

All the buildings are located in Karachi, having dense soil or soft rock. The site class "D" is selected for all three buildings from the VS30 map [15]. The seismic assessments of the buildings are carried out considering the buildings are found to be in the moderate seismic zone (zone 2B for Karachi as mentioned in the seismic zoning map of Pakistan for Karachi). Soil type Sd (stiff soil) is used and seismic coefficients were taken as Ca = 0.24 and Cv = 0.32 from UBC-97 [16].

3.4. Loading and Performance Criteria

The dead load of the buildings consists of the self-weight including 3in thick finishes as well as an additional load for the infill masonry which was taken as 36 psf superimposed dead load and any other superimposed load according to the architectural plans. Live load is taken as 100 psf for the buildings. The buildings are evaluated as a concrete moment frame. Considering the occupancy use of the building, the seismic assessment exercise performed for the immediate occupancy (IO) performance level as one of the limit states reported in ASCE-41 [7] corresponding to a 475 years recurrence interval of an earthquake.

3.5. Tier-1 Analysis

The buildings that were assessed for the tier-01 analysis using the ASCE 41-17 [7]. Various parameters modified for Pakistan's condition are also incorporated in the tier-01 analysis. The assessment performed indicates several non-compliant items found in the structures in the Tier-01 category.

Tables 3 and 4 show various results of the Tier 1 analysis that are non-compliant, which would further be investigated. The visual inspection suggests that there is a significant chance of damage occurring in building 1 as the number of irregularities found non-complaint is more than the buildings 2 and 3.

Table 3. Tier-01 Rapid Visual Screening Horizontal Irregularities.

Horizontal Irregularity	Building 1	Building 2	Building 3
Plan Irregularity	NC	NC	C
Re-entrant Corner	C	NC	C
Non-Parallel System	C	C	C
Out-of-Plane Offset	NC	NC	C
Torsion Irregularity	NC	NC	C
Slab Opening (Greater than 50% of Slab)	C	C	C
Presence of Cantilever	NC	C	C
Visible Deflection of Beam	C	C	C
Lateral Column Drift	NC	NC	NC
Visible Deflection of Slab	C	C	C
Short/Captive Column	NC	C	C
Diaphragm Continuity	C	C	C

Table 4. Tier-01 Rapid Visual Screening Vertical Irregularities.

Vertical Irregularity	Building 1	Building 2	Building 3
Setback	NC	C	C
Complete Load Path	C	C	C
Redundancy	C	C	C
Weak Story	NC	NC	NC
Soft Story	NC	NC	NC
Vertical Discontinuity (Pickup Column)	NC	C	C
Pounding	NC	NC	NC
Strong Column Weak Beam	C	C	C
Mass Irregularity	NC	NC	NC
Transfer to Shear Wall	C	C	C
No Flat Slab Frames	C	C	NC
Height to thickness wall ratio not less than 8	C	C	C
The infill walls are not cavity walls	NC	C	C
Opening adjacent to Shear wall less than 15% of wall length	C	C	C
Infill walls are continuous to the soffits of the beam	C	C	C
Opening at Exterior masonry shear wall is not less than 4 ft long	NA	NA	NA

NC = Non-Complaint, C = Complaint, NA = Not Applicable.

3.6. Tier-2 Analysis

The structural system of the buildings comprises of reinforced concrete moment frame. Further investigation is required to ascertain that the buildings are safe. To do so, Tier-2 is performed for immediate occupancy level incorporating moderate to high seismicity [7]. The FEA models of the buildings are developed using a commercially viable computation tool named CSI ETABS. The plan and 3-D view of the models are shown in Figure 4.

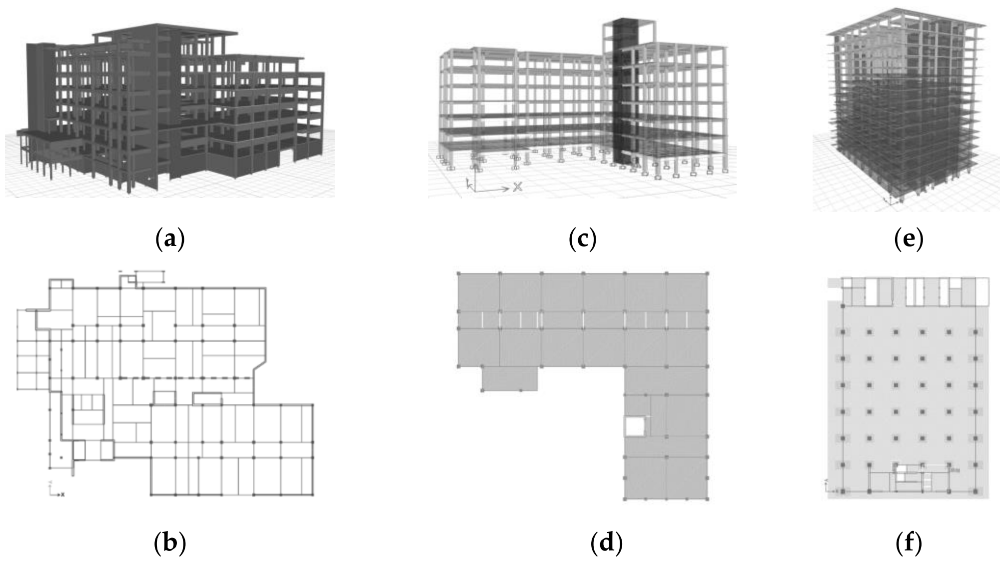


Figure 4. Typical Plan and Finite Element Model (**a**) Building-01 FEM 3-D (**b**) Building-01 Plan View (**c**) Building-02 FEM 3-D (**d**) Building-02 Plan View (**e**) Building-03 FEM 3-D (**f**) Building-03 Plan view.

Torsional irregularity found in non-compliant in Tier-1 is further evaluated in Tier-2. The maximum to average displacement ratio check was deployed to assess the structure in both principal directions X and Y. The maximum to average displacement ratio should be less than 1.2 for compliancy. Building-03 passes the torsional irregularity check, however, building-01 and 02 were found deficient in the torsional irregularity check after tier-02 analysis. Building-01 fails by 16% while building-02 exceeds the limit by a margin of more than 25%.

Multiple soft stories are being developed in both X and Y principal directions in all three structures. This was determined by comparing the stiffness of consecutive stories. The difference in stiffness between two adjacent stories should be less than 30% for compliance. There are severe soft-story occurring in the structure as the difference of stiffness in the stories in which this irregularity is occurring are up to 82%, 60%, and 65% simultaneously in building-01, 02, and 03.

The percentage difference of the masses between two adjacent floors should be within 50%. The structures were found to be compliant as an outcome of this irregularity check. All the structures passed this check by a reasonable margin as the difference in mass was observed to be less than 16% in all of the structures.

Building-01 was found to be compliant with the weak-story irregularity while building-02 and 03 were non-compliant. This was evaluated by comparing the shear strength of the structure on each story to adjacent stories. The criteria for compliance is the shear strength of the adjacent story should not be less than 80%. Building-01 passes the check with a higher margin as the difference does not exceed 10%, while building-02 and building-03 fail the check by a margin of 7% and 30%.

The inter-story drift limit for hospital buildings is 1% for immediate occupancy limit state performance level. The three structures considered in this study failed the inter-story drift limit check. Building-01, 02, and 03 exceed the limiting value by the code. If we compare the three buildings building-02 fails to a greater extent than the other two buildings.

4. Conclusions

Hospitals are termed as safe havens in wake of any kind of disaster but hospitals themselves are susceptible to damage particularly in strong seismic events the only possible solution to keep the hospital functional in such an event is to identify the existing deficiencies in the structure and mitigate it. A modified Rapid Visual Screening (RVS) procedure was adopted in this paper catering to the requirement of construction norms of Pakistan and applied to the three hospital buildings located in Karachi. The existing sources of vulnerabilities found in tier-1 were re-evaluated in the tier-2 phase. During the tier-1 evaluation phase, building-01 and building-02 were found more susceptible to damage in an earthquake, building-03 was comparably better than building-01 and 02 because building-03 had no severe plan irregularities. All three buildings were further evaluated in tier-02 and linear finite element models were developed employing a commercially viable software CSI ETABS. The three buildings failed the inter-story drift check, they exceeded the code prescribed value by a large extent. Building-01 showed compliancy in weak-story irregularity by a reasonable extent as the difference in strength was observed up to only 10% while the limit is 20%, on the other hand, building-02 and 03 failed the check by crossing the limit and the difference of strength was observed to be 27% and 52%. All three buildings failed the soft-story check and the difference in stiffness was found to be 82%, 60%, and 65% while the limit was 30%. Mass irregularity showed compliance for all the structures as the difference in mass did not even exceed 16%. Building-01 and 02 failed the torsional irregularity by 16% and 25% crossing the limit, on the contrary building-03 passes the torsional irregularity check because building-03 has a regular plan. The three structures need to be further evaluated in the tier-3 phase and if still found deficient it would be recommended that the building need to be retrofitted.

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