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SEISMIC SAFETY IN HEALTHCARE: ENHANCING HOSPITAL RESILIENCE TO EARTHQUAKES

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Abstract: Earthquakes are a type of disaster that we often have to face posing risks to both people and buildings. The design of hospitals plays a significant role in ensuring the safety of patients and the smooth functioning of healthcare facilities during disasters. To address this challenge effectively a comprehensive design approach is required, incorporating architectural, structural resilience, functional continuity and operational responsiveness. This article explores strategies and principles that can enhance the earthquake resilience of hospital buildings. It involves using construction materials and techniques of withstanding seismic movements within the structure during an earthquake. Techniques like reinforced frames, damping systems, base isolators and other mechanisms help the building absorb kinetic energy during seismic events. Adaptable space layout and modular design allow adjustments to meet requirements while maintaining critical services like emergency care and surgery accessibility for patients. Incorporating redundancy in utility systems such as power supply, water sources and communication networks reduces the likelihood of system failures in case of disruptions to power supply or communication services. This analysis offers an approach, to designing earthquake hospital structures. This research emphasizes the significance of assessing risks developing building regulations constructing structures and utilizing advanced technology to reduce the impact of earthquake dangers.

Keywords: disaster preparedness, earthquake resilience, hospital architecture, seismic-resistant materials

1. INTRODUCTION

Earthquakes are considered one of the natural dangers worldwide posing serious risks, to human life and buildings. They occur when energy is suddenly released in the Earth’s crust generating waves that travel through the ground and cause it to shake. This shaking can result in varying levels of harm to structures, infrastructure and landscapes. Earthquakes may arise from movements involving the Earths lithospheric plates sliding along faults, volcanic events or human activities such as mining or reservoir induced seismicity. These tremors are among the natural disasters capable of causing extensive destruction to communities and infrastructure. Hospitals, essential for providing healthcare services during and after calamities like earthquakes are particularly vulnerable to threats due to their infrastructure’s susceptibility. Hence there is a call for improving earthquake resilience in hospital design.

The increasing frequency and intensity of events in times emphasize the necessity for proactive strategies to protect hospitals from earthquake related disruptions. The repercussions of damage operational halts and breakdowns in healthcare facilities, during earthquakes can have outcomes by affecting patient care quality worsening injuries and hindering disaster response efforts.

Hence tackling the diverse obstacles presented by earthquakes requires a strategy that incorporates engineering, technological and socio-cultural aspects. In the wake of seismic occurrences, like the devastating earthquakes in Gujarat in 2001 Nepal in 2015 and the more recent Ridgecrest earthquakes in Turkey in 2023 there has been a growing emphasis on the importance of prioritizing earthquake resistance when designing hospitals. These seismic events have had an impact on healthcare infrastructure causing damage to hospitals, utility failures and disruptions to medical services. The potential repercussions of harm to these facilities are immense affecting safety, healthcare services and community resilience. Recognizing this vulnerability various initiatives have been put in place to enhance hospital resilience against earthquakes through building regulations retrofitting efforts and disaster readiness plans.

This study aims to explore the intricacies of earthquake resilience within hospital architecture by investigating approaches, design principles and interventions to strengthen hospital structures against risks. By consolidating existing knowledge along with practices and cutting-edge advancements in this field this research seeks to establish a framework for improving hospitals ability to withstand seismic events effectively. The importance of this study lies not in its impact on reducing the effects of earthquakes on healthcare services but also in its broader implications, for community resilience and disaster preparedness. By bolstering the durability of hospitals, we not protect the provision of vital healthcare services but also improve the overall resilience of communities in the face of seismic events.

2. IMPORTANCE OF SEISMIC SAFETY IN HEALTHCARE ARCHITECTURE

Earthquakes present risks, to healthcare buildings emphasizing the need to integrate strong seismic safety measures into healthcare facility design. This section delves into the vulnerabilities of healthcare structures to threats the effects of earthquakes on healthcare services and the overarching importance of seismic safety protocols in hospital construction. Healthcare facilities face heightened vulnerability to risks due to factors. Factors such as aging infrastructure, inadequate structural planning and insufficient upgrades contribute to hospitals susceptibility to earthquake impacts. Common deficiencies in healthcare buildings include ductile concrete structures, unreinforced masonry walls and inadequate foundations all of which worsen their exposure to earthquake related damages. Additionally having infrastructure like equipment, utilities and life support systems increases the potential consequences of seismic disturbances in healthcare settings.

The repercussions of earthquakes on healthcare services go beyond damage. Extend to operational disruptions and compromised patient care. Structural failures can render medical facilities nonfunctional hindering the provision of services during crises. Furthermore, damage to structural components like partitions, ceilings and utility systems complicates recovery efforts and adds challenges in delivering care to patients. Moreover, seismic events can lead to a surge, in numbers further straining healthcare resources and staff members.

It's crucial to include safety measures, for earthquakes, in hospital design to reduce risks and make sure healthcare facilities can withstand disasters. Planning ahead and making design changes can strengthen the buildings lower the chances of earthquake damage and help medical services bounce back quickly. Furthermore, seismic safety measures encompass not only structural considerations but also the integration of non-structural elements such as medical equipment anchorage, utility systems protection, and emergency preparedness protocols. By prioritizing seismic safety in hospital design, healthcare facilities can mitigate risks, protect human lives, and maintain operational continuity during seismic events.

3. DESIGN CONSIDERATIONS FOR SEISMIC SAFETY

Creating earthquake resistant healthcare facilities involves attention to design elements that enhance hospital structure’s ability to withstand risks. Key steps include selecting a location and conducting evaluations of the site’s geotechnical aspects. Factors, like risks, soil conditions and proximity to fault lines must be considered during site selection. Geotechnical assessments offer insights into soil properties, liquefaction risks and seismic ground movements guiding decisions on foundation design and structural layout. The arrangement and architecture of healthcare buildings significantly impact their performance during earthquakes. Optimal building layouts with footprints and distributed mass can boost structural integrity and minimize seismic vulnerabilities. It's also vital to incorporate functions placement emergency escape routes and evacuation areas into the building design for operation during seismic events.

Choosing systems and materials is crucial for ensuring healthcare facilities resilience against earthquakes. Structural systems like reinforced frames, steel moment frames and braced frames provide ductility and energy absorption capabilities in earthquake scenarios. Similarly using materials such as reinforced concrete, structural steel and seismic isolation components can enhance hospital structures overall performance, under seismic stresses. Ensuring redundancy and resilience, in infrastructure systems is crucial for sustaining operations during events. Backup power systems, water distribution redundancies and safety measures play a role, in maintaining functionality and reducing the impact of potential service interruptions.

Robust structural detailing and redundant structural elements can enhance the resilience of hospital buildings to seismic forces, reducing the likelihood of catastrophic failure. Non-structural elements, such as partitions, ceilings, equipment, and utility systems, represent vulnerabilities in healthcare facilities during earthquakes. Proper anchorage, bracing, and vibration isolation of non-structural components are essential for mitigating risks and minimizing damage. Seismic restraint systems for medical equipment, fire suppression systems, and utility piping help maintain functionality and ensure the safety of patients and staff during seismic events.

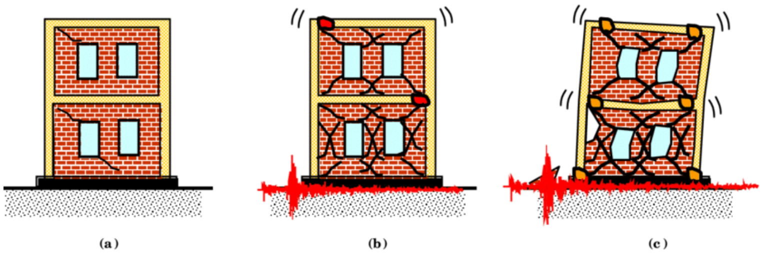

Figure 1 Earthquake-resistant Design Philosophy: (a) Minor (Frequent) Shaking-No/Hardly any damage, (b) Moderate Shaking-No structural damage, but some non-structural damage, and (c) Severe (Infrequent) Shaking-Structural damage, but NO collapse

4. STRUCTURAL ENGINEERING PRINCIPLES:

Structural engineering plays a role, in safeguarding healthcare facilities against events. This section explores the principles and techniques used in engineering to bolster the earthquake resistance of hospital structures. Performance based design (PBD) methods take an approach to design prioritizing specific performance goals over adhering strictly to traditional building codes. PBD takes into account factors like building use, structural functionality and anticipated seismic risks to craft customized design solutions that optimize performance across varying conditions. By conducting analysis and simulations PBD enables engineers to evaluate how hospital buildings behave during earthquakes and implement targeted design improvements to enhance their resilience. Seismic retrofitting involves making modifications to existing structures to enhance their ability to withstand earthquake forces. Retrofitting approaches vary based on the vulnerabilities of each building. May involve strengthening structural components introducing additional lateral bracing or installing base isolation systems. Common retrofitting methods for healthcare facilities include incorporating steel bracing systems, reinforcing columns with jackets and installing dampers for energy dissipation. Through retrofitting efforts on existing hospital structures engineers can reduce risks. Prolong their operational lifespan.

Ensuring foundation design is essential, for maintaining the stability and earthquake resilience of hospital buildings. When designing engineers need to take into account how the structure interacts with the soil factoring in the types of soil, site characteristics and the stiffness of the foundation. In regions, with soil conditions or significant seismic risks deep foundation systems, like piles or drilled shafts are utilized to offer improved support and stability. Moreover employing base isolation methods, like isolators or friction pendulum systems can effectively detach the building from ground movement decreasing forces transferred to the structure. Damping mechanisms are vital in dissipating energy and lessening the impact of forces on hospital structures. Various damping devices such as dampers, friction dampers and tuned dampers can be incorporated into the structural system to reduce building oscillations and manage deformations during earthquakes. These damping systems bolster the resilience of hospital constructions by minimizing damage and disruptions to services. Routine structural evaluations and upkeep are crucial for ensuring the term robustness of healthcare facilities. Structural inspections, monitoring systems and performance assessments aid in recognizing weaknesses and decay, over time. Prompt repairs, retrofitting and maintenance measures are imperative to rectify deficiencies and guarantee the safety and functionality of hospital buildings under conditions.

5. TECHNOLOGICAL INNOVATIONS FOR SEISMIC SAFETY:

Technological progress significantly contributes to strengthening the ability of healthcare facilities to withstand earthquakes. Advances, in technology have greatly enhanced the construction of buildings that can better withstand activities. Innovations in tools, methods and materials enabled by technologies improve the resilience of buildings allowing for more accurate evaluations and enhanced monitoring capabilities. Measures such as base isolation and damping devices are implemented to enhance the resilience of buildings. Base isolation involves placing the building on energy absorbing bearings or isolators which helps reduce the impact of ground motion, on the structure.

Viscosity dampers and tuned dampers are two types of devices used to dissipate energy and reduce vibrations, in buildings. These mechanisms can be incorporated into systems to mitigate the impact of earthquakes. Cutting edge structural monitoring systems offer real time data on how hospital structures perform and behave during events. These systems use sensors, accelerometers and wireless communication technologies to measure reactions such as displacements, accelerations and deformations. By monitoring the health and integrity of structures engineers can pinpoint weaknesses evaluate damage and implement timely measures to improve the earthquake resilience of healthcare facilities. Isolation and base isolation methods are strategies used to separate hospital structures from ground movements and lower the transfer of seismic forces, to the building's upper parts. Typically involving isolation bearings, sliders or pendulum devices placed between the foundation and the structure to absorb and dissipate energy effectively. By isolating buildings from ground motion these systems help minimize damage and maintain services during earthquakes.

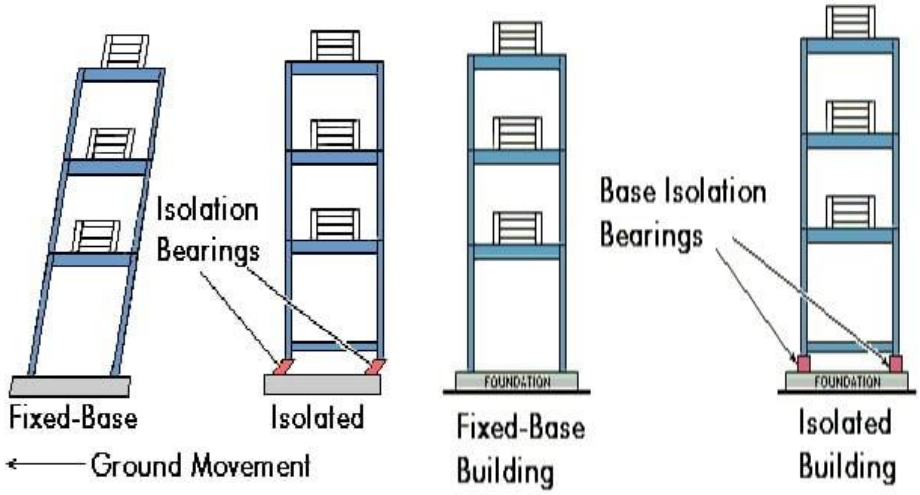

Figure 2 Base isolation

Advancements in materials science have led to the development of innovative materials with enhanced seismic resistance properties. Fiber-reinforced polymers (FRPs), high-performance concrete, and advanced steel alloys offer improved strength, ductility, and durability compared to traditional building materials. These innovative materials can be used in structural elements, such as columns, beams, and shear walls, to enhance the seismic performance of hospital buildings and reduce the risk of structural failure during earthquakes. Emergency power backup systems and redundant utility systems are critical for maintaining operational continuity in healthcare facilities during seismic events. Backup power generators, uninterruptible power supply (UPS) systems, and redundant utility connections ensure the availability of essential services, such as lighting, heating, ventilation, and medical equipment operation, in the event of power outages or disruptions. By providing reliable backup systems, healthcare facilities can minimize downtime and ensure uninterrupted patient care during earthquakes. Telemedicine and remote healthcare delivery technologies offer alternative means of delivering medical services during seismic events when traditional healthcare facilities may be inaccessible or compromised. Telemedicine platforms enable healthcare providers to remotely assess and treat patients, conduct consultations, and monitor vital signs using telecommunications and digital technologies. By leveraging telemedicine solutions, healthcare facilities can maintain continuity of care, alleviate strain on physical infrastructure, and ensure access to medical services during emergencies.

6. MATERIALS FOR EARTHQUAKE-RESISTANT CONSTRUCTION:

1. High-Performance Reinforced Concrete:
   - High-performance reinforced concrete is a widely used material in earthquake-resistant construction due to its inherent strength, durability, and ductility.
   - Reinforced concrete structures can effectively withstand seismic forces by distributing loads and dissipating energy through the reinforcement bars embedded within the concrete.
   - Concrete shear walls and moment-resisting frames provide structural stability and flexibility, allowing buildings to resist lateral forces generated by earthquakes.
   - Proper design and detailing of reinforced concrete elements, such as columns, beams, and slabs, are essential to ensure optimal performance during seismic events.

2. Steel Framing:
   - Steel framing offers excellent resilience to seismic forces and is commonly used in earthquake-resistant construction.
   - Steel moment-resisting frames are designed to undergo controlled yielding during earthquakes, dissipating energy and reducing structural damage.
   - Steel structures provide flexibility and ductility, allowing buildings to withstand ground motion without suffering catastrophic failure.
   - The lightweight nature of steel also makes it an attractive choice for constructing hospitals in seismic regions, as it minimizes building mass and reduces seismic loads.

3. Fiber-Reinforced Polymers (FRPs):
   - Fiber-reinforced polymers, such as carbon fiber and fiberglass, are increasingly being used to enhance the seismic performance of existing structures through retrofitting.
   - FRP materials offer high strength-to-weight ratios, excellent corrosion resistance, and superior durability compared to traditional construction materials.
   - FRP composites can be externally bonded or internally reinforced to strengthen structural elements, such as beams, columns, and walls, against seismic forces.
   - Retrofitting with FRPs is a cost-effective solution for improving the seismic resilience of older hospital buildings without extensive structural modifications.

4. Advanced Composite Materials:
   - Advances in composite materials technology have led to the development of innovative combinations of concrete, steel, and polymers tailored for seismic-resistant construction.
   - These advanced composites offer superior performance characteristics, including enhanced strength, stiffness, and energy absorption capacity.
   - Composite materials can be engineered to exhibit specific properties tailored to the seismic demands of hospital structures, such as increased ductility and deformation capacity.
   - By leveraging the unique properties of advanced composite materials, engineers can design hospital buildings that effectively withstand the dynamic forces of earthquakes while maintaining the safety and functionality of critical healthcare facilities.

7. DESIGN CODES AND STANDARDS

Seismic design principles are critical considerations in the architectural planning and construction of healthcare facilities in India. The National Building Code (NBC) of India serves as a comprehensive guideline for seismic design and construction, including specific provisions aimed at ensuring the earthquake resistance of various structures, including healthcare facilities such as hospitals. In adherence to the NBC, hospitals are meticulously designed and constructed with consideration given to the seismic zone in which they are situated, ranging from Zone II to Zone V, reflecting varying levels of seismic activity across the country.

1. Common foundation types suitable for seismic design include spread footings, mat foundations, and deep pile foundations. In areas with high seismic activity, deep pile foundations may be preferred to transfer building loads to deeper, more stable soil layers.
2. Employ appropriate structural systems, such as reinforced concrete frames or steel moment-resisting frames, designed to withstand seismic forces and ensure adequate ductility and stiffness.

3. Avoid irregularities in building geometry, such as setbacks, projections, or asymmetric layouts, that may concentrate seismic forces and increase vulnerability to collapse.
4. foundation depths in earthquake-prone regions may range from 1.5 to 2 times the width of the foundation footing.
5. Anchor non-structural components, including architectural finishes, mechanical and electrical systems, and medical equipment, to resist seismic forces and prevent detachment or damage during earthquakes.

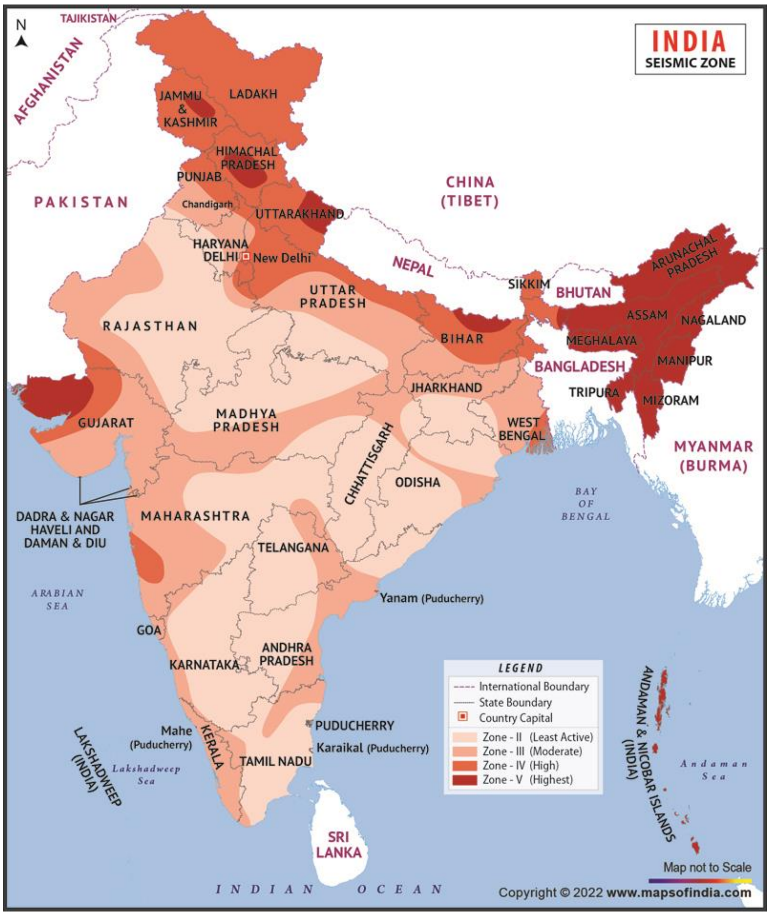

Figure 3 Seismic zones of India

8. PLANNING AND PREPAREDNESS FOR SEISMIC EVENTS

Planning effectively and being prepared are aspects of reducing the impact of earthquakes, on healthcare facilities. In this section we delve into the strategies and factors that can help hospitals improve their ability to handle emergencies through planning and response preparation. Hospital administrators work closely with emergency management experts to create emergency response plans specifically tailored for events. These plans outline roles, duties and communication channels for staff ensuring a well-coordinated and prompt reaction in case of an earthquake. Regular drills and training sessions help familiarize personnel with emergency protocols promoting readiness and resilience in situations. Evaluating the integrity of hospital buildings and identifying vulnerabilities is essential to prioritize actions for improvement. By involving engineers and seismic specialists' healthcare facilities assess how well their structures can withstand earthquakes determine retrofitting requirements and implement measures to enhance strength. Regular inspections and monitoring programs keep track of the condition of hospital infrastructure allowing for maintenance and risk reduction. Hospitals also create plans to ensure operation of critical medical services like emergency care, surgery and intensive care units during or, after earthquakes. They establish power systems, redundant communication networks and supplies reserves to sustain operations if infrastructure is disrupted.

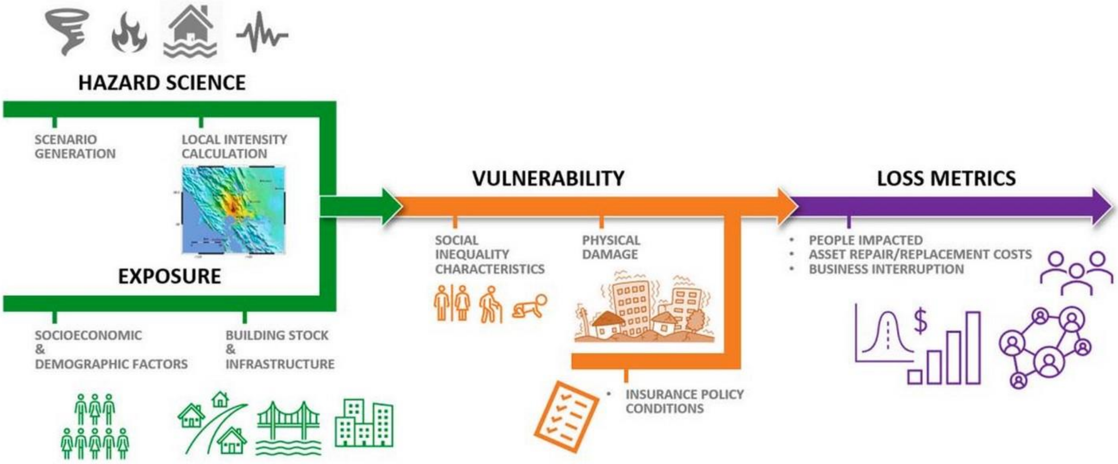

Figure 4 Disaster-risk model components

Collaborating with healthcare centers enables the establishment of mutual aid pacts and the sharing of resources to strengthen response initiatives. Hospitals devise evacuation strategies customized to cater to the requirements of groups, such, as vulnerable individuals and those, in need of specialized medical attention. Designated evacuation routes, assembly areas, and evacuation assistance teams ensure orderly and safe evacuation procedures. In cases where evacuation is not feasible, hospitals establish shelter-in-place protocols, reinforcing designated safe zones within the facility to protect occupants from hazards. Harnessing technology and innovation enhance the effectiveness of seismic event preparedness and response efforts. Hospitals leverage advanced seismic monitoring systems, early warning technologies, and real-time situational awareness platforms to detect seismic activity, assess impacts, and deploy timely alerts to healthcare stakeholders. Additionally, digital communication tools, telemedicine platforms, and mobile applications facilitate remote coordination, patient triage, and resource allocation, optimizing response coordination and resource utilization in dynamic disaster environments.

9. LITERATURE CASE STUDY: HARBIN INSTITUTE OF TECHNOLOGY, CHINA

This case study focuses on the seismic resilience assessment of a hospital building located in a seismically active region. The hospital, a five-story reinforced concrete frame structure, plays a critical role in providing emergency medical services to the community. The study aims to evaluate the hospital's ability to withstand and recover from seismic events, considering both structural and functional aspects. The hospital under study is a five-story reinforced concrete frame building, measuring 68m in length, 45m in width, and 18.9m in height.

Figure 5 Harbin institute of technology, China

The structural design of the building complies with Chinese seismic design standards, with a seismic fortification intensity of seven and soil class II. Fourteen ground motion records were selected for nonlinear dynamic analysis, meeting specific criteria related to seismic event magnitude and soil characteristics. Nonlinear time history analysis was conducted using SAP2000, considering beam-column-slab interaction and P-delta effects. The hospital's functionality is described in detail, including the layout of critical departments in the emergency service, architectural features, and utility systems. Fragility functions for non-structural components and medical equipment were adopted from FEMA P-58, with consequence functions determined for basic events in the fault tree analysis. The fault tree of emergency service was developed in collaboration with hospital managers, considering interdependencies between damage to non-structural components, medical equipment, and utility systems. The failure probability and repair time of external electric grids under different seismic hazards were assumed for the analysis. Non-structural components and medical equipment were assigned allowable damage states based on operational requirements. Performance Assessment Calculation Tool (PACT) was utilized to calculate repair cost and time under different repair strategies. The median repair cost and probability of emergency functionality under various seismic intensities were analyzed.

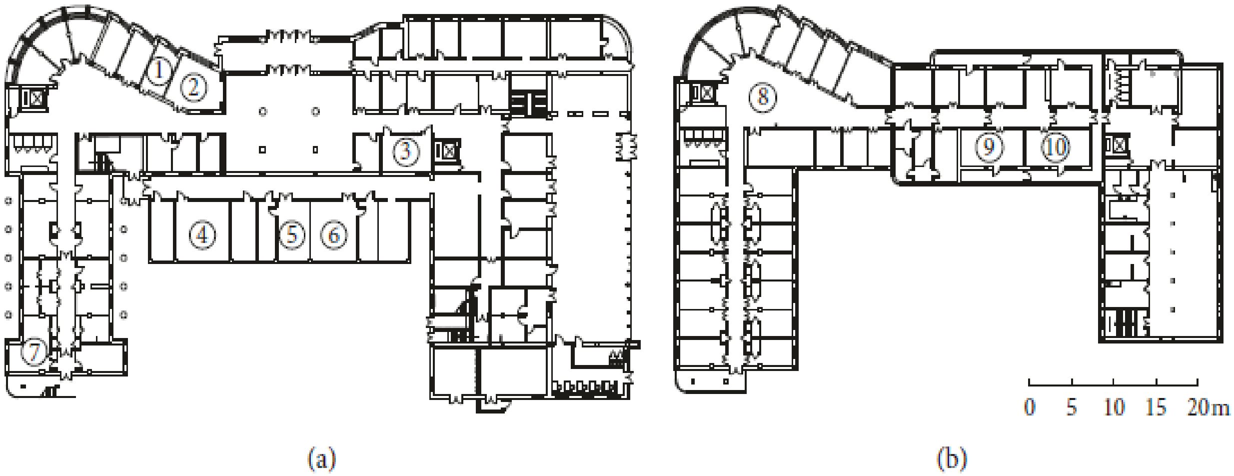

Figure 6 Hospital building plans. (a) 1st floor (b) 5th floor rooms numbered from 1 to 9 are resuscitation room, pharmacy, distribution room, magnetic resonance imaging (MRI) room, digital radiography (DR) room, computed tomography (CT) room, supply room, ward, operation room 1, and operation room 2, respectively.

The hospital's resilience assessment involved updating functionality levels with repair processes and plotting recovery curves over time. Three main repair strategies (parallel, serial, and REDi methods) were considered, with parallel strategy assuming simultaneous repair work at all floors, serial strategy repairing work from ground to top floor, and REDi method making improvements on labour allocation and repair scheme. The quantification of functionality levels was crucial for computing resilience index using the proposed framework. Recovery curves were plotted for different earthquake levels and repair strategies, highlighting the impact of repair strategy on recovery time and resilience index.

The seismic resilience assessment of the hospital revealed critical insights into its ability to withstand and recover from seismic events. The adoption of fault tree analysis facilitated a realistic assessment of interdependencies between damage to structural and non-structural components, medical equipment, and utility systems. The study identified the need for improvement in the hospital's seismic resilience, particularly in reducing the recovery time for emergency functionality after severe seismic events. Decision-makers are urged to take necessary measures to enhance the hospital's seismic resilience, considering the clear effects of repair strategy on recovery time and resilience assessment results. The proposed framework provides a comprehensive evaluation criterion for updating strategies and can be further applied to other critical facilities to improve their seismic resilience.

10. CONCLUSION

The safety of healthcare buildings, during earthquakes is crucial for ensuring that vital medical services can continue without disruption. As the importance of safety in healthcare infrastructure planning and design grows there are both opportunities and tough challenges ahead. Innovations in engineering have the potential to transform the field offering levels of resilience against earthquake forces with advanced building systems and materials. The use of technologies like intelligence and digital twins holds promise for improving predictive modelling and real time monitoring leading to better risk management and performance optimization. Additionally, a focus on climate resilience and sustainability is becoming more prominent as healthcare facilities adopt design principles that're adaptable to climate change and utilize energy solutions to boost resilience against both seismic events and climate related risks while supporting environmental conservation efforts. Community involvement plays a role in enhancing resilience by allowing local communities to actively engage in the design, planning and management of healthcare infrastructure fostering unity and responsibility. Despite these trends there are challenges ahead. Limited resources, technological obstacles and gaps in regulations present barriers to implementing seismic safety measures especially in areas with limited resources or underserved populations. Socio economic inequalities further increase vulnerabilities underlining the need for access, to resilient infrastructure and resources.

The intricate interactions of development and the expansion of settlements pose a variety of obstacles, in planning, for city resilience. This calls for strategies that tackle the intertwined factors of risk, vulnerability and socio-economic progress. In response to this challenge, stakeholders need to adopt an integrated, multidisciplinary approach that emphasizes innovation, the healthcare sector can pave the way for a future where earthquake safety is no longer an afterthought but an essential part of physical strength and human health that ensures safety, health and well-being in society for the next generation.

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