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A methodology to estimate seismic vulnerability of health facilities. Case study: Mexico City, Mexico

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Abstract We developed a model to estimate seismic vulnerability of health facilities in Mexico City, Mexico, following these steps: (1) designing a theoretical framework (TF) to measure structural, non-structural, functional, and administrative-organizational vulnerabilities; (2) measurement of the vulnerability conditions of the analyzed facility by using the TF; and (3) estimation of the hospital's seismic vulnerability by comparing the measured vulnerability to the TF's vulnerability indicators by taking into account the optimal case. The TF was developed considering a scoring system and international standards for risk management in hospitals. The methodology establishes the degree of vulnerability of the analyzed institution as well as its interrelations with external infrastructure systems. This tool also identifies existing failures to estimate expected damage. The methodology was applied to the National Cardiology Hospital, the Children's Hospital "Dr. Federico Gómez," and the "Hospital de Jesus" of Mexico City. The vulnerability problems in these three hospitals are common within them, and some of the main causes of vulnerability found are: (1) the lack of technology to resistant seismic shaking; (2) the need to develop or update disaster response plans; (3) the need of periodic and proper maintenance to hospitals' buildings; (4) the lack of sufficient financial resources for vulnerability reduction projects and autonomous operations of the hospital during 3–5 days after a disaster occurs. We believe that vulnerability in these health facilities can be reduced with low-cost procedures and that the methodology developed here will support the decision-making processes to reduce seismic risk in Mexico City.

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1 Introduction

1.1 Background

In 2016, an estimated 54.5% of the world's population was concentrated in urban centers and large cities (United Nations 2016). Many cities in the world are highly exposed to natural hazards, and therefore, they are prone to disaster situations (Gencer 2013). The proper functionality of critical facilities in any community is essential in everyday conditions. Although health facilities are essential infrastructure during disasters, they are also usually highly vulnerable installations in the case of the occurrence of local large earthquakes. Damage to medical buildings may cause serious disruption of medical services. Thus, it is important and necessary to maintain functioning of all local health's infrastructure after the impact of an earthquake to satisfy the need for medical care of the affected population (Dajer 2011). The proper operation of hospitals depends significantly on the adequate performance of the overall local health infrastructure system (Rinaldi 2004). These facilities are required to function efficiently to deal with a significant number of injured people in a short period of time. If a health facility is seriously damaged, it cannot accomplish its function properly when most of it is needed (Lai et al. 2003). In this case, hospitals may become a casualty of the disaster.

At present, there are few specific methods for assessing vulnerability of health facilities, among these, the vulnerability assessment of healthcare facilities (VAHCF) that measures the operational vulnerability of a healthcare facility during disaster events (Arboleda et al. 2009). The guidelines of the Safe Hospital Program (SHP) developed by the Mexican Government (SEGOB) and the Mexican National System for Civil Protection (SINAPROC) define a "safe hospital" as a unity whose services remain accessible and functional at maximum capacity within the same infrastructure immediately after a disaster (Secretaria de Gobernación y Sistema Nacional de Protección 2008). The VAHCF and SEGOB methods evaluate the administration and organization conditions in health facilities to obtain a risk indicator and the security level, respectively. However, no one of these methodologies provides a level of vulnerability. The World Health Organization (WHO) developed a method for hospital's administrators to assess preliminary structural, non-structural, and administrative-organizational vulnerabilities by identifying possible weak elements in main areas of the facility (World Health Organization 2006).

Cardona and Hurtado (2000) developed a holistic approach to estimate risk by incorporating geological and structural elements as well as social, political, cultural, and recovery aspects. The method uses mathematical tools to estimate vulnerability and risk on urban areas by determining a risk management indicator (RMI). This methodology provides consistently measuring key factors of vulnerability and the performance of the disaster risk management at country level. Novelo-Casanova and Suárez (2015) developed a similar approach to estimate RMI at local level by using statistical analysis. The community vulnerability assessment tool (CVAT) is a risk and vulnerability assessment methodology designed by the National Oceanic and Atmospheric Administration's Coastal Services Center (NOAA) to assist emergency managers and planners in their efforts to reduce vulnerability through hazard mitigation, comprehensive land use, and development planning at community level (Flax et al. 2002).

In the majority of the methodologies described above, critical facilities are considered as an integral part of vulnerability. Those methods that assess vulnerability and risk for single facilities are focused mainly on structural aspects by using: (1) a damage probabilistic matrix (Masi et al. 2014),(2) fragility curves (Monti and Nuti 1996; Vanzi et al. 2015), and (3) indices of structure, non-structural, and administrative-organizational vulnerability (Boroschek Krauskopf and Retamales Saavedra 2004; World Health Organization 2006; Aiello et al. 2012). On the contrary, the functional vulnerability hazard has not been fully developed. However, none of these methodologies consider all the elements that constitute vulnerability in health facilities. This type of critical installations must guarantee the safety of their buildings and occupants as well as an efficient operation in emergency situations.

The main objective of this work is to develop a vulnerability assessment tool for health facilities with a holistic approach. The main differences to other methodologies previously developed by other authors are: (1). Results are presented in quantitative form (indices) and qualitative description (expected damage); (2) seismic level of vulnerability is identified for each evaluated element; (3) through classifications of expected damage due to failures found in the different hospital's areas, the method provides to hospital's authorities the possibility to prioritize actions needed to reduce the level of vulnerability. These characteristics of the method provide important elements for decision making. Besides, the methodology developed here is structured under a theoretical framework (TF), and using a scoring system, the levels of the different types of vulnerabilities are determined. Also, possible mitigation measures to reduce vulnerability to an acceptable level are provided, and this tool can be applied to any kind of health facility in the world.

Vulnerability indexes in a determined model must consider the relative importance of each element involved as well as the interaction among these elements (Sandi et al. 2007). An example is the fact that the response of a non-structural element in case of an earthquake depends on the safety of the structural element and the safety of a structural element depends on proper maintenance and use of seismic technology in its components. These concepts when are applied to the measurement of vulnerability make a convenient approach because it can extend the framework of the evaluation by including the different elements involved in the functionality and safety of the facility during the emergency response (Morán-Rodríguez and Novelo-Casanova 2016).

We applied this methodology to three study cases in Mexico City: (1) the Cardiology Hospital of the National Medical Center "Siglo XXI" (CaH) that is one of the most important local public health institutions; (2) the Children's Hospital "Dr. Federico Gómez" (ChH), one of the largest pediatric hospitals in Mexico; and (3) the "Hospital de Jesus" (JeH) that is a private health institution located in the historic center of the city. These three hospitals are located on the lakebed zone of Mexico City (Morán-Rodríguez and Novelo-Casanova 2012) that has high water content and exhibits huge amplification of ground motion due to earthquakes (Ordaz and Singh 1992). Also, these hospitals have different years of construction and typologies.

1.2 Damage in hospitals

Earthquakes can have devastating effects on hospitals. On January 12, 2010, a 7.0 magnitude earthquake struck the Republic of Haiti with its epicenter located approximately 25 km south and west of Port-au-Prince (DesRoches et al. 2011). The earthquake left more than 316,000 people dead, 300,000 injured, and over 1.3 million homeless. The damage was staggering, and it is estimated that 60% of the nation's administrative and economic infrastructure was lost and 80% of the schools and more than 50% of the hospitals were destroyed or damaged (Government of the Republic of Haiti 2010).

On August 15, 2007, a 7.9 magnitude earthquake occurred southwest the coast of Peru, near the Department of Ica and about 60% of the health facilities reported some damage. However, only 78% of the facilities reported providing medical care within the first 48 h after the earthquake (Chapin et al. 2009). On December 2004, the Indian Ocean tsunami impacted the entire national healthcare system and millions of people of the Aceh Province. The tsunami destroyed 30 health facilities out of 240, seriously damaged 77, and caused minor damage to additional 40. The loss of health personnel was also substantial, 700 health workers died (Carballo et al. 2005). As a consequence, Aceh's public health system recovery required intensive investment. These few examples highlight the importance to carefully design the structure as well as the geological and geographical location of hospitals to minimize their risk to geological hazards (Rashed and Weeks 2003; Nateghi-Alahi and Izadkhah 2004; Smith 2013).

Seismic hazard has caused major damages to health facilities in greater proportion than other natural phenomena (Akbari et al. 2004; Organización Panamericana de la Salud (OPS) and Organización Mundial de la Salud (OMS) 2004; Achour et al. 2011). Under these considerations, we developed this earthquake-specific tool because of the present need to evaluate seismic vulnerability for each hospital's buildings considering structural, non-structural, functional, and administrative-organizational as well as the level of vulnerability due to the dependence of external suppliers. Although the approach of the Hospital Safety Index (Boroschek Krauskopf and Retamales Saavedra 2004) comprises all hazards that may impact a hospital, it only provides an overall index without identifying specific types of vulnerability for each building of the analyzed institution.

For these reasons, it is necessary to implement non-structural mitigation measures and enforce building regulations of countries located in areas highly exposed to earthquake hazards (Fawcett and Oliveira 2000; Brandeau et al. 2009; Chapin et al. 2009; Birkmann 2011).

In addition, hospitals rely on the basic community's infrastructure systems to operate properly such as water, electricity, and transportation. This was the case of the disaster caused in New Orleans, USA, by Hurricane Katrina in August 2005, when healthcare facilities were evacuated because it was impossible to operate the power generators located in the lower levels of the hospitals and delivery of medical resources was delayed due to floods of the road network (Centers for Disease Control and Prevention 2006). When a critical infrastructure fails during disasters, the consequences are not restricted to the infrastructure itself. There might be significant damage to other systems connected to the impaired infrastructure. Hence, the evaluation of the consequences of a failure should include not only the direct effects, but also the possible deterioration of interconnected systems (Mendonca et al. 2004; Lee et al. 2007).

1.3 Seismic hazard in Mexico City

Mexico City is considered one of the largest cities in the world, and its urban development is complex including its health infrastructure. Morán-Rodríguez and Novelo-Casanova (2012) determined that about 70% of the main hospitals in Mexico City have a level of exposure to seismic hazards between moderate and high. The other 30% although have low level of exposure, the level of damage during a large earthquake will depend on their vulnerability conditions. These authors also identified that more than 50% of the main and reference hospitals in Mexico City are highly exposed to seismic hazards. Thus, it is important to identify those elements in local health facilities that can be severely damaged by an earthquake posing a threat to life and the functionality of the hospital.

The most recent devastating earthquake in Mexico City occurred on September 19, 1985 (magnitude 8.1) (Unam Seismology Group 1986). During this earthquake, five main health facilities suffered major damage and at least 11 hospitals had to be evacuated (Zeballos 1986; Degg 1989). Also, 13 hospitals of six or more floors were partially damaged or totally destroyed. One out of every four hospitals' beds in the city was lost. More than 900 patients, physicians, nurses, and paramedical workers died in the initial shock (Soberon et al. 1986).

1.4 Legislations of disaster preparedness in health facilities in Mexico

At present, in Mexico there is no a specific legislation to reduce vulnerability of health facilities and prevent disaster situations. Among the laws that support the prevention of risk to natural phenomena is the Mexican Official Norm NOM-006-SEGOB-2015 (Diario Oficial de la Federacion (DOF) 21-2-2017). This legislation establishes that all, public, social, or private spaces and mercantile establishments that are located in the Pacific Ocean coastline must have better conditions of security through the prevention of risk associated with tsunamis establishing prevention, early warnings, and evacuation routes. This legislation also provides a protocol for developing an operational emergency tsunami plan including evacuation drills.

Another existing legislation is for fire prevention NOM-002-STPS-2010 (Diario Oficial de la Federación 2010). This legislation establishes that all workplaces must have emergency equipment and special installations to prevent fire as well as an emergency action plan. A recommendation was issued under the Distrito Federal Civil Protection Law in 2010 (NTC-002-SPCDF-PV-2010; Norma Técnica Complementaria) for public buildings located in Mexico City to install the Mexican earthquake early warning system (SAS). The National Prevention Disaster Center (CENAPRED) and the Secretariat of Government of Mexico published the standards to assess the level of damage caused by seismic hazards. However, this assessment is suggested post-event (Jumonji 2001). In addition, there are complementary norms to the legislation that are applied to construction of critical facilities. The purpose of these norms is to reduce the degree of seismic risk and vulnerability in tall buildings (Gobierno del Distrito Federal 2004a, b). However, there are international recommendations aimed to reduce the expected damage by natural phenomena that Mexico established as goals for disaster reduction and mitigation. One of the main development objectives of Mexico in the next millennium is to increase its resilience to disasters (Gobierno de la República and Organización de Naciones Unidas 2015). During the Global Platform for Disaster Risk Reduction 2017 held in Cancun, Mexico, local authorities established a short-term goal to develop the mechanisms for the Mexican hospital's infrastructure to work in optimal conditions to provide proper medical care in emergency and disaster situations.

2 Methodology

2.1 Considerations and definitions

Our model was developed based on a system of indicators from a TF based on a series of assessments with scoring systems and on international standards and recommendations for risk management in hospitals (Soberon et al. 1986; Monti and Nuti 1996; Rashed and Weeks 2003; Boroschek Krauskopf and Retamales Saavedra 2004; Nateghi-Alahi and Izadkhah 2004; Secretaria de Gobernación y Sistema Nacional de Protección Civil 2008; Arboleda et al. 2009; Brandeau et al. 2009; Miniati and Iasio 2012; Aragón Cárdenas et al. 2011; Vanzi et al. 2015; Franco et al. 2006). The objective of this methodology is to provide a tool to identify seismic vulnerability. The results identify and prioritize actions to reduce vulnerability in the short, medium, and long term.

It is recommended that this tool be applied by a multidisciplinary and previously trained team that should be constituted by at least one member of the hospital's maintenance personnel (technicians, engineers, and architects) as well as from the local civil protection and medical staff. It is also convenient that at least one or two members of this team to be from an external institution. The model considers the following types of vulnerabilities:

1. *Structural* Those conditions that will cause damage to the structural components of the installations (basement of the buildings, concrete roofs, columns, type of construction, load-bearing walls, concrete slabs, architectural shapes, construction joints, overweight of the original construction, alterations and remodeling, etc.)
2. *Non-structural* Components of the hospital that are crucial for the effective operation of the facility: architectural components (ceiling, doors, windows, walls), installations (electricity, air conditioning, gas, power and water systems, fire alarm, and suppression system), medical equipment, furnishings, chemical and toxic substances, waste products, steam, etc.
3. *Functional* Includes the geographical location of the hospital's buildings, accessibility during possible disaster scenarios, medical services as well as the use of the architectural spaces, local hygiene's conditions, functionality, safety and security, critical services as surgery, water and electricity, etc. Also includes the level of dependence during disaster situations on external supplies and services as well as on those elements that are located outside the health facility and that threaten the functioning of the hospital (lifelines, communications, roads and access to the hospital, sewage, garbage removal, etc.) Additionally, the relationships with nearby hospitals to manage injured and sick people are analyzed.
4. *Administrative-organizational* Considers the administration and organization within the health facility as well as the existing emergency and evacuation plans to mitigate the impact of disasters (internal communications, management of information, computers and their networks, equipment and supplies management, skill of the staff to manage disasters, support services: food and catering, laundry, maintenance, etc.)

As part of our methodology, we consider the following terms:

- *Parameter* Component of any of the four types of vulnerabilities considered (walls, roofs, furniture, equipment, etc.)
- *Failure* Any structural, non-structural, functional, and social administrative condition that increases vulnerability (broken windows, unlocked baby cribs, lack or inadequate response plans, lack of regular building maintenance, etc.)

We considered ten parameters and 45 kinds of failures for each type of vulnerability analyzed. Each failure has a previously assigned numerical value depending on the classification of damage. The structural vulnerability is obtained for each hospital's building (Online Resource 1). In this case, failures by classification of areas are not considered (Fig. 1). The total number of failures is obtained from the sum of failures in each hospital's building.

Failures in the non-structural vulnerability are quantified taking into account the classification of damage for the different hospital's areas A, B, or C (Morán Rodríguez 2012; Morán-Rodríguez and Novelo-Casanova 2016) (Online Resource 2). The total number of failures is estimated considering the number of failures found in each area.

The functional vulnerability is calculated from the failures in the different hospital's areas. Some of these failures have three numerical values as the non-structural vulnerability. However, there are some failures with only one numerical value. This is because these types of failures do not require the classification of hospital's areas (Online Resource

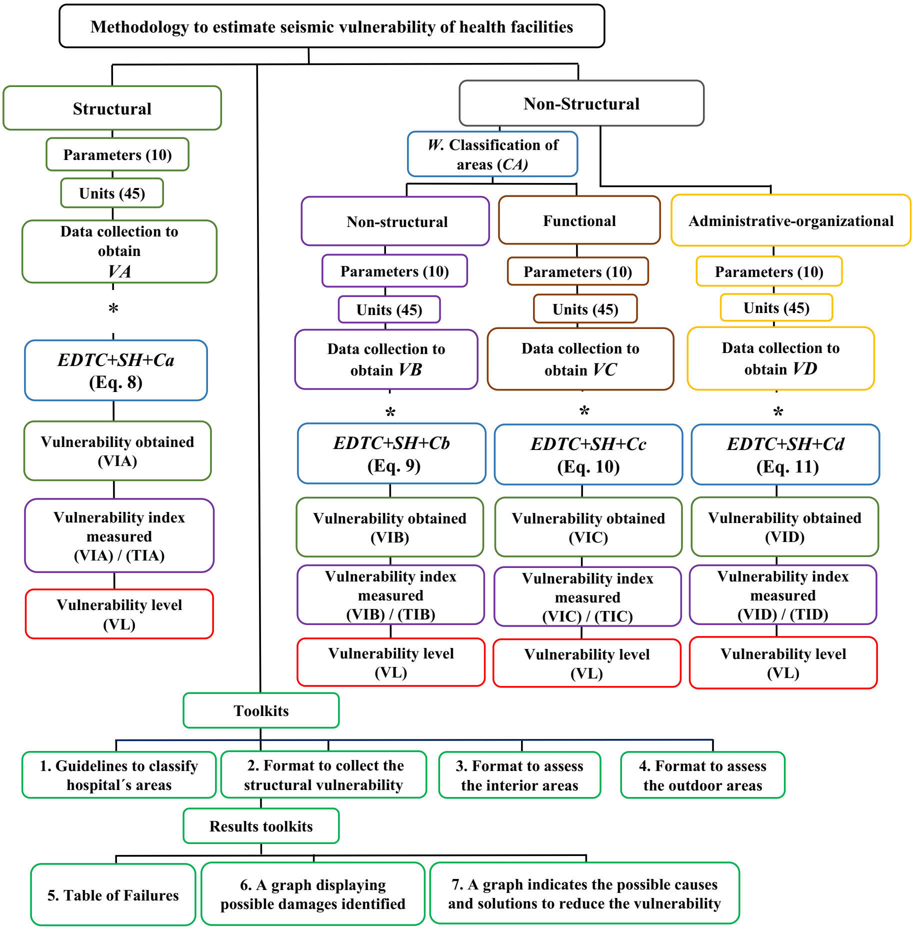

Fig. 1 Schematic procedures to estimate seismic vulnerability of health facilities

3). Considerations for the administrative-organizational vulnerability are similar to the structural vulnerability (Online Resource 4).

2.2 Determination of theoretical indicators

Theoretical indicators (TI) are obtained from the worst cases scenarios in our TF considering the occurrence of a large earthquake. The equations to estimate the theoretical indicators of structural vulnerability for any building system combined with steel (TIA_1) and for any other system (TIA_2) are the following:

$$\mathrm{TIA}_1 = [\mathrm{AI}_1 * (\mathrm{EDTC} + \mathrm{SH})] = 9.42 \tag{1}$$

$$\mathrm{TIA}_2 = [\mathrm{AI}_2 * (\mathrm{EDTC} + \mathrm{SH})] = 8.39 \tag{2}$$

where

$$\mathrm{AI1} = \sum_{I=A}^{J} \mathrm{IA} = 10.47 \tag{3}$$

$$\mathrm{AI2} = \sum_{I=A}^{J} \mathrm{IA} = 9.32 \tag{4}$$

Expected damage according to topology of construction (EDTC) is 0.30, and it represents the maximum weight assigned to the type of topology construction (Table 1). Seismic hazard (SH) = 0.60 is the maximum weight assigned to the seismic hazard location (see point 3 of Sect. 2.4). IA is the theoretical vulnerability value of the structural element obtained from the sum of the numerical values given to each failure for each parameter represented by the second letter of each element (Morán Rodríguez 2012). Thus, the parameters of the structural element are represented by (AA, AB, AC,…, AJ) and the failures of AA by (AA1, AA2, AA3,… AAN). As mentioned before, the total number of failures is 45 in each type of vulnerability, independently that the number of failures in each parameter can be different (Morán Rodríguez 2012; Morán-Rodríguez and Novelo-Casanova 2016). Thus, the sum of the assigned theoretical numerical values for each failure is 10.47 and 9.32 for AI_1 and AI_2, respectively (Eqs. 3 and 4).

The non-structural (TIB), functional (TIC), and administrative-organizational (TID) theoretical indicators are estimated by:

$$\mathrm{TIB} = \sum_{I=A}^{J} \mathrm{IB}*(\mathrm{EDTC} + \mathrm{SH}) = 14.45 * 0.90 = 13.01, \tag{5}$$

Table 1 Weight of expected level of damage by topology of construction (EDTC)

Classification by topology of construction[a]	EDTC	Weight
A	5	0.30
B	4	0.25
C	3	0.20
D	2	0.15
E and F	1	0.10

[a] See point 2 of Sect. 2.4 for description

$$\mathrm{TIB} = \sum_{I=A}^{J} \mathrm{IC}^{*}(\mathrm{EDTC} + \mathrm{SH}) = 9.01 * 0.90 = 8.10, \tag{6}$$

$$\mathrm{TIB} = \sum_{I=A}^{J} \mathrm{ID}^{*}(\mathrm{EDTC} + \mathrm{SH}) = 10.14 * 0.90 = 9.13, \tag{7}$$

where IB (14.45), IC (9.01), and ID (10.14) were obtained as described above for AI (Morán Rodríguez 2012).

2.3 Classification of damage

We used the following classification of damage (Morán Rodríguez 2012): DL = damage to life; DF = damage that limits the functioning of the hospital; DO = damage that inhibits the optimal operation of the installation. The greatest damage is DL to which we assigned a weight equal to 0.50. To DF we considered a weight of 0.40 because it generates less damage with respect to DL. To DO we assigned a weight of 0.10 because it is less important than the previous two kinds of damages. We considered this classification to prioritize actions to reduce the levels of vulnerability found in the different hospital's areas (i.e., reducing DL is the main priority in any hospital). Besides, this classification allows a better understanding of results to hospitals' authorities. Also, available economic resources can be assigned to the most important identified problems that increase vulnerability.

2.4 Weighing

Five weighing factors are considered (Morán Rodríguez 2012):

1. Classification of Areas (CA).
   The different areas in a hospital are classified as follows (Morán Rodríguez 2012; PAHO 2000; WHO 2006):

   - *Area A* Zone of vital importance to protect life (emergency and surgery rooms, intensive care unit, trauma, diagnostic imaging, blood bank, laboratories, pharmacy, administration offices, etc.)
   - *Area B* Zone required for proper functioning of the hospital, however, less important than Areas A in disaster situations. It includes recovery rooms, neurology, hemodialysis facilities, internal medicine, nutrition, urology, neonatology, infectious diseases, pathology and anatomy, laundry services, etc.)
   - *Area C* Areas less important than Areas A and B (ophthalmology, otorhinolaryngology, filing and case management, dermatology, psychiatry, oncology, physiotherapy, dental services, therapy, rehabilitation, etc.)

   Based on this classification of areas, we considered that 100% of areas A are required for proper functioning of the hospital during disasters. Thus, we arbitrarily multiply by 0.50 the numerical vulnerability measured for these areas. Areas B are less important for proper functioning of the hospital. However, we consider that at least 80% of these facilities must work properly during an emergency by multiplying the obtained numerical vulnerability by 0.40. Areas C are less important than areas B, and we believe that at least 20% of these facilities must be functional in disaster situations.

Under these considerations, we multiply the measured numerical vulnerability for these areas by 0.10.

2. Expected damage according to topology of construction (EDTC).
   The weight for this factor is determined by considering the characteristics of the construction material of the hospital. This classification varies from the most to the less vulnerable installations that are those facilities that have incorporated anti-seismic technology. We consider six categories classified from A to F (Table 1) with A as the most vulnerable installation (with a numerical value of 5) and E and F as the less vulnerable (with a numerical value of 1) (Grünthal 1998; Morán Rodríguez and Novelo Casanova 2015, 2016).
3. Seismic hazard (SH).
   The Mexico City's building code classifies the soil of the city in three seismic zones (Gobierno del Distrito Federal 2004b;). Zone I (hill zone) is mainly basalt lava flows with little water content; Zone II (transition zone) is composed of sands with fairly high water content from eroding volcanic cones that surround the Valley of Mexico; Zone III (lakebed zone) consists of silt and volcanic clay sediments of the bed of the historic Lake Texcoco with high water content and exhibits huge amplification of ground motion, resulting in severe damage to the installations located in this area (Ordaz and Singh 1992; Lermo and Chávez-García 1994). For these reasons, we granted to Zone III a weight of 0.60. Because in Zone II the expected damage is less than in Zone III, we considered a value of 0.30 and to Zone I we assigned 0.10 because edifications in this area have less susceptibility to be damaged (Chávez-García and Bard 1994; Ovando-Shelley et al. 2007).
4. Calibration constant (C).
   As part of our methodology, we considered a calibration constant for the structural (VIA), non-structural (VIB), functional (VIC), and administrative-organizational (VID) measured vulnerabilities (see 2.5). The values of these constants were assigned according to their importance with respect to each other. In this work, VID is considered as the most important element for reducing vulnerability in a hospital. For this reason, we assigned to this type of vulnerability a calibration constant $[C(d)] = 0.40$. This is justified by the fact that actions for mitigating risk and reducing vulnerability depend on the decisions of the authorities and personnel of the hospital (De Goyet et al. 2006). VIA is calibrated with a constant value $[C(a)] = 0.30$. This is based on the assumption that the building's safety depends on the structural stability (PAHO 2000; WHO 2006). VIB was calibrated with $[C(b)] = 0.20$. This parameter is considered the third most important in our model because damage in the non-structural parameter supposes substantial economic losses in any hospital (Takahashi and Shiohara 2004; Cimellaro et al. 2010). VIC was calibrated with $[C(c)] = 0.10$ because this element has the less influence in the installation's safety (PAHO and WHO 2012; WHO 2006).
5. Failures
   The weights assigned to failures' numerical values are obtained by multiplying the weight of the type of expected damage (DL, DF, or DO) by the weight of the area where the failure is identified (A, B, or C) (Table 2).

Table 2 Weight values assigned to failures

Classification of damage	Weight applied to failures in areas A ($w = 0.50$)	Weight applied to failures in areas B ($w = 0.40$)	Weight applied to failures in areas C ($w = 0.10$)
Damage type DL ($w = 0.50$)	0.25	0.20	0.05
Damage type DF ($w = 0.40$)	0.20	0.16	0.04
Damage type DO ($w = 0.10$)	0.05	0.04	0.01

2.5 Measurement of the vulnerability index (VI)

Considering all variables and constants previously described, the indices for VIA, VIB, VIC, and VID are determined as follows:

$$\mathrm{VIA} = \frac{[\mathrm{VA} * (\mathrm{EDTC} + \mathrm{SH} + C(a))]}{\mathrm{TIA}} \tag{8}$$

$$\mathrm{VIB} = \frac{[\mathrm{VB} * (\mathrm{EDTC} + \mathrm{SH} + C(b))]}{\mathrm{TIB}} \tag{9}$$

$$\mathrm{VIC} = \frac{[\mathrm{VC} * (\mathrm{EDTC} + \mathrm{SH} + C(c))]}{\mathrm{TIC}} \tag{10}$$

$$\mathrm{VID} = \frac{[\mathrm{VD} * (\mathrm{EDTC} + \mathrm{SH} + C(d))]}{\mathrm{TID}}, \tag{11}$$

where VA, VB, VC, and VD are the numerals of the measured vulnerabilities obtained from the sum of the previously assigned numerical values to each failure for each parameter (Morán Rodríguez 2012).

2.6 Estimation of vulnerability level (VL)

Once VIA, VIB, VIC, and VID are determined, the level of vulnerability is estimated using Table 3.

2.7 Toolkits

For data collection, we developed different tools to identify those failures that determine the different kind of vulnerabilities:

- *Tool* 1 Guidelines to classify hospital's areas (A, B, C).
- *Tool* 2 Format to collect the structural vulnerability data.
- *Tool* 3 Format to assess interior areas. This allows identifying the probable damages in each area of the hospital by classifying the problems according to the TIA, TIB, TIC, and TID parameters (Eqs. 1, 2, 5, 6, and 7).
- *Tool* 4 Format to assess outdoor areas to identify problems that increase vulnerability.

Table 3 Levels of vulnerability

Description	Level of risk	Observations and recommended mitigation measures
Unacceptable	0.81–1.0	Retrofitting of the hospital's buildings is completely necessary. Most elements of the hospital are in very high risk, and structural collapse is possible
Very high	0.61–0.8	The implementation of mitigation measures to diminish the level of vulnerability is necessary. The health facility is in very high risk of losing functioning and structural safety
High	0.41–0.6	The implementation of actions to reduce vulnerability to an acceptable level is urgent. The hospital is in high risk to suffer severe damage
Moderate	0.21–0.4	The hospital can suffer some damage affecting the proper functioning of the installation
Low	0.00–0.2	Regular building maintenance and updating the response and mitigation plans are recommended

- *Tool* 5 Table and graph of failures that classifies those identified problems that increase or decrease vulnerability. This classification allows us to prepare a complete report of potential and existing damages.
- *Tool* 6 Graph displaying a summary of potential damages for each type of analyzed vulnerability.
- *Tool* 7 Graph indicating the possible causes of the levels of vulnerability and possible solutions to reduce it.

2.8 Classification of causes of vulnerability

The causes of vulnerability are classified as follows: (1) C1: lack of enforcement of local regulations for disaster prevention and mitigation; (2) C2: socio-organizational factors that increase risk or lack of awareness of the existing vulnerability problems; and (3) C3: insufficient financial resources for disaster prevention actions. This classification allows us a rapid process to identify the main causes of possible expected damages.

2.9 Proposal of solutions to reduce vulnerability

Three categories of possible solutions are taken into account: (1) S1: implement actions for disaster prevention and reduction; (2) S2: reduce the level of vulnerability to which the hospital is exposed and training of medical and administrative staff for cases of emergency and disasters; (3) S3: provide economic resources to mitigate risk and vulnerability levels. This classification based on categories identifies the main solutions needed for the different hospital's areas.

2.10 Report preparation and presentation of results to hospital's authorities

As last step of the methodology, a report is prepared that includes the identification and classification of failures and their causes as well as proposed solutions to reduce vulnerability and the analysis of the dependence on external supplies. A summary of the procedures to estimate vulnerability using the methodology described above is presented in Fig. 1.

3 Case studies analyses: key findings and recommendations

The three hospitals selected for this study are located on the lakebed zone of Mexico City. This area has high water content and exhibits huge amplification of ground motion (Chávez-García and Aguirre 2012). Henceforth, results are represented in the following manner: (1) All possible failures detected in DL, DF, and DO are reported as percentages. As example, DL = 84% for the structural risk of CaH (see below) was estimated considering that the number of failures is: DL = 37, DF = 6, DO = 0. Total failures = 43. Thus, DL = 37/43 = 84%; (2) the number of causes that generate failures is expressed by C1, C2, and C3; and (3) the number of proposed solutions is indicated by S1, S2, and S3.

3.1 The Cardiology Hospital (CaH)

This hospital suffered serious damage during the 1985 Michoacan earthquake (Singh et al. 1988). As a consequence, all buildings (A, B, C, D, and E) of this health facility that did not collapse were reinforced with seismic resistant technology. For these reasons, the estimated structural vulnerability of this hospital is between low and moderate (Fig. 2a; Table 4). However, 43 structural failures were identified distributed as follows: building

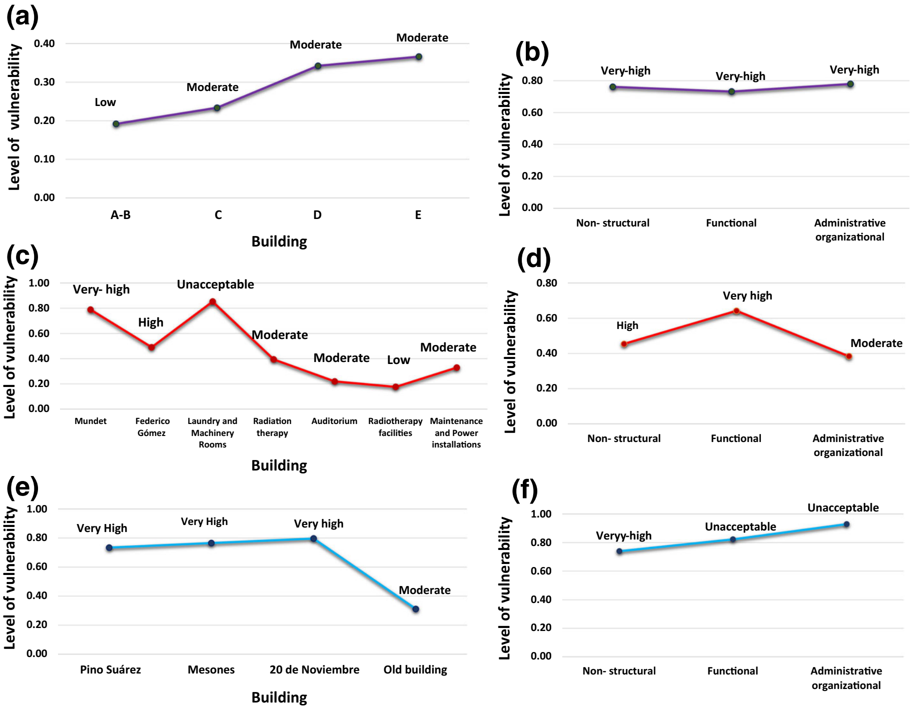

Fig. 2 **a** Structural vulnerabilities of buildings and **b** Non-structural, functional, and administrative-organizational vulnerabilities for the Cardiology Hospital (CaH); **c** Structural vulnerabilities of buildings and **d** Non-structural, functional, and administrative-organizational vulnerabilities for the Children's Hospital (ChH); **e** Structural vulnerabilities of buildings and **f** Non-structural, functional, and administrative-organizational vulnerabilities for the Jesus Hospital (JeH)

Table 4 Structural vulnerability of the Cardiology Hospital's buildings

(C1) Building	(C2) VA[a]	(C3) Description	(C4) Classification topology of construction[b]	(C5) EDTC[b]	(C6) SH (Zone III)[c]	(C7) Calibration constant $C(a)$[d]	(C8) (C5 + C6 + C7)[e]	(C9) VIA* (C2*C8)[e]	(C10) TIA[f]	(C11) ($C9$/ $C10$)[e]	Level of vulnerability VL[g]
A–B	1.39	Reinforced concrete (RC) with moderate seismic design	E	0.10	0.60	0.30	1.00	1.39	8.39	0.19	LOW
C	2.13	Reinforced concrete (RC) with moderate seismic design	E	0.10	0.60	0.30	1.00	2.13	8.39	0.23	MODERATE
D	2.28	Reinforced concrete (RC) with moderate seismic design	E	0.10	0.60	0.30	1.00	2.18	8.39	0.34	MODERATE
E	2.63	Reinforced concrete (RC) with moderate seismic design	E	0.10	0.60	0.30	1.00	2.63	8.39	0.37	MODERATE

[a] Equation (8); [b] See Table 1; [c] See point 3 of Sect. 2.4; [d] See point 4 of Sect. 2.4; [e] See Eq. (8); [f] See Eq. (2); [g] See Table 3

A–B = 7; building C = 9; building D = 13; and building E = 14 (Fig. 3a1). The main failures in this hospital have high and moderate impact to life (DL = 84%) and functioning aspects (DF = 14%), respectively (Fig. 3a2). The main causes of the failures mentioned above are the lack of: (1) appropriate internal regulations for disaster prevention (C1 = 21); (2) risk prevention actions (C2 = 15); and (3) sufficient economical resources for preventive initiatives (C3 = 7) (Fig. 3a3). Some proposed solutions for reducing vulnerability at CaH are: (1) implement actions for disaster prevention and reduction (S1 = 21). In this case, we suggest to get rid of the bridge connections between buildings and remove heavy objects from the building's roofs as well as discard the pipeline

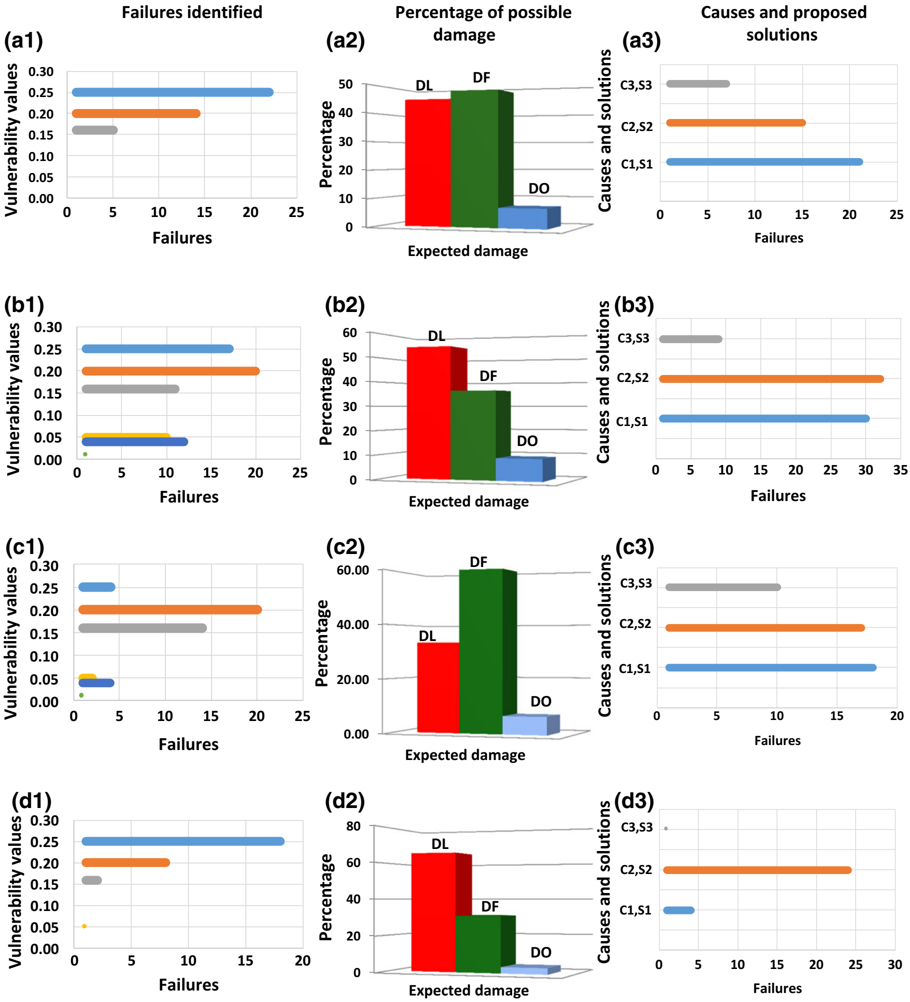

Fig. 3 Vulnerability of CaH. **a1** Number of identified failures; **a2** Percentage of possible damage; **a3** Number of causes (C1–C3) and number of proposed solutions (S1–S3) for the structural vulnerability failures; **b1**–**b3** Same as **a1**–**a3** for the non-structural vulnerability; **c1**–**c3** Same as **a1**–**a3** for the functional vulnerability; **d1**–**d3** Same as **a1**–**a3** for the administrative-organizational vulnerability; DL= Damage to life; DF= Damage that limits the functioning of the hospital; DO= Damage that inhibits the optimal operation of the health facility. For description of C1, C2, C3, S1, S2, and S3 see text

installations and the machinery that are not currently used; (2) provide maintenance to those structures identified with high level of vulnerability for proper hospital's functioning in case of a major earthquake impacting Mexico City including the buildings' foundations to prevent collapse (S2 = 15); and (3) invest economic resources to mitigate risk and vulnerability levels (S3 = 3) (Fig. 3a3). We also recommend installing earthquake-resistant technology in all buildings for their stability and providing maintenance to this system that has been already installed in some of the hospital's edifices.

The non-structural vulnerability in CaH is very high (Fig. 2b), and the number of failures found was 71, where 33 failures are in areas A, 19 in areas B, and 19 in areas C (Fig. 3b1). Some of these failures are: (1) heavy panels placed at the ceiling finish and objects blocking evacuation routes (DL = 55%); (2) most windows, furniture, shelves with medications and other objects will fall during the impact of an earthquake (DF = 36%); (3) incomplete installations of medical gases in the hospital's rooms to provide medical care to patients in areas A and B (DO = 9%) (Fig. 3b2). The main causes of these failures are: (1) Some areas within the hospital are not functioning properly because part of their equipment is out of order (C1 = 16); (2) the hospital's authorities are unaware of their installations' level of seismic vulnerability (C2 = 14); (3) the economic resources available to implement risk reduction measures are insufficient (C3 = 3) (Fig. 3b3). Some of the main solutions proposed to minimize failures are: (1) Replace heavy materials placed on the roofs of the buildings by lightweight materials (S1 = 16); (2) provide adequate emergency signals and remove those objects that are blocking the evacuation routes (S2 = 14); and (3) install prevention systems to ensure that large glass surfaces will not be broken and provide furniture, equipment, and medical material that are necessary for proper functioning of areas A and B (S3 = 3) (Fig. 3b3).

The functional vulnerability in CaH is very high (Fig. 2b). A total of 45 failures were identified, 37 in areas A, four in areas B, and four in areas C (Fig. 3c1). Some of these failures are related to external supplies dependence representing possible damage to life and proper operation of the institution in disaster situations. The main identified failures are: (1) Some emergency exits are locked; (2) lack of enough internal resources for independent proper functioning during 3–5 days after a disaster (DL = 41%); (3) supply pipes such as medical gases, electricity, water, and drainage need maintenance because of leaking; (4) lack of a local plan to manage the physical and medical resources available in case of a large number of injured people (DF = 51%); (5) critical areas are located in different buildings of the facility, and this feature does not allow an efficient medical care during disasters; and (6) the existing hospital's emergency plan does not consider medical and staff resources that could be available from nearby health facilities (DO = 8%); (Fig. 3c2). The main causes of this vulnerability conditions are: (1) lack of a department within the hospital responsible for monitoring the furniture and equipment's safety during earthquakes; (2) hospital's authorities are unaware of the need to develop actions to reduce their dependence on external supplies during disasters (C1 = 16); (3) hospital's authorities are unaware of their level of seismic vulnerability. For this reason, actions to reduce their vulnerability have not been implemented yet (C2 = 15); and (3) lack of economic resources for risk mitigation and vulnerability measures (C3 = 6) (Fig. 3c3). We propose some activities for solutions of the failures detected: (1) Provide maintenance to supply pipes and change rigid materials for flexible materials in their joints (S1 = 16); (2) critical facilities must be located in the same area (emergency and surgery rooms, intensive care unit, sterilization, diagnostic imaging, blood bank, etc.). At least the emergency and surgery rooms as well as the intensive care unit must be close to each other; (3) establish with nearby hospital's authorities agreements to support themselves in case of disaster situations

(S2 = 15); (4) hospital's authorities need to implement an operational emergency plan considering possible secondary roads to transport patients in case of disasters; and (5) install all resources for proper autonomous operation of the hospital during 3–5 days after a disaster strikes including medical supplies, water, and electricity (S3 = 6) (Fig. 3c3).

The administrative-organizational vulnerability is very high (Fig. 2b). We identified 29 failures related to possible damages (Fig. 3d1). The main failures observed are: (1) The existing emergency plan is not used and it is not updated (DL = 66%); (2) the medical staff lacks of training for disaster management or triage (DF = 31%); and (3) hospital's authorities are unaware of the physical and human resources that can share with nearby hospitals in case of a disaster (DO = 3%) (Fig. 3d2). The main causes for the very high administrative-organizational vulnerability are: (1) The hospital does not have a department for disaster response or/and prevention (C1 = 4); (2) hospital's authorities do not allocate financial resources to mitigate the existing seismic vulnerability (C2 = 24); and (3) mitigation actions to reduce the level of vulnerability are not a main priority for hospital's authorities (C3 = 1), (Fig. 3d3). Some proposed solutions are: (1) The hospital's authorities must establish a department for local civil protection and should develop a fully operational emergency plan (S1 = 4). (2) Provide permanent training to medical and administrative staff on issues regarding the hospital' safety in case of disaster situations (S2 = 24) and invest economic resources in actions to reduce the institutions' vulnerability (Fig. 3d3).

3.2 The Children's Hospital (ChH)

The unacceptable very high and high levels of structural vulnerability measured at ChH (Fig. 2c) are mainly because some of its buildings are more than 70 years old and their characteristics of construction do not incorporate earthquake-resistant technology. The "Mundet" and "Federico Gomez" buildings as well as the laundry and machinery installations have very high probability to be seriously damaged in case of being impacted by a large earthquake. However, the other main buildings have low and moderate level of vulnerability. The number of failures found is 109, considering the failures found in each of the hospitals' buildings (Mundet = 26, Federico Gómez = 17, Laundry = 28, Rehabilitation = 13, Auditorium = 8, Radiotherapy room = 6, Machinery room = 11) (Fig. 4a1). The identified failures represent high level of damage to life (DL = 92%). However, functionality in ChH will be moderately impacted (DF = 8%), and damage to proper functioning of the facility is absent (Fig. 4a2). Some of the failures identified are: (1) oxidized cracks greater than 3 mm in some buildings; (2) detachment of large and heavy exterior finishes and parapets; (3) bridge connections between buildings that increase their vulnerability; and (4) architectural H and large rectangles shapes that can be seriously damaged by the passage of seismic waves. The main causes for the very high and high levels of structural vulnerability are lack of: (1) appropriate internal regulations for disaster prevention (C1 = 58); (2) implementation of prevention actions (C2 = 20); and (3) sufficient economical resources for preventive actions such as the installation of earthquake-resistant technology (C3 = 31) (Fig. 4a3). Some of the proposed specific solutions for reducing the structural vulnerability at ChH are: (1) Retrofit the laundry and machinery buildings; (2) remove heavy objects from the main buildings' roofs such as machinery and water containers; (3) remove mechanical parts of the pipeline installation and the machinery that are not currently used (S1 = 58); (4) provide maintenance to local building's finishes to prevent falling; (5) waterproof walls and ceilings (S2 = 20); and (6)

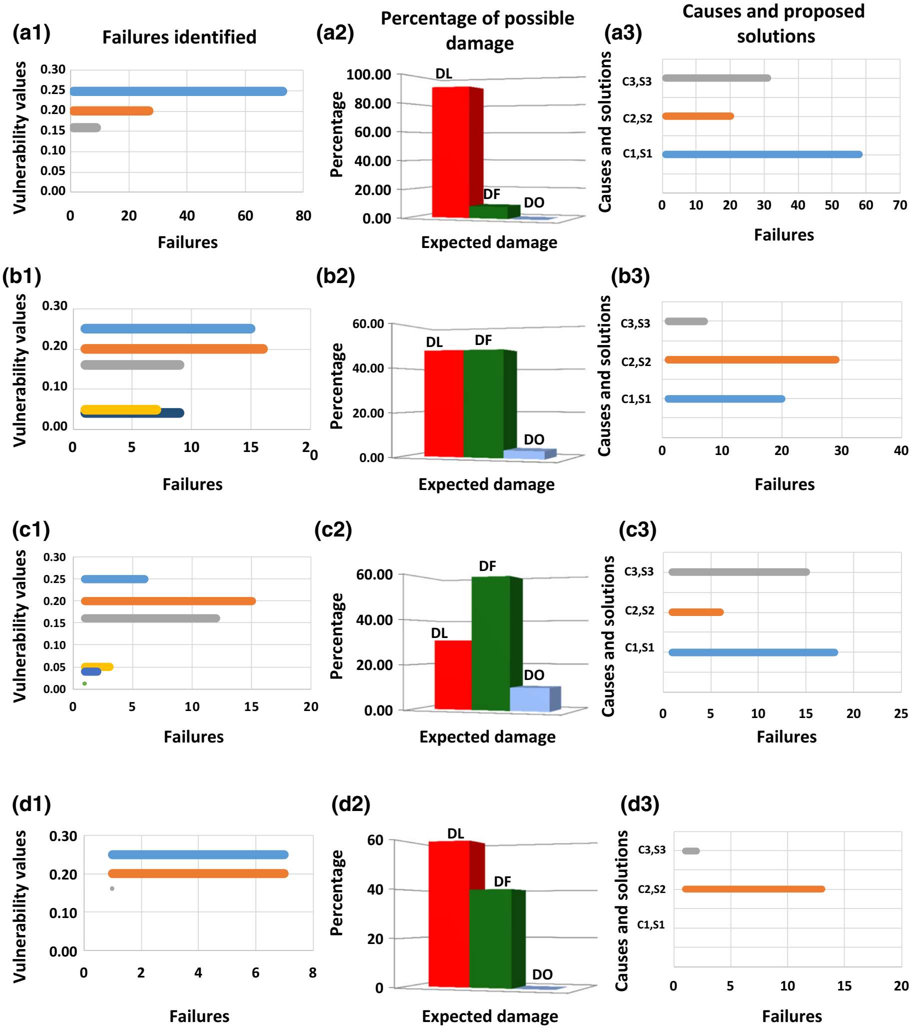

Fig. 4 Vulnerability of ChH. **a1** Number of identified failures; **a2** Percentage of possible damage; **a3** Number of causes (C1–C3) and number of proposed solutions (S1–S3) for the structural vulnerability failures; **b1**–**b3** Same as **a1**–**a3** for the non-structural vulnerability; **c1**–**c3** Same as **a1**–**a3** for the functional vulnerability; **d1**–**d3** Same as **a1**–**a3** for the administrative-organizational vulnerability; DL= Damage to life; DF= Damage that limits the functioning of the hospital; DO= Damage that inhibits the optimal operation of the health facility. For description of C1, C2, C3, S1, S2, and S3 see text

incorporate earthquake-resistant technology to buildings to improve their stability (S3 = 31) (Fig. 4a3).

The non-structural vulnerability in ChH is high (Fig. 2d), and we identified 56 failures where 28 are in areas A, 14 in areas B, and 14 in areas C. The main problems and the expected damage associated are: (1) Fire and explosions are possible due to spilling of dangerous substances; (2) heavy panels in ceilings can fall down; (3) existence of large windows with glass surfaces without protection to prevent breaking (DL = 61%); (4) the local emergency plan is not adequate for the three medical work shifts; (5) insufficient medical staff and equipment to provide medical care to patients in areas A and B in disaster situations (DF = 32%); and (6) lack of enough basic emergency equipment (fire fighting systems, seismic alert, etc.) (DO = 7%) (Fig. 4b2). The main causes for the high non-structural risk at ChH are: Some medical equipment is out of order and needs to be replaced or fixed (C1 = 12); Local authorities are not aware of the high level of seismic vulnerability of their installations neither of the factors that increase risk (C2 = 13). Also, up to present, not enough economic resources are available for risk reduction measures (C3 = 3). Specific proposed solutions to reduce ChH's non-structural vulnerability are: (1) Install emergency equipment, flexible joints in piping installations, and brackets on shelves and furniture to avoid downfall objects during the possible impact of a large earthquake (S1 = 12); (2) replace heavy materials placed on the roofs of the installations and finishes by lightweight materials; (3) replace old equipment (power generators, elevators, washing machines, etc.) by new ones and remove obsolete equipment and material from the installations (S2 = 13); (4) invest financial resources to reduce the degree of vulnerability in this element (S3 = 3) (Fig. 4b3).

The functional vulnerability is very high in ChH (Fig. 2d). The number of failures identified was 39, and 34 of them are located in areas A, three in areas B, and two in areas C (Fig. 4c1). The main problems identified are: (1) lack of special rooms for patients in shock; (2) lack of emergency exits and stairs; (3) lack of autonomy to maintain functioning of the hospital during 72 h without external supplies; (4) lack of hydrants or emergency equipment in outdoor areas (DL = 35%); (5) the security and triage areas have not been established; (6) small temporary food shops operating in the surroundings of the hospital with inappropriate gas installations; (7) the heliport is not operating (DF = 53); (8) heavy equipment and water tanks are placed on rooftops of some of its installations; and (9) the main access routes to the hospital may be seriously damaged in case of a major earthquake (DO = 12%) (Fig. 4c2). The main causes of the identified damage are: (1) lack of actions to comply with the legal framework governing hospital institutions (C1 = 18); (2) the hospital authorities have not implemented actions to reduce seismic risk yet and the current emergency plan does not include the analysis of external supplies (C2 = 6); (3) insufficient economical resources for developing vulnerability reduction measures (C3 = 10). The main solutions recommended are: (1) Provide maintenance to emergency exits and stairs; (2) hydrants and emergency equipment should be placed in key areas according to hospital's regulations; (3) establish security and triage areas (S1 = 18); (4) it is necessary to establish coordination actions with nearby hospitals to optimize medical care and human resources on disaster situations; (5) it is necessary to prepare alternate routes for the arrival of ambulances and injured in emergency conditions; (6) temporary food shops must be removed from the surroundings of the hospital; (7) remove heavy equipment and water tanks that are on rooftops of the main buildings (S2 = 6); (8) provide to hospital's areas A and B appropriate equipment and installations; and (9) implement actions to ensure external supplies for at least 72 h after a disaster strikes (S3 = 10) (Fig. 4c3).

The administrative-organizational vulnerability at ChH is high (Fig. 2d), and a total of 15 failures were identified (Fig. 4d1). The main problems found are: (1) The emergency response plan was developed only for the morning and afternoon's medical staff and did not include the night staff; (2) medical staff is untrained on the use of triage cards to classify injured people during disasters (DL = 60%); (3) the list of staff and service providers is incomplete; (4) blueprints of buildings are obsolete (DF = 40%); in this case, DO is absent (Fig. 4d2). The main cause of these problems is that hospital's authorities are not aware of their level of seismic vulnerability (C2 = 13), and economic investment is required to implement measures to reduce the level of vulnerability (C3 = 2). Causes of type C1 were not identified (Fig. 4d3). Some suggested solutions are: (1) Prepare a list of available medical personnel and of supply companies in case of disasters; (2) update emergency plans and provide staff training for patient care in case of disaster situations; (3) the emergency plan must be operational independently of the time of the emergency (S2 = 13); (4) provide equipment (air conditioning, environment purifiers, oxygen, and liquids' suction and furniture for optimal medical care in areas A and B (S3 = 2). Solutions of type S1 are not necessary (Fig. 4d3).

3.3 The Hospital de Jesus (JeH)

The structural vulnerability of most buildings of the Hospital de Jesus (JeH) is very high and high (Fig. 2e). In general, this installation could be seriously damaged due to the impact of a major earthquake in Mexico City. In the structural element, 90 failures were identified in the four buildings of the hospital (Pino Suarez = 25; Mesones = 26; 20 de Noviembre = 27; and historic building = 12) (Fig. 5a1) and the expected damage to life is very high (DL = 91%). The main issues that condition the structural vulnerability are: (1) Contemporary buildings (20 de Noviembre, Pino Suarez, and Mesones) can be seriously damaged; (2) none of the buildings of this hospital has anti-seismic technology although this kind of technology is recommended due to the characteristics of the soil where the facility is located; (3) some of its buildings can be seriously damaged due to the torsion forces that are generated by their elongated rectangle geometric form; (4) there is the possibility of pounding effect between contiguous buildings due to an earthquake because of their height difference and the lack of proper separation between them; (5) detachment of large and heavy exterior finishes and parapets; and (6) all buildings require maintenance (DF = 9%). In this case, DO is absent (Fig. 5a2). The main cause of these problems is the lack of enforcement of local regulations for disaster prevention and mitigation (C1 = 43); the hospital's authorities are unaware of the level of the seismic vulnerability that this institution is exposed to, and for this reason, no action has been implemented to reduce their risk (C2 = 10). Finally, investment for implementation of earthquake-resistant technology is needed (C3 = 37) (Fig. 5a3). Proposed solutions are: (1) Provide adequate and regular maintenance to the structure; (2) incorporate earthquake-resistant technology for stability of the hospital's buildings (S1 = 43); (3) replace heavy finishes in frontage and interiors of buildings by lighter material; (4) remove heavy objects from the roofs (S2 = 10); and (4) invest economic resources to mitigate risk and vulnerability levels (S3 = 37) (Fig. 5a3).

The non-structural vulnerability in JeH is very high (Fig. 2f), and 59 failures were identified in this hospital, where 35 of these failures are located in areas A, 14 in areas B, and ten in areas C (Fig. 5b1). Some of these failures are similar to those found at ChH. Additional problems are: (1) overload of electrical power contacts (DL = 69%); (2) large objects blocking evacuation routes (DF = 26%); and (3) areas of triage and care of patients in disaster situation lack of all necessary equipment (DO = 5%) (Fig. 5b2). The main causes identified are: (1) lack of seismic shock absorber for heavy equipment (C1 = 15); (2) the hospital's authorities are unaware of the level of seismic vulnerability that the facility is exposed to (C2 = 9); (3) lack of sufficient financial resources for vulnerability reduction projects (C3 = 11) (Fig. 5b3). Some of the proposed solutions are: (1) No to overload power contacts (they can cause fires). It is necessary to install additional electrical contacts in the hospital's areas A and B (S1 = 15); (2) remove any object that obstructs evacuation routes (S2 = 9); and (3) provide financial resources for seismic prevention actions (S3 = 11) (Fig. 5b3).

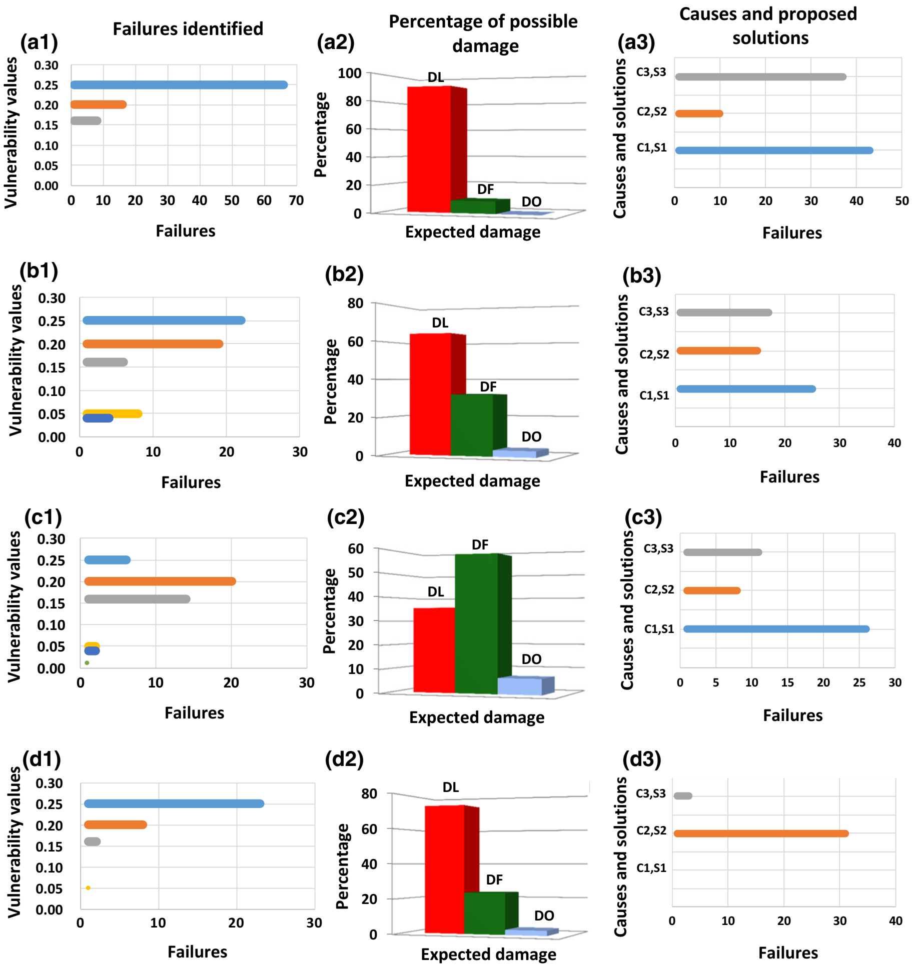

Fig. 5 Vulnerability of JeH. **a1** Number of identified failures; **a2** Percentage of possible damage; **a3** Number of causes (C1–C3) and number of proposed solutions (S1–S3) for the structural vulnerability failures; **b1**–**b3** Same as **a1**–**a3** for the non-structural vulnerability; **c1**–**c3** Same as **a1**–**a3** for the functional vulnerability; **d1**–**d3** Same as **a1**–**a3** for the administrative-organizational vulnerability; DL= Damage to life; DF= Damage that limits the functioning of the hospital; DO= Damage that inhibits the optimal operation of the health facility. For description of C1, C2, C3, S1, S2, and S3 see text

The functional vulnerability at JeH has an unacceptable level (Fig. 2f), and 45 failures were identified, 39 of these are in areas A, four in areas B, and two in areas C (Fig. 5c1). The main problems identified were: (1) The pipeline and machinery installations are highly deteriorated; (2) the period of autonomy of JeH is very short, and it needs to be revised as well as the availability of medical supplies providers after a disaster strikes (DL = 41%); (3) lack of proper signals for evacuation routes and hazardous materials (DF = 51%); (4) inappropriate access for disabled patients; and (5) JeH needs to be self-sufficient in case of disasters (DO = 8%) (Fig. 5c2). The main causes are: (1) lack of guidelines for people's safety (C1 = 21); (2) lack of knowledge of hospital's authorities about their installation's level of seismic vulnerability (C2 = 8); and (3) lack of financial resources for building maintenance (C3 = 10) (Fig. 5c3). Proposed solutions are: (1) Design appropriate evacuation routes and safety areas; (2) analyze alternative roads for arrival of injured people during disasters (S1 = 21); (3) provide periodic maintenance to installations and equipment; (4) implement a plan for proper functionality of the facility without external supplies for a period of 5 days (S2 = 8); and (3) make sure of proper operation of hospital's areas A and B (S3 = 10) (Fig. 5c3).

The administrative-organizational vulnerability is unacceptable (Fig. 2f) because 34 failures were found (Fig. 5d1). The main problems identified were: (1) lack of an operational emergency response plan (DL = 74%); (2) hospital's authorities have not implemented any vulnerability reduction actions (DF = 24%); and (3) financial resources are insufficient for disaster prevention actions (DO = 3%) (Fig. 5d2). The main causes are: (1) Hospital's authorities are not aware of their level of seismic vulnerability (C2 = 31) and insufficient financial resources for disaster prevention actions (C3 = 3). Causes of type C1 were not found (Fig. 5d3). Proposed solutions are: (1) Hospital's authorities need to be trained on disaster management issues; (2) updating of the emergency response plan (S2 = 31); and (3) financial resources need to be allocated to reduce the vulnerability of the health facility (S3 = 3). Solutions of types S1 are unnecessary (Fig. 5d3).

4 Discussion

Hospitals play a critical role in providing treatment and support to victims in the aftermath of a disaster. For this reason, both hospital administrators and medical staff must be extremely sensitive to the types of functions and medical equipment that are necessary to support their vital role during disasters.

When an earthquake strikes, it first directly impacts the structural and lifeline systems, medical facilities, and medical services in terms of structural damage. Second, structural damage will result in non-structural systems impairment. Third, the lifeline system damage will influence the proper operation of medical equipment. And fourth, collectively, the damage or inoperability of the building's structure, lifelines, and/or medical equipment will impact the overall delivery of medical services. Thus, it is important to ensure that all components in hospitals perform adequately in the event of a strong ground motion. For each medical service provided to a patient, many supporting resources are needed, including human and physical facility resources. Hospitals are complex systems containing a large quantity of seismically fragile machinery, often more fragile than the structures containing them.

Our methodology demonstrates the importance of detailed measurements to determine vulnerability in a health facility to prioritize actions to reduce the impact of a large earthquake. It is important for any method used to determine the vulnerability of a health facility also to identify the expected damage in each hospital's area including the structural, non-structural, functional, and administrative-organizational elements. In this work, the main failures that represent high and very high damage to life and to the proper functioning of the health facility were identified.

The observed very high and high levels of structural vulnerability in our case studies are mainly due to the lack of maintenance and technology to stand seismic shaking as well as the use of complex architectural shapes. Another factor that increases structural vulnerability is the lack of enough separation among the different hospital's installations that may generate a pounding effect among these buildings in the case of the occurrence of a local earthquake. Also, the type and age of the hospital as well as heavy objects or architectural elements placed on top of the roofs that are not considered in the original structural design increase the susceptibility of these buildings to suffer severe damage by passing seismic waves.

Related to the non-structural vulnerability, the main failures are the use of structures not appropriate for hospitals such as heavy panels in ceilings and large windows with glass surfaces without protection to prevent breaking. However, possible solutions are to reduce the high level of vulnerability by implementing low-cost measures such as protection of large glass surfaces and the exchange of heavy to lightweight materials placed on the roofs of the installations. The main problem identified in the functional vulnerability is the lack of knowledge of hospital's authorities about their installation's level of seismic vulnerability. The unacceptable and very high level of the administrative-organizational vulnerability is caused by the lack of an emergency plan to stand a large earthquake. We believe that it is possible to reduce significantly risk and vulnerability in hospitals with the development and implementation of a complete operational emergency plan and providing periodic structural maintenance to the different health facility's buildings as well as installing anti-seismic technology.

Also, it is important to implement security measures such as installing emergency materials as well as fire fighting systems and the seismic early warning system that is available in Mexico City (Espinosa Aranda et al. 1995). Also, the high functional vulnerability measured is mainly due to the lack of rooms in areas A and B to support life of patients in shock, absence of triage, and intensive care areas. It is necessary for the analyzed hospitals to provide training to medical staff on disaster response management. Besides, the administrative-organizational vulnerability is high because of the need of sufficient financial resources for disaster prevention actions. It is important to perform an assessment of the supplies required for a proper autonomous operation of health facilities during at least 72 h after a disaster strikes. From the combined results of Morán-Rodríguez and Novelo-Casanova (2012) and those obtained here, we can consider that the health infrastructure of Mexico City has high level of vulnerability to seismic hazards. Thus, it is necessary to assess in detail the level of vulnerability of each main hospital in this city. The percentage of the cost of non-structural elements at a total cost of construction is much higher in hospitals than in other urban buildings. In some cases, the non-structural elements represent about 60% of the value of residential housing, whereas for hospitals the range is from 85 to 90%, mainly due to the cost of medical equipment (World Health Organization 2015).

5 Conclusions

The methodology developed here is an important tool that allows to implement and/or strength existing programs to reduce the levels of structural, non-structural, functional, and administrative-organizational vulnerabilities of health facilities in Mexico City and other seismic prone areas. The method also provides mechanisms to facilitate data collection, and the results classify the urgent actions that are required to reduce the degree of vulnerability to an acceptable level. It also analyzes the interrelation with the external infrastructure systems needed in disaster situations. The methodology identifies possible failures that increase vulnerability and expected damages associated with these failures in the different hospitals' areas and buildings. Results are presented for the medical and administrative personnel in an accessible manner. We believe that the methodology developed here has more strength than others developed with the same objective.

The vulnerability problems found in the three case studies are common among them even having different structural, organizational, medical specialties, and geographical location. For these reasons, we believe that it is important for the Mexican government to develop a specific program to determine the level of vulnerability to seismic hazards of at least the main and secondary health facilities in Mexico City by applying the method developed here. Hospitals are only truly safe from disasters when they are functioning at maximum capacity immediately after a hazard strikes. Although the general working principles and systems are the same in all hospitals, each hospital has its own unique adaptation that makes them different from the systems in another hospital. Since damage is often directly related to these differences, it is necessary to develop hospital-specific detailed seismic vulnerability analyses.

The JeH is the most vulnerable of the three case studies with unacceptable level of functional and administrative-organizational vulnerabilities. The structural vulnerability of its buildings varies from high to very high. The ChH has very high structural and operational vulnerabilities and high non-structural vulnerability. In general, the CaH was identified with the lowest level of structural vulnerability. However, the operational and the social administrative vulnerabilities are very high

In general, hospital administrators of the three case studies must identify vulnerable areas of the hospital complex, particularly those areas that provide essential support to the facility. They must establish a cost-effective mitigation plan to minimize their vulnerability to seismic hazards. Such an investment in mitigation will ensure that a hospital is able to fulfill its essential role as a provider of critical care to victims following a disaster.

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