CHAPTER III

THEORETICAL FRAMEWORK

3.1 Earthquake

Earthquake has been becoming one of the most renowned disasters all over the world. Based on the causes, earthquake can be classified into four types namely, explosion earthquake, volcanic earthquake, collapse earthquake, and tectonic earthquake (Prawirodikromo, 2012). The latter, tectonic earthquake is the most common and the frequently occurred.

Tectonic earthquake is strongly connected to the existence of Ring of Fire (See Figure.3.1). About 90% of the world's earthquakes occurred near the Ring of Fire or also called Circum-Pacific Belt (Holbrook, 2011). Additionally, based on the magnitude, earthquake can be categorized into six classes (see Table 3.1). Moderate up to great earthquakes can cause the loss of life or injury, property damages, social and economic disruption, or environmental degradations.

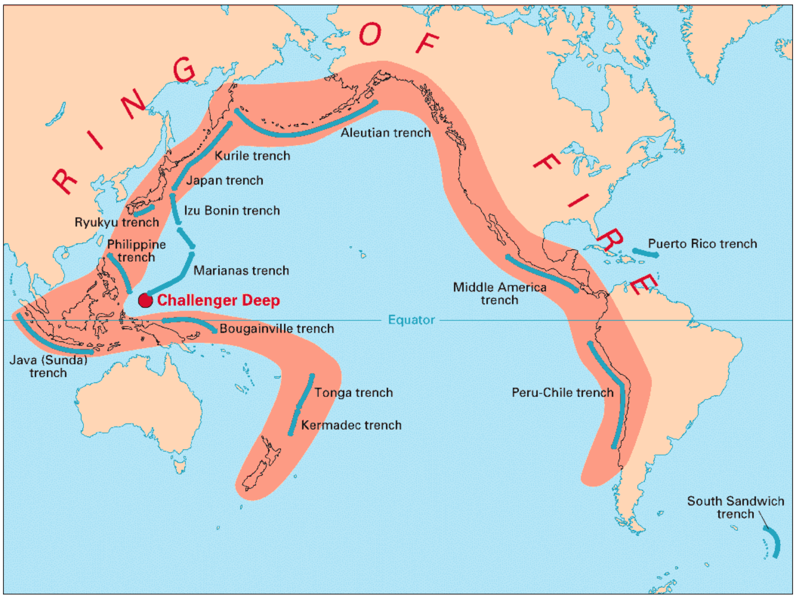


Figure 3.1 The Ring of Fire or Circum-Pacific Belt

(Source: USGS, 1999)

Table 3.1 Earthquake Magnitude Classes

Class	Magnitude
Great	8 or more
Major	7 - 7.9
Strong	6 - 6.9
Moderate	5 - 5.9
Light	4 - 4.9
Minor	3 -3.9

Source: UPSeis (2017)

3.2 Seismicity of Indonesia

Indonesia is one of the most disaster-prone countries in the world. In the last three decades, Indonesia faced multiple hazards including geological or geophysical, hydro-meteorological, epidemical, and social hazards (Priester, 2016). Of these, geological/geophysical and hydro-meteorological hazards are the main threats that have resulted in national disaster. Additionally, over the past 20 years, Indonesia has become headlines in the media around the world due to devastating natural disasters and the impacts, such as loss of life, economic activities disruption, and destructive effect on buildings and infrastructures (Indonesia Investments, 2017).

Geographically speaking, Indonesia is located on the Ring of Fire and at the meeting point of three major tectonic plates, namely Indo-Australian Plate, Eurasian Plate, and Pacific Plate. This geographical features lead to high seismic activity and formation of volcanoes. In addition, located in a tropical area, Indonesia is also prone to other disasters such as drought, tornadoes, floods, extreme rainfall, and landslides (BNPB, 2017).

Based on the frequency of occurrence, flooding is on the top of the list of the most frequently occured disasters. Between 1990 and 2014, the occurence frequency of flooding was the highest with 43.8% and then followed by earthquake with 25.9% (EM-DAT, 2015). However, based on the fatalities and damages, earthquakes and tsunamis have topped the list of the disasters in Indonesia occurred between 1980 and 2015 (CFE-DMHA, 2015) (See Table 3.2). The Indian Ocean earthquake and tsunami solely has caused more than 160 thousand fatalities. This number is even higher than the total fatalities of the remaining disasters occurred between 1980 and 2015 combined. This is one of the worst disasters ever occurred on earth.

Table 3.2 Ten Deadliest Disaster in Indonesia Between 1980 and 2015

No.	Disaster Type	Year	Fatalities	Description
1	Earthquake & Tsunami	2004	165,708	Indian Ocean 9.2RS
2	Earthquake	2006	5,778	Yogyakarta & Central Java 6.3RS
3	Earthquake	1992	2,500	Flores 7.8 RS
4	Earthquake	2009	1,117	West Sumatra 7.6RS
5	Earthquake	2005	915	Nias 8.7RS
6	Earthquake	2006	802	Tasikmalaya 7.7RS
7	Epidemic	1998	777	Dengue, Jakarta
8	Drought	1997	672	Central Papua
9	Epidemic	1998	672	Rabies, Flores
10	Epidemic	2004	658	Dengue, Jakarta

Source: CFE-DMHA (2015)

Earthquake has become a scourge for human beings due to its potency to cause devastations. In Indonesia, earthquakes occur daily. In average, the occurrence of earthquake is around 6000 times a year stated by Sutopo Purwo Nugroho, Head of Information Data and Public Relation Center BNPB (Liputan 6, 2018). During the period of 1992 to 2000, thousands of earthquake were recorded. The epicenters of the earthquake were plotted into a map as shown in Figure 3.2. We can see on the map that the only island of Indonesia which has less earthquake events is Kalimantan Island, while Sumatera, Java, Sulawesi, and Papua have enermous earthquake events history.

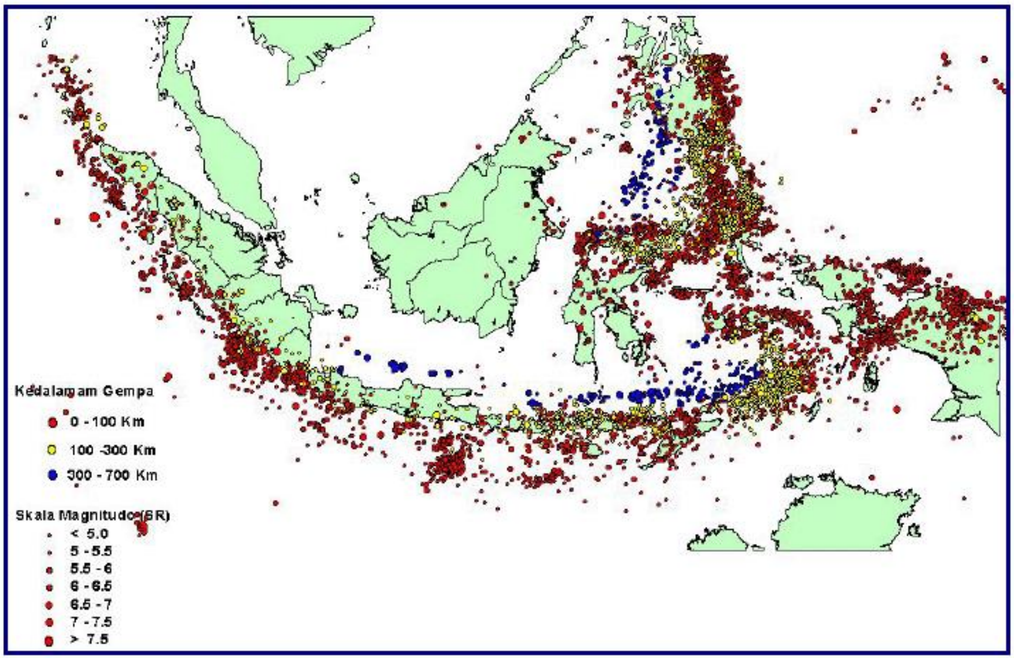


Figure 3.2 Recorded Earthquake in Indonesia during 1992-2000
(Source: BMKG as cited in Pribadi, Kusumastuti, Rildova, 2008)

Given that earthquake hazard is unavoidable in most of the areas of Indonesia, it is very important to ensure that buildings built in these areas perform well during earthquake. Buildings should be built by following the latest codes and the existing structures should be assessed to check their performances. Therefore, through assessment, the probability of physical damages states can be obtained and further action plans can be prepared.

3.3 Banjarnegara Earthquake April 18th, 2018

Banjarnegara is one of the districts within Central Java Province. Geologically speaking, most of the areas of Banjarnegara deposit landslide-prone soil layers that have led to a number of lanslide events in the past. The latest lanslide event occurred on 2014 in sub-district of (*Kecamatan*) Karangkobar. The landslide buried 43 dwellings and caused 300 people internally displaced (Naryanto, 2017).

Besides renowned as lanslide-prone area, Banjarnegara also deposits a number of faults which lead to earthquake events (see Figure 3.2). In the last ten years, besides the 2018 earthquake, there were at least two earthquakes hit

Banjarnegara in 2009 and 2011 respectively. These earthquakes were also triggered by local faults, however, the magnitude were below Mw 4.

On April 18^{th}, 2018, a Mw 4,4 earthquake hit Kalibening sub-district, Banjarnegara (see Figure 3.3). The magnitude was relatively small, yet it was able to cause major damages. Explained by the Head of BMKG, Dwikorita, the magnitude was below Mw 5, but the MMI reached IV and V scale because the earthquake hipocenter was shallow and triggered by a local fault or slip (Liputan 6, 2018). The fault constitues a newfound fault which has not been identified in earthquake hazard map issued by Indonesia Government 2012. BMKG (2018) stated that the fault is located around Kalibening-Wanayasa faults. The soil layer also contributed to make the impacts worse. The soil layer amplify the ground acceleration because it consist of loose and soft layers (Pemkab Banjarnegara, 2013).

The National Disaster Management Authority (BNPB) reported that the earthquake caused damages on dwellings, mosques, schools, and public facilities. Further, on April 18^{th} 2018 evening, BNPB released the number of casualties. Two people were killed, 21 people were injured, and more than 2000 people were internally displaced. The report of rapid visual screening of building damages on April 18^{th} 2018 shows that there were 317 building damaged. These building are mostly located in Kasinoman, Kertosari, and Plorengan Village. Local government immediately declared emergency response status for the next 14 days.

After the occurrence of Mw 4 Banjarnegara Earthquake, there were around 13 aftershock earthquakes recorded from April 18^{th} to 22^{nd} , 2018 (MSN, 2018). . However, all of the magnitudes are below Mw 4,4. The largest aftershock earthquake is Mw 3,4 and the smallest is Mw 1,4. Figure 3.4 shows the occurence of mainshock and the aftershocks. These aftershocks did not cause further damages to the buildings in Kalibening.

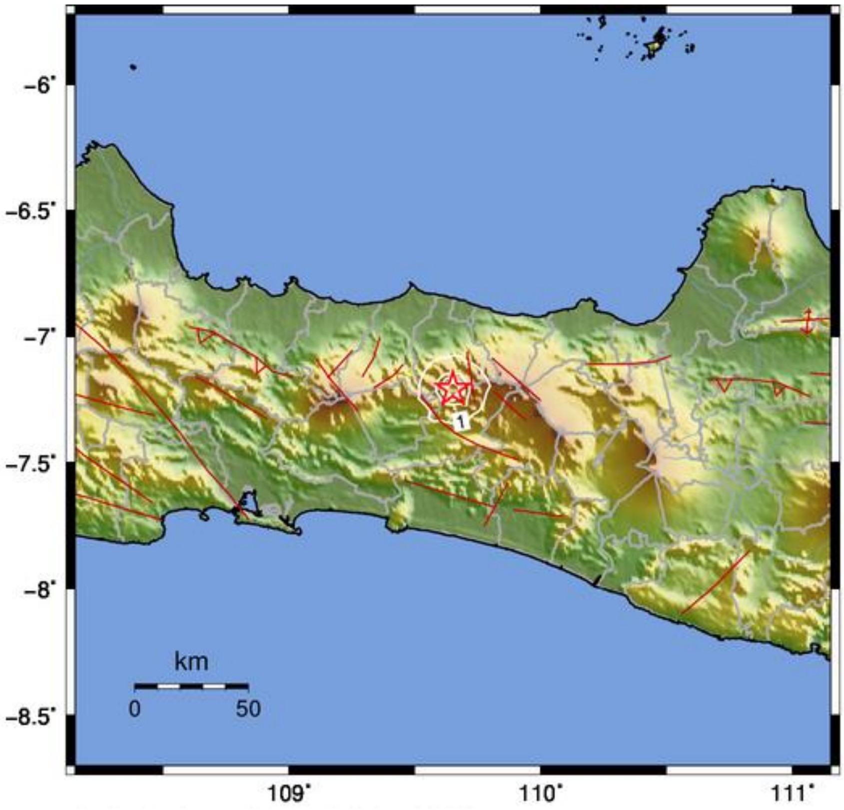


Figure 3.3 The epicenter of Mw 4,4 Banjarnegara Earthquake and the surrounding faults
(Source: BMKG 2018)

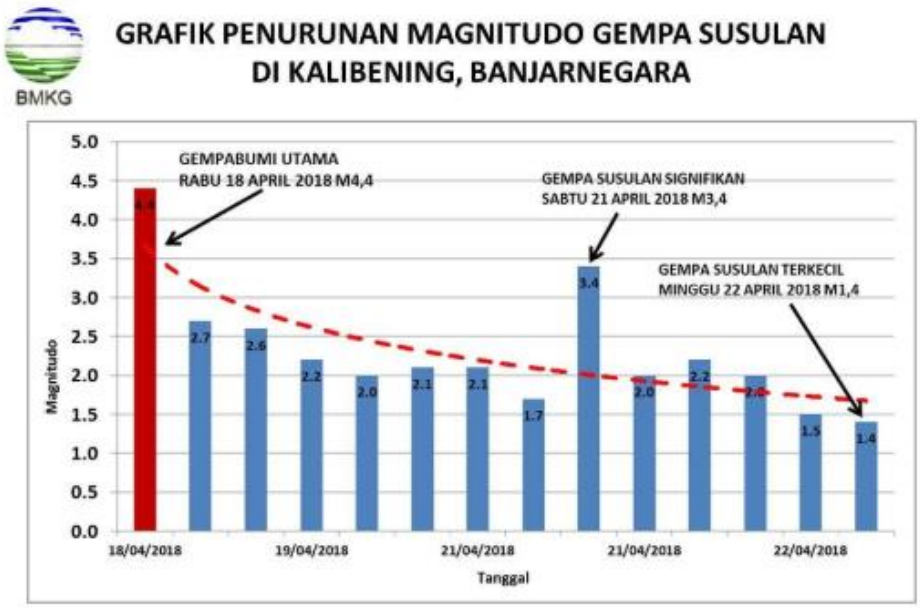


Figure 3.4 The decline of Aftershocks Magnitude in Kalibening Sub-district
(Source: BMKG, 2018)

3.4 Earthquake Intensity

Even though the magnitude of Banjarnegara Earthquake 2018 was relatively small, but the intensity was significant. Magnitude measures different characteristics of earthquake compared to intensity. Magnitude measures the energy released at the source of an earthquake and is measured by seismograph. Meanwhile, intensity of an earthquake measures the strength of shaking at certain location on the earth's surface. Intensity is determined from effects on people, human structures, and the natural environment.

There are numerous intensity scales developed over the last century. One of the most well-known intensity scales is Modified Mercalli Intensity (MMI). This scale is widely used all over the continents. The MMI measures intensities and categorizes them into I to XII scale. The lower numbers of intensity scale generally deal with the manner in which the earthquake is felt by people. The higher numbers of intensity are based on observed structural damage. At scale of IV and higher MMI, the damages on building such as walls make cracking, windows broken, fallen plaster are observed, and at the highest level of intensity it may cause collapse on structures. Table 3.3 describes each level of intensity according to MMI scale.

Table 3.3 Description of the levels of Modified Mercalli Intensity (MMI)

Intensity	Description/Damage	Illustrations
I	Not felt except by a very few under especially favorable conditions.	

Intensity	Description/Damage	Illustrations
II	Felt only by a few persons at rest,especially on upper floors of buildings.	
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.	
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.	

Intensity	Description/Damage	Illustrations
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.	
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.	
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.	
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.	

Intensity	Description/Damage	Illustrations
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.	
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.	
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.	

Intensity	Description/Damage	Illustrations
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.	

Source: USGS (2016) and BMKG (n.d)

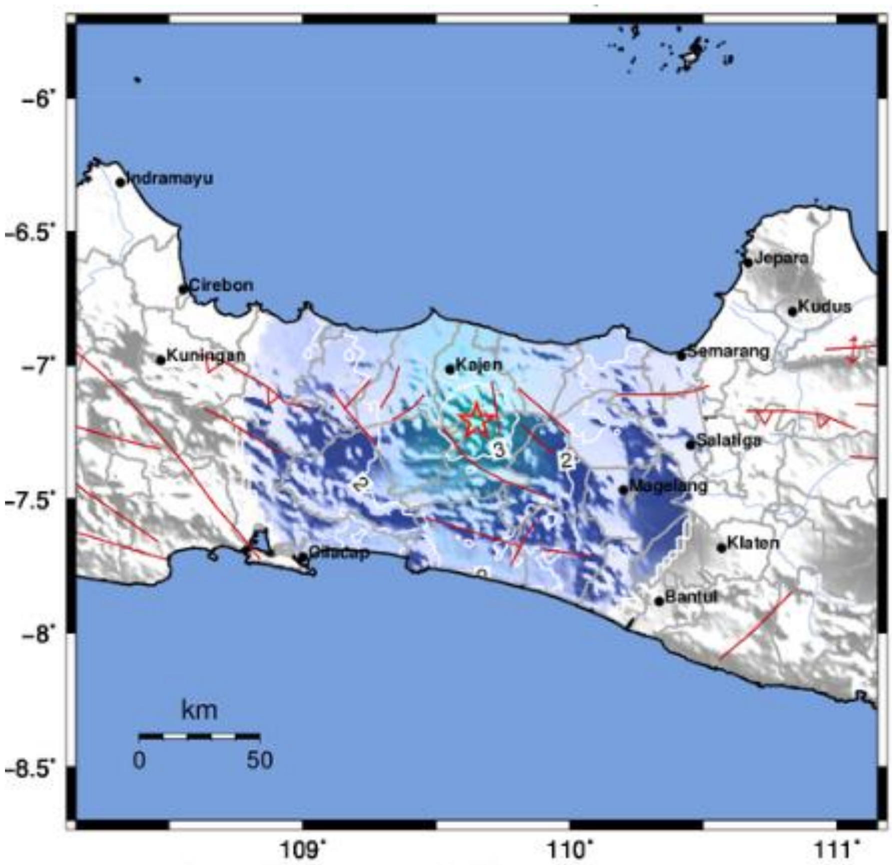
Indonesia has its own intensity scale named Skala Intensitas Gempa BMKG (SIG-BMKG) or Earthquake Intensity Scale of BMKG. This intensity scale was prepared by BMKG to accomodate the damage descriptions of earthquake in accordance with the type of Indonesia buildings. The intensity scale adopted the MMI scale but it is simplified into I-V scales. Table 3.4 shows the description of SIG-BMKG scales.

Table 3.4 SIG-BMKG Scale compared to MMI Scale

SIG-BMKG	Short Description	Detail Description	MMI Scale
I	Not Felt	Not felt or felt only by a few people but recorded by instruments	I-II
II	Felt	Felt by people but do not cause damages. Hanging light-objects start moving and windows disturbed.	III-V
III	Slight Damage	Non-structural building components are slightly damaged, walls crack, roof tiles slide down partially.	VI
IV	Moderate Damage	Plenty of cracks on the wall are observed, partially collapsed, glass breaks, fallen plaster, most of roof tiles slide down, buildings are slightly to moderately damaged	VII-VIII
V	Heavy Damage	Vast majority of the walls are collapsed. Building structures are heavily damaged. Rails bent	IX-XII

Source: BMKG (n.d)

The shakemap released by BMKG shows that the intensity of Banjarnegara earthquake 2018 is around III-V MMI or equals to II-III SIG-BMKG (see Figure 3.5).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	*none*	*none*	*none*	*Very light*	*Light*	*Moderate*	*Mod./Heavy*	*Heavy*	*Very heavy*
MMI	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

Figure 3.5 BMKG Shakemap of Banjarnegara earthquake 2018

(Source: BMKG, 2018)

3.5 Risk, Hazard, Vulnerability, Exposure, and Capacity

Risk is a combination of hazard, vulnerability, exposure, and capacity (Prawirodikromo, 2012). Humans have nothing to do with the natural hazards, but humans can contribute to decreasing the vulnerability and exposure or increasing the capacity. Higher vulnerability and exposure mean higher risk. On the contrary, higher capacity means lower risk. Therefore, to minimize the risk, humans should decrease the vulnerability and exposure and increase the capacity. The relationship of these components can be stated in a simple formula as shown in Figure 3.6.

$$RISK = Hazard \times \frac{Vulnerability \times Exposure}{Capacity}$$

Figure 3.6 Components of Risk

3.5.1 Risk

According to the Office of the United Nations Disaster Relief Coordinator (UNDRO), the risk is defined as "the expected losses from a particular hazard to a specified element at risk in a particular future time period. Loss may be estimated in terms of human lives, or buildings destroyed or in financial terms" (Cardona; Burton as cited in Peduzzi et al, 2009).

Loss estimation is a key component to seismic building risk assessment as it gives decision-makers critical information in developing and planning pre- and post-disaster policies (Khalfan, 2013). In this research, fragility curves method using HAZUS is chosen to estimate building losses.

3.5.2 Hazard

Hazard and disaster are related one to another. Some of us, sometimes, are confused about these two words. Some of us think that hazard and disaster have the same definition, or we misunderstand the definition of these words. Hazard is "a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation" (UNISDR, 2007). When the hazard comes and brings impacts as mentioned above then it becomes a disaster. If hazard comes but causes no impacts, then it is not a disaster.

Nature possesses the potency of hazards such as earthquakes, volcanic eruptions, tsunami, and so forth. Humans cannot prevent the hazards from occurring. If an earthquake occurs and followed by a tsunami, then there is nothing human can do to prevent it from occuring. However, humans can prevent it from becoming a disaster or at least limit the adverse impacts. If the earthquake and the tsunami strike a vacant island in the middle of the ocean, it will be a natural hazard only. However, if the earthquake and the tsunami strike a city like the case of Japan Earthquake and Tsunami 2011, then it becomes a disaster. That is why, in every disaster, there is the contribution of human beings and even human beings are responsible for turning most of the hazards into disasters by doing deforestation, rapid urbanization, environmental degradation, and climate change (Leoni, Radford, & Schulman, 2011). According to Ronan & Johnstone (2005), the hazard itself can be divided into two, natural and human-caused hazard (See Table 3.5).

Table 3.5 Types of Hazards

Causes	Hazards
Natural Hazards*	Flood
	Storms with High winds (Hurricanes, Cyclones, Tornadoes)
	Thunderstorms/Lightning Strikes
	Extreme Temperature (Cold and Heat)
	Earthquakes
	Volcanos
	Tsunamis
	Landslide, Avalanches, Mudslides (Debris Flows)
	Fires
Technological and Man-Made Hazards	Hazardous Material (Chemical spills, Household Chemical Emergencies)
	Nuclear Accidents (National Security Emergencies, Terrorism and Mass Violence, Chemical and Biological Incidents, Nuclear and Radiological Incidents)

* This categorization is oversimplified for convenience reason. That is, some hazards depicted as natural have at times human-made origins such as fires, landslide, floods.

3.5.3 Vulnerability

Nowadays, vulnerability and exposure to disasters are increasing as more people and assets located in areas of high risk (UNISDR & WMO, 2012). Vulnerability can be defined as “the characteristics of a person or group and their situation that influences their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard." (Wisner, as cited in Donner & Rodriguez, 2011). There are several types vulnerability, namely physical, economic, social, psychological, physiological (see Table 3.6).

Table 3.6 Types of Vulnerability

Vulnerability	Description
Physical	unstable locations, closer proximity to hazards, fragile unprotected houses
Economic	no productive assets, limited income earning opportunities, poor pay, single income revenue, no savings and insurance
Social	low status in society, gender relations, fewer decision-making possibilities, oppressive formal and informal institutional structures, and political, economic and social hierarchies
Psychological	fears instigated by religious and other belief systems, ideologies, political pressures, mental illness
Physiological	status in life – young, old, adolescent, pregnant, lactating mothers, chronic illness, disability, exposure to sexual violence and harassment, HIV/Aids and other infections

3.5.4 Exposure

Exposure refers to 'element at risk' including individuals, dwellings or households and communities, buildings and structures, public facilities and infrastructure assets, as well as agricultural commodities and environmental assets (Geoscience Australia, n.d). Exposure information is useful for natural hazard risk analysis when those characteristics are related to models of vulnerability that describe how the 'elements at risk' are likely to behave when subjected to natural and artificial forces. Meanwhile, capacity is "the combination of all the strengths, attributes, and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience" (UNISDR, 2009). Capacity in dealing with disaster is divided into three categories, namely individual capacity, institution capacity, and enabling capacity (policy, strategy etc) (Prawirodikromo, 2012).

3.6 HAZUS-MH

HAZUS-(MH) or Hazard US-Multi Hazard is a damage- and loss-estimation software developed by Federal Emergency Management Agency (FEMA) in cooperation with the National Institute of Building Sciences (NIBS) to estimate potential losses from natural disasters such as flooding, hurricanes, and earthquakes. Federal, state, regional, and local governments use the HAZUS earthquake model for earthquake risk mitigation, preparedness, response, and recovery planning (Neighbors et al, 2013).

FEMA has developed the formula in HAZUS to estimate building damage due to ground shaking. HAZUS defines five damage states: none, slight (minor), moderate, extensive (major), complete (collapse), using physical (qualitative) descriptions of damage to building elements. The functions for estimating building damage due to ground shaking include: (1) fragility curves that describe the probability of reaching or exceeding different states of damage given peak building response, and (2) building capacity (push-over) curves that are used to determine peak building response (Aswandono, 2011).

Khalfan (2013) explains that fragility curves are derived using the capacity spectrum method where the intersection of the response spectrum with the capacity curve in an S_a-S_d space, known as the “performance points” shown in Figure 3.7, are used as inputs to the fragility functions. The HAZUS methodology has been applied to several seismic risk assessment studies by adapting the capacity and fragility curves for buildings in specific regions (Gulati 2006; Levi et al. 2010; Yeh et al. 2000; 2006). The example of damage states of HAZUS are shown in Figure 3.8.

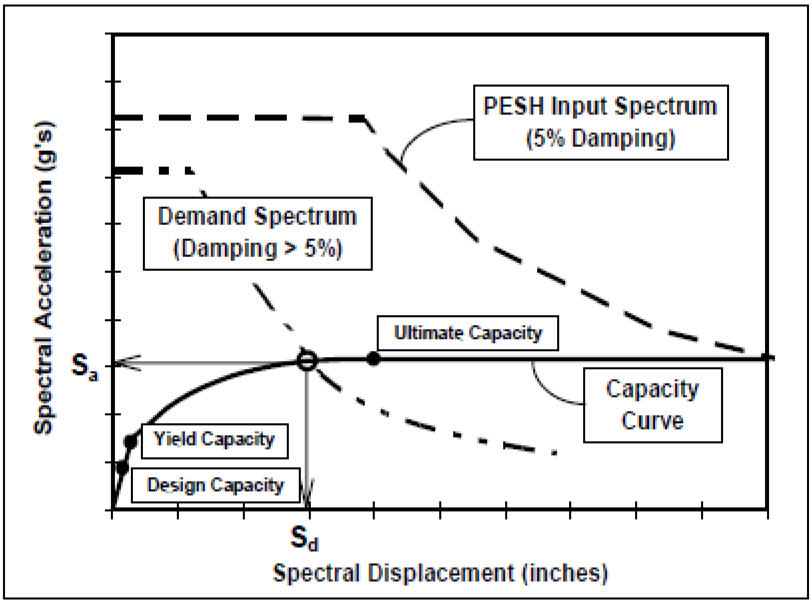


Figure 3.7 Example building capacity curve and demand spectrum

Source: FEMA (2003)

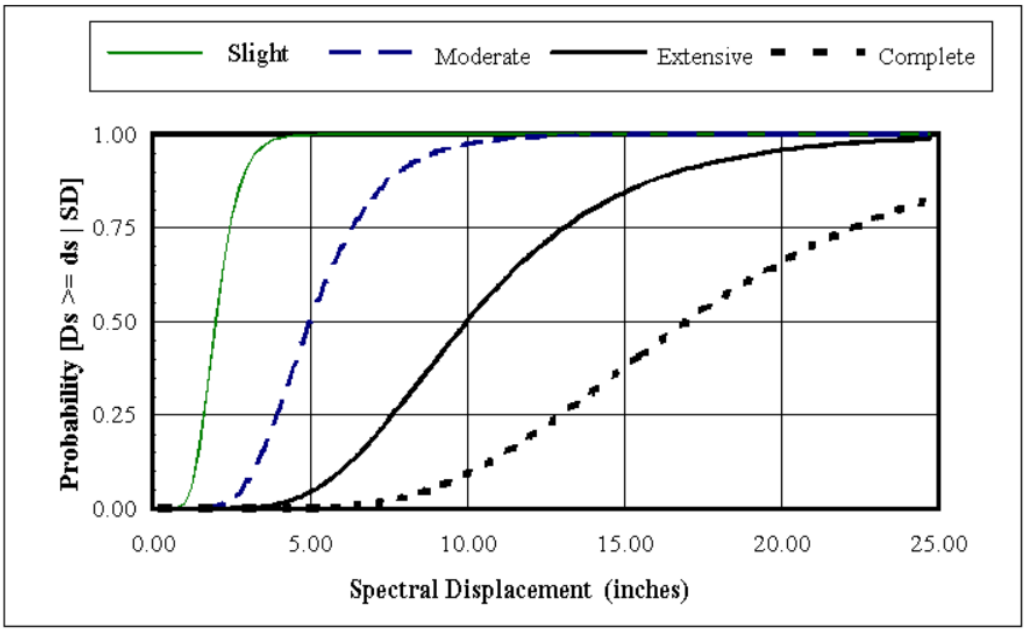


Figure 3.8 Example of Fragility Curves for states of damage

Source: FEMA (2003)

3.7 Building Inventory Classification

In HAZUS, FEMA classifies building into several groups. The purpose of a building inventory classification system is to group buildings with similar damage/loss characteristics into a set of pre-defined building classes. Damage and loss prediction models can then be developed for model building types which represent the average characteristics of the total population of buildings within each class.

The building inventory classification system used in this methodology has been developed to provide an ability to differentiate between buildings with substantially different damage and loss characteristics. The following primary parameters affecting building damage and loss characteristics were given consideration in developing the building inventory classification system, such as:

1. structural parameters affecting structural capacity and response such as
   basic structural system (steel moment frame),
   building height (low-rise, mid-rise, high-rise), and
   seismic design criteria (seismic zone),
2. nonstructural elements affecting nonstructural damage,
3. occupancy (affecting casualties, business interruption and contents damage),
4. regional building practices, and
5. variability of building characteristics within the classification.

Table 3.7 shows the building structure (model building) types according to FEMA. Meanwhile, Table 3.8 shows the building classifications based on occupancy class. Table 3.9 describes the structural system of conrete and masonry buildings of HAZUS.

Table 3.7 Building Structure Types

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1 2	W1 W2	**Wood, Light Frame (≤ 5,000 sq. ft.)** **Wood, Commercial and Industrial (> 5,000 sq. ft.)**		1 - 2 All	1 2	14 24
3 4 5	S1L S1M S1H	**Steel Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
6 7 8	S2L S2M S2H	**Steel Braced Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
9	S3	**Steel Light Frame**		All	1	15
10 11 12	S4L S4M S4H	**Steel Frame with Cast-in-Place Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
13 14 15	S5L S5M S5H	**Steel Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
16 17 18	C1L C1M C1H	**Concrete Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
19 20 21	C2L C2M C2H	**Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
22 23 24	C3L C3M C3H	**Concrete Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
25	PC1	**Precast Concrete Tilt-Up Walls**		All	1	15
26 27 28	PC2L PC2M PC2H	**Precast Concrete Frames with Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
29 30	RM1L RM1M	**Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms**	Low-Rise Mid-Rise	1-3 4+	2 5	20 50
31 32 33	RM2L RM2M RM2H	**Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
34 35	URML URMM	**Unreinforced Masonry Bearing Walls**	Low-Rise Mid-Rise	1 - 2 3+	1 3	15 35
36	MH	**Mobile Homes**		All	1	10

Table 3.8 Building Occupancy Class According to FEMA

Label	Occupancy Class	Example Descriptions
	Residential	
RES1	Single Family Dwelling	House
RES2	Mobile Home	Mobile Home
RES3	Multi Family Dwelling RES3A Duplex RES3B 3-4 Units RES3C 5-9 Units RES3D 10-19 Units RES3E 20-49 Units RES3F 50+ Units	Apartment/Condominium
RES4	Temporary Lodging	Hotel/Motel
RES5	Institutional Dormitory	Group Housing (military, college), Jails
RES6	Nursing Home	
	Commercial	
COM1	Retail Trade	Store
COM2	Wholesale Trade	Warehouse
COM3	Personal and Repair Services	Service Station/Shop
COM4	Professional/Technical Services	Offices
COM5	Banks	
COM6	Hospital	
COM7	Medical Office/Clinic	
COM8	Entertainment & Recreation	Restaurants/Bars
COM9	Theaters	Theaters
COM10	Parking	Garages
	Industrial	
IND1	Heavy	Factory
IND2	Light	Factory
IND3	Food/Drugs/Chemicals	Factory
IND4	Metals/Minerals Processing	Factory
IND5	High Technology	Factory
IND6	Construction	Office
	Agriculture	
AGR1	Agriculture	
	Religion/Non/Profit	
REL1	Church/Non-Profit	
	Government	
GOV1	General Services	Office
GOV2	Emergency Response	Police/Fire Station/EOC
	Education	
EDU1	Grade Schools	
EDU2	Colleges/Universities	Does not include group housing

The parameters used in HAZUS as mentioned above are prepared for the US buildings. Should the HAZUS methodology is applied to any other regions, some adaptation and modification of the capacity and fragility curves for buildings are needed.

Table 3.9 Concrete and Masonry Structural Systems of HAZUS Buildings

Building Type	Structural System
Reinforced Concrete Moment Resisting Frames (C1)	These buildings are similar to steel moment frame buildings except that the frames are reinforced concrete. There are a large variety of frame systems. Some older concrete frames may be proportioned and detailed such that brittle failure of the frame members can occur in earthquakes leading to partial or full collapse of the buildings. Modern frames in zones of high seismicity are proportioned and detailed for ductile behavior and are likely to undergo large deformations during an earthquake without brittle failure of frame members and collapse.
Concrete Shear Walls (C2)	The vertical components of the lateral-force-resisting system in these buildings are concrete shear walls that are usually bearing walls. In older buildings, the walls often are quite extensive and the wall stresses are low but reinforcing is light. In newer buildings, the shear walls often are limited in extent, generating concerns about boundary members and overturning forces.
Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3)	These buildings are similar to steel frame buildings with unreinforced masonry infill walls except that the frame is of reinforced concrete. In these buildings, the shear strength of the columns, after cracking of the infill, may limit the semi-ductile behavior of the system.
Precast Concrete Tilt-Up Walls (PC1)	These buildings have a wood or metal deck roof diaphragm, which often is very large, that distributes lateral forces to precast concrete shear walls. The walls are thin but relatively heavy while the roofs are relatively light. Older or non-seismic-code buildings often have inadequate connections for anchorage of the walls to the roof for out-of-plane forces, and the panel connections often are brittle. Tilt-up buildings usually are one or two stories in height. Walls can have numerous openings for doors and windows of such size that the wall looks more like a frame than a shear wall.

Table 3.9 (Continued)

Building Type	Structural System
Precast Concrete Frames with Concrete Shear Walls (PC2)	These buildings contain floor and roof diaphragms typically composed of precast concrete elements with or without cast-in-place concrete topping slabs. Precast concrete girders and columns support the diaphragms. The girders often bear on column corbels. Closure strips between precast floor elements and beam-column joints usually are cast-in-place concrete. Welded steel inserts often are used to interconnect precast elements. Precast or cast-in-place concrete shear walls resist lateral loads. For buildings with precast frames and concrete shear walls to perform well, the details used to connect the structural elements must have sufficient strength and displacement capacity; however, in some cases, the connection details between the precast elements have negligible ductility.
Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1)	These buildings have perimeter bearing walls of reinforced brick or concrete-block masonry. These walls are the vertical elements in the lateral-force-resisting system. The floors and roofs are framed with wood joists and beams either with plywood or braced sheathing, the latter either straight or diagonally sheathed, or with steel beams with metal deck with or without concrete fill. Interior wood posts or steel columns support wood floor framing; steel columns support steel beams.
Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2)	These buildings have bearing walls similar to those of reinforced masonry bearing wall structures with wood or metal deck diaphragms, but the roof and floors are composed of precast concrete elements such as planks or tee-beams and the precast roof and floor elements are supported on interior beams and columns of steel or concrete (cast-in-place or precast). The precast horizontal elements often have a cast-in-place topping.

Table 3.9 (Continued)

Building Type	Structural System
Unreinforced Masonry Bearing Walls (URM)	These buildings include structural elements that vary depending on the building's age and, to a lesser extent, its geographic location. In buildings built before 1900, the majority of floor and roof construction consists of wood sheathing supported by wood framing. In large multistory buildings, the floors are cast-in-place concrete supported by the unreinforced masonry walls and/or steel or concrete interior framing. In unreinforced masonry constructed after 1950 (outside California) wood floors usually have plywood rather than board sheathing. In regions of lower seismicity, buildings of this type constructed more recently can include floor and roof framing that consists of metal deck and concrete fill supported by steel framing elements. The perimeter walls, and possibly some interior walls, are unreinforced masonry. The walls may or may not be anchored to the diaphragms. Ties between the walls and diaphragms are more common for the bearing walls than for walls that are parallel to the floor framing. Roof ties usually are less common and more erratically spaced than those at the floor levels. Interior partitions that interconnect the floors and roof can reduce diaphragm displacements.

(Source: HAZUS Technical Manual)

3.8 Estimation of Earthquake Damage to Buildings

This sub-chapter describes methods for determining the probability of damage states (None, Slight, Moderate, Extensive, Complete) of general building stock as classified by FEMA in the book of HAZUS. General building stock represents typical buildings of a given model building type designed to the Seismic Design Levels.

FEMA classifies buildings into several four Seismic Design Levels (High-Code, Moderate-Code, Low-Code, and Pre-Code buildings) based on the seismicity level and the year of built. For seismicity level, FEMA differentiates building into two categories, seismically designed and not seismically designed buildings. Meanwhile, for year of built, buildings are divided into three groups, after about 1973, between 1940 and 1973, and before about 1940. Buildings built in an area with significant seismicity post-1973 would be best considered as High-Code, while buildings of older construction (between 1940 and 1973) would be best considered as Moderate-Code, or considered as Low-Code if built before about 1940. Pre-Code damage functions are appropriate for modeling older buildings that were not designed for earthquake load.

To estimate building damage using fragility and capacity curves, there are two items that should be prepared, that are:

1. model building type (including height) and seismic design level that represents building of interest, and
2. response spectrum at the site of the building or at the centroid of the census tract area where the building is located.

3.8.1 Capacity Curve

Capacity curve is a plot of a building's lateral load resistance as a function of a characteristic lateral displacement. It is derived from a plot of static equivalent base shear versus building displacement. Building Capacity curves developed in HAZUS are based engineering design parameters and judgment. There are three control points that define model building capacity describe each curve, namely (1) Design Capacity, (2) Yield Capacity, and (3) Ultimate Capacity.

Design capacity represents the nominal building strength required by current model seismic code provisions (e.g., 1994 *NEHRP Provisions*) or an estimate of the nominal strength for buildings not designed for earthquake loads. Yield capacity represents the true lateral strength of the building considering redundancies in design, conservatism in code requirements and true (rather than nominal) strength of materials. Ultimate capacity represents the maximum strength of the building when the global structural system has reached a fully plastic state. Ultimate capacity implicitly accounts for loss of strength due to shear failure of brittle elements. Typically, buildings are assumed capable of deforming beyond their ultimate point without loss of stability, but their structural system provides no additional resistance to lateral earthquake force.

Up to the yield point, the building capacity curve is assumed to be linear with stiffness based on an estimate of the true period of the building. The true period is typically longer than the code-specified period of the building due to flexing of diaphragms of short, stiff buildings, flexural cracking of elements of concrete and masonry structures, flexibility of foundations and other factors observed to affect building stiffness. From the yield point to the ultimate point, the capacity curve transitions in slope from an essentially elastic state to a fully plastic state. The capacity curve is assumed to remain plastic past the ultimate point. An example building capacity curve is shown in Figure 3.9.

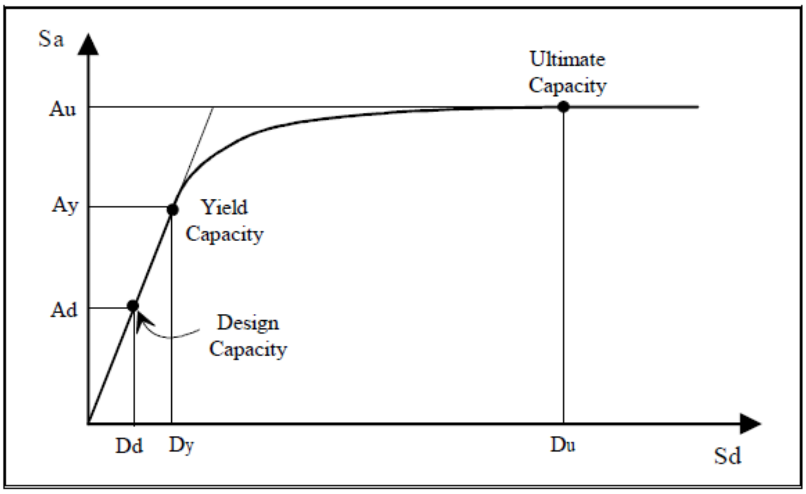


Table 3.10 Example of Building Capacity Curve

3.8.2 Fragility Curve

Building damage functions are in the form of lognormal fragility curves that relate the probability of being in, or exceeding, a building damage state to for a given PESH demand parameter (e.g., response spectrum displacement). Each fragility curve is defined by a median value of the PESH demand parameter (i.e., either spectral displacement, spectral acceleration, PGA or PGD) that corresponds to the threshold of the damage state and by the variability associated with that damage state. The conditional probability of being in, or exceeding, a particular damage state, ds, given the spectral displacement, S_d, (or other PESH parameter) is defined by the function:

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{S_{d,ds}}\right)\right] \qquad (3.1)$$

Where:

$S_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state, ds,

β_{ds} is standard deviation of the natural logarithm of spectral displacement for damage state, ds, and

Φ is the standard normal cumulative distribution function.