# Strengthening Tsunami and Earthquake Preparedness in Pakistan

Earthquake Hazard Assessment
Tsunami Risk Assessment
Tsunami Bye Laws and Building Codes
Tsunami Early Warning SOPs
Database of Elements at Risk
Tsunami Safe Structures

## Vulnerability Assessment of Buildings

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# Executive Summary

This report presents the seismic vulnerability assessment of buildings and lifelines structures in Karachi particularly for the coastal belt, based on probabilistic seismic hazard analysis (PSHA) results. The outcome is to present the direct physical damage in built infrastructure include buildings, bridges, electric power network system, harbour system, oil and gas systems, telecommunication system and water and waste water systems. The scope of the work limited to the development of damage matrices considering probabilistic earthquakes to existing structures for an intensity measure peak ground acceleration (PGA) with different damage states (i.e., minor, moderate, extensive or collapse). Fragility curves are developed for each classification based on empirical or analytical approach. The work is mainly divided in to four steps. In the first step, a detailed data collection rubric considering the scope of the project for considered inventories has been developed. In the second step, GIS mapping has been done based on typology classification regarding different existing structures. In the third step, intensity measure peak ground acceleration (PGA) has been extracted from the hazard analysis for different probability of exceedance having a specific return period. In the fourth and final step, the suitable fragility curves are identified from the literature and the corresponding damage matrices for different structures have been plotted. Results show that 25% reinforced concrete buildings, 26% unreinforced concrete buildings, 44% bridges, 10% electric power network system, 5% oil and gas system, 3% telecommunication systems and 9% water and waste water systems are exceeding the collapse limit state at 10% probability of exceedance earthquake.

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# Chapter 1 – General Overview

As urban development continues in seismically hazardous regions of the Pakistan, there is growing concern about the exposure of buildings, lifelines (e.g., utilities and transportation systems), and population to the potential effects of earthquakes. Earthquake risk analysis begins with hazard evaluation, and goes beyond that to determine the potential earthquake consequences on people and property, including buildings, lifelines and environment.

The prime focus of this report is to estimate the direct physical damage to the built infrastructure in Karachi including buildings, bridges, electric power network system, harbor system, oil and gas system, telecommunication system and water and waste water systems.

The key assumption in the vulnerability assessment of buildings and lifeline components is that structures having similar structural characteristics (and being in similar geotechnical conditions) are expected to perform in the same manner for a given seismic loading (SYNER-G, 2013).

In seismic risk assessment or seismic vulnerability analysis, the fragility curve is a valuable tool to estimate the degree of damage to infrastructure during an earthquake. Fragility curves express the conditional probability of reaching or exceeding a particular damage state (DSi) given a certain level of seismic intensity measure (IM). A lognormal cumulative distribution function (CDF) typically used to develop the fragility function with respect to the intensity measure (IM) such as peak ground acceleration-PGA (NIBS, 2004; Argyroudis and Pitilakis, 2012; Qiu et al., 2018).

Fragility curves can be classified into the four generic groups; empirical, judgmental, analytical, and hybrid, according to whether the damage data used in their generation stems mainly from observed post-earthquake surveys, expert opinion, analytical simulations, or combinations of these, respectively (Rossetto & Elnashai, 2003). The empirical fragility curves are derived for a damage state through the statistical damage data reported in post-earthquake surveys from previous seismic events (Rota et al. 2008; Spenceet al., 2008). The limitations of empirical approach are the unavailability of sufficient and reliable statistical data for a wide range of intensities. The judgement based fragility functions rely on the opinions of expert panels of engineers with experience in earthquake engineering who are asked to make estimates of the likely damage distribution within building populations when subjected to earthquakes of variant intensities. The analytical fragility curves are derived through the numerical simulations of structures process through real/artificial ground motions or by pushover analysis. Finally, the hybrid fragility curves attempt to compensate for the scarcity of observational data, subjectivity of judgmental data and modelling deficiencies of analytical procedures, by combining data from different sources. In this report, the analytical and empirical both approaches are utilized to estimate the degree of damage in buildings, bridges and others utilities.

# Chapter 2 – Classification of Building Structures

Classification of structures is the key step for vulnerability assessment studies. This report broadly categorized structures into building and non-building structures. The building structures categorized into reinforced concrete (RC) buildings and unreinforced masonry (URM) buildings.

## 1.1 Reinforced Concrete Framed Buildings

The general building stock in Karachi includes residential, commercial, industrial, religious, government and educational buildings. Majority of the buildings are not designed and constructed as per modern seismic code provisions. These buildings can be categorized as pre-code building structures which comprise of concrete frame with unreinforced masonry infill walls (low-rise to mid-rise) and unreinforced masonry bearing wall buildings (low-rise). Only, limited building stock in Karachi after the 2005 earthquake has been designed and constructed as per Building Code of Pakistan (BCP)-2007. These well design structures include concrete moment resisting frame and concrete shear wall frame typically used for mid-rise to high-rise construction and designed for moderate level of seismicity.

### 1.1.1 Reinforced Concrete Moment Framed Building (C1)

These buildings have a frame of concrete columns and beams, in which lateral and gravity loads are resisted by beams and columns (Figure 1). Usually the structure is concealed on the outside by exterior non-structural walls, which can be of almost any material (curtain walls, or concrete blocks). Diaphragms (slabs) transfer the lateral loads to moment-resisting frames. The frames develop their stiffness by full or partial moment connections. 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.

Figure 1: Reinforced Concrete Moment Framed Building (C1)

### 1.1.2 Reinforced Concrete Shear Wall Framed Building (C2)

These building structures have higher stiffness as compared to reinforced concrete moment resisting frame buildings and are typically used in high-rise construction (Figure 2). The vertical components of the lateral-force-resisting system in these buildings are reinforced concrete columns and shear walls, significant part of lateral loads is resisted by concrete shear walls.

Figure 2: Reinforced Concrete Shear Wall Framed Building (C2)

### 1.1.3 Reinforced Concrete Infilled Framed Building (C3)

Reinforced concrete infilled framed building-C3 is the older and widely used building typology in Karachi (Figure 3). These buildings are less ductile as compared to moment resisting framed buildings due to the presence of unreinforced masonry infill walls. In these buildings, the shear strength of the columns (after cracking of the infill) may limit the semi-ductile behaviour of the system.

Figure 3: Reinforced Concrete Infilled Framed Building (C3)

## 1.2 Unreinforced Masonry Building (URM)

In these buildings, lateral and gravity loads are resisted by bearing walls. Bearing walls are generally made of concrete blocks and stone masonry. These buildings include structural elements that vary depending on the building's age. In buildings built before 1900, the majority of floor and roof construction consists of wood sheathing supported by wood framing (Figure-04).

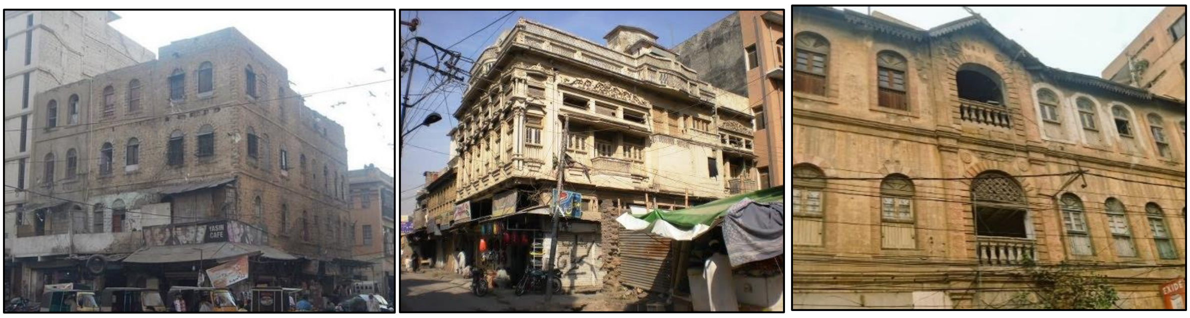

Figure 4: Unreinforced Masonry Building (URM)

# Chapter 3 – Classification of Non-Building Structures

The non-building stocks include bridges and flyovers, electric power network system (EPN), harbor system, oil and gas system, communication system, and water and waste water systems.

## 3.1 Bridges and Flyovers

Similar to other essential structures such as hospitals, police stations and fire stations, bridges and flyovers are also important components of a road network which are termed as lifeline structures. It is vital that these structures remain functional in case of a natural calamity to facilitate relief operations. In current study, bridges and flyovers have been classified in this report on the basis of supporting sub-structure and mainly on the typology of pier below the superstructure. On the basis of pier, there are three types of bridges and flyovers, (a) supported on single column, (b) supported on multiple columns or bent, and (c) supported on wall pier. In order to estimate the different levels of damage fragility functions obtained through analytical study (Khan et al., 2015) have been employed in this report. Nonlinear static pushover analysis is primarily used in analytical approach to estimate the damage at component level and particularly in piers.

### 3.1.1 Wall Piers

Solid wall piers (Figure 5) are often used at water crossings since they can be constructed to proportions that are both slender and streamlined. These features lend themselves well for providing minimal resistance to flood flows.

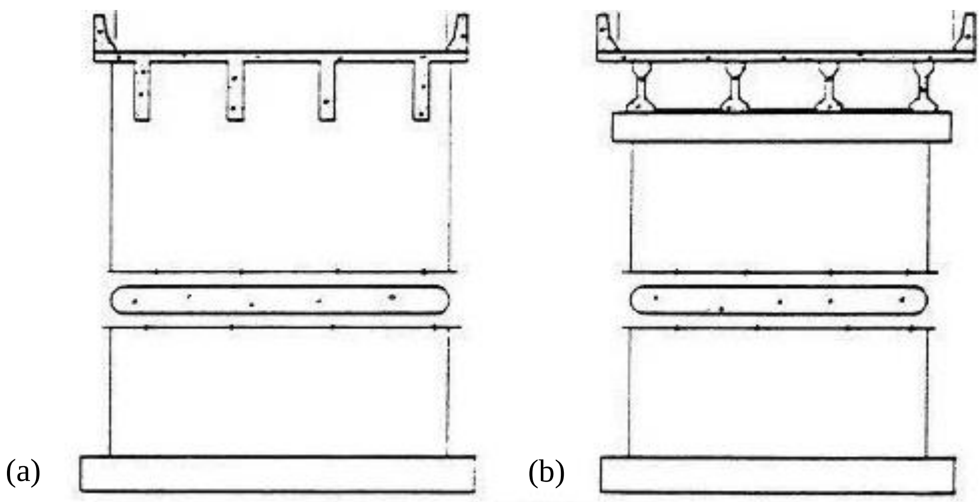


Figure 5: Solid Wall Piers (a) monolithic with superstructure, (b) non-monolithic with superstructure

### 3.1.2 Multiple Columns/Bent Piers

A column bent pier consists of a cap beam and supporting columns forming a frame. Column bent piers (Figure 6) can either be used to support a steel girder superstructure or be used as an integral pier where the cast-in-place construction technique is used. The columns can be either circular or rectangular in cross section. These are by far the most popular forms of piers in the modern highway system.

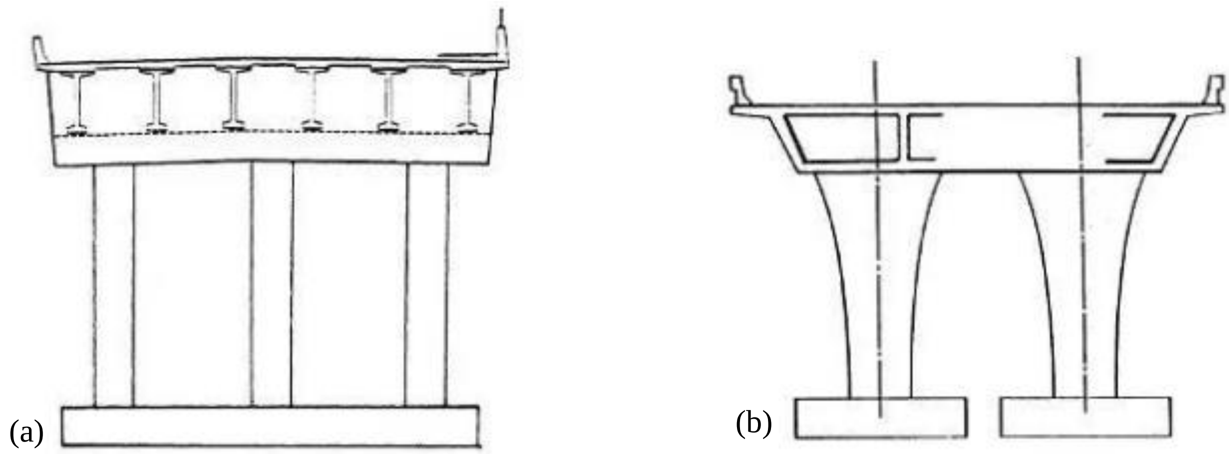


Figure 6: Bent Pier (a) for precast girders, and (b) for cast-in-place girders

#### 3.1.3 Single Column/Hammerhead Piers

Hammerhead piers (Figure 7) are often found in urban areas where space limitation is a concern. These are used to support steel girder or precast pre-stressed concrete superstructures, aesthetically appealing, generally occupy less space and provide more room for the traffic underneath.

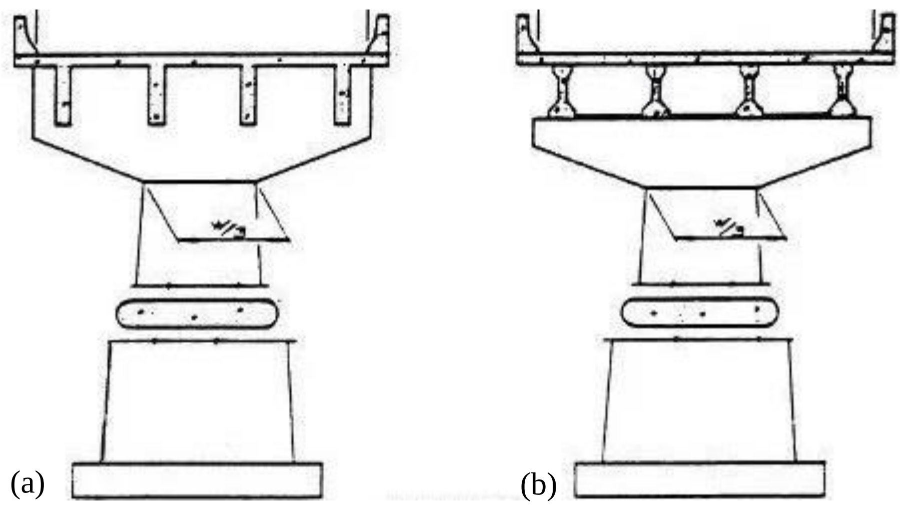


Figure 7: Single Column hammerhead Pier (a) monolithic with superstructure, (b) non-monolithic with superstructure

## 3.2 Electric Power Network (EPN) Inventory

A modern EPN system is a complex interconnected system, which includes electric power grids, generation facilities, substations, etc. All of these components are vulnerable to damage during the earthquakes, which may result in significant disruption of power supply. Three components of EPN System have been considered such as electric power grid (EPN-01), generation plant (EPN-02) and substation (EPN-03).

### 3.2.1 Electric Power Grid (EPN-01)

Electric power grid (also known as the distribution system) is divided into a number of circuits. A distribution circuit includes poles, wires, in-line equipment and utility-owned equipment at customer sites. A distribution circuit also includes above ground and underground conductors. Distribution circuits either consist of anchored or unanchored components. EPN-01 is further categorized into high voltage (capacity greater than 350KV), moderate voltage (capacity ranges from 350KV to 150KV) and low voltage (capacity less than 150KV) transmission lines (Figure 8).

Figure 8: Electric Power Grid (EPN-01)

### 3.2.2 Generation Plant (EPN-02)

Generation plants (

Figure 9) produce alternating current (AC) and these plants subcomponents include diesel generators, turbines, racks and panels, boilers and pressure vessels, and the building in which these are housed. The size of the generation plant is determined from the number of Megawatts of electric power that the plant can produce under normal operations. Generation plants have been classified as small generation plants having a generation capacity less than 200

Megawatts. Medium/large generation plants having a capacity greater than 200 Megawatts. The classification is also a function of whether the subcomponents are anchored or unanchored.

Figure 9: Generation Plant (EPN-02)

### 3.2.3 Substations (EPN-03)

An electric substation (Figure 10) is a facility that serves as a source of energy supply for the local distribution area in which it is located, and has several main functions such as,

- Change or switch voltage from one level to another
- Provide points where safety devices such as disconnect switches, circuit breakers, and other equipment can be installed
- Regulate voltage to compensate for system voltage changes
- Eliminate lightening and switching surges from the system
- Convert AC to direct current (DC) and DC to AC, as needed
- Change frequency, as needed

Substations can be entirely enclosed in buildings where all the equipment are assembled into one metal clad unit. In the employed loss estimation methodology, only transmission (138 kV to 765 kV or higher) and sub-transmission (34.5 kV to 161 kV) substations are considered. These will be classified as high voltage (350 kV and above), medium voltage (150 kV to 350 kV) and low voltage (34.5 kV to 150 kV). The classification is also a function of whether the subcomponents are anchored or unanchored.

Figure 10: Substation (EPN-03)

## 3.3 Harbour System

Harbour system consists of four components: waterfront structures (e.g., wharfs, piers and seawalls); cranes and cargo handling equipment; fuel facilities; and warehouses. In many cases, these facilities were constructed prior to widespread use of engineered fills; consequently, the wharf, pier, and seawall structures are prone to damage due to soil failures such as liquefaction. Other components may be damaged due to ground shaking as well as ground failure.

### 3.3.1 Waterfront Structures

Waterfront structures include wharves (harbour embankments), seawalls (protective walls from erosion), and piers (break-water structures which form harbours) that exist in the port system (Figure 11). Waterfront structures typically are supported by wood, steel or concrete piles. Many also have batter piles to resist lateral loads from wave action and impact of vessels. Seawalls are caisson walls retaining earth fill material.

 

Figure 11: Waterfront Structures (Wharves, Seawalls and Piers)

### 3.3.2 Cranes and Cargo Handling Facilities

These are large equipment items used to load and unload freight from vessels (Figure 12). These are stationary or mounted on rails.


Figure 12: Cranes and Cargo Handling Facilities

### 3.3.3 Fuel Facilities

The fuel facility consists mainly of fuel storage tanks, buildings, pump equipment, piping, and, sometimes, backup power (Figure 13). The functionality of fuel systems is determined with a fault tree analysis.

Figure 13: Fuel Facilities

## 3.4 Oil and Gas Systems

Oil and gas systems are on high risk and susceptible to damage from moderate to severe earthquakes. Past earthquakes show that seismic damage to oil and gas elements can cause extended direct and indirect socio-economic losses with significant environmental impact. This system consists of refineries, pipelines, pumping stations and tank farms. All of these components are vulnerable to damage during earthquakes, which may result in a significant disruption to the oil and gas network. Three components of oil and gas system have been considered in this report refineries, pumping plants and tank farms.

### 3.4.1 Refineries

A refinery (Figure 14) is an industrial process plant where crude oil is processed and refined into useful petroleum products. Oil refineries serve an important role in the production of transportation and other fuels. Refineries are categorized into small and medium/large refineries based on capacity in barrels per day with anchored and unanchored components.

Figure 14: view of a Refinery

### 3.4.2 Pumping Plants

Pumping plants (Figure 15) serve to maintain the flow of oil in cross-country pipelines. Pumping plants usually use two or more pumps. Pumps can be of either centrifugal or reciprocating type. However, no differentiation is made between these two types of pumps in the analysis of oil systems. Pumping plants are classified as having either anchored or unanchored subcomponents.

Figure 15: Pumping Plants

### 3.4.3 Tank Farms

Tank farms are facilities that store fuel products (Figure 16). They include tanks, pipes and electric components. Tank farms are classified as having either anchored or unanchored subcomponents.

Figure 16: Tank Farms

## 3.5 Communication System

A communication facility consists of a building (generic type is assumed in the methodology of work in this report), central switching equipment (i.e., digital switches, anchored or unanchored), and back-up power supply (i.e. diesel generators or battery generators, anchored or unanchored) that may be needed to supply the requisite power to the center in case of loss of off-site power. Telecommunication infrastructures are designed to provide connections over long distance for communication. The seismic vulnerability assessment of communication systems comprises of two main ingredients, the functionality assessment of network components and the interconnection among them.

Common failures found in telecommunication network components are failures of electronic equipment, such as computers, server cabinets, switch boards, circuit boards, and battery racks. Without proper anchorage, they are likely to rock or overturn during an earthquake. On 26th December 2004, an earthquake of 9.0 -9.3 magnitude hit the Sumatra and Andaman Islands. Depending on the region, there were tremendous number of injuries, casualties, property damage and destruction to lifeline. Tsunami (Figure 17) crippled telecommunication system by damaging poles, towers and local switching equipment.

Figure 17: 2004, Indian Ocean Tsunami

Functionalities of infrastructural networks are dependent upon functionalities of their components. The concept of system reliability and fault tree analysis are frequently used to assess probabilistic functionality of infrastructure facilities and systems (FEMA 2004, Leelardcharoen 2005, Adachi 2007). A fault tree diagram is a representation of a failure event which consists of combined effects of several sub-events (Melchers 1999). A fault tree diagram typically consists of event blocks and operation gates. Figure 18 presents the fault tree diagram of the failure of a telephone central office as described in (FEMA 2004). The failure results from moderate damage to the central office structure, a dislodged digital switching board, or loss of electric power, where the loss of electric power results from the loss of backup power and commercial power at the same time.

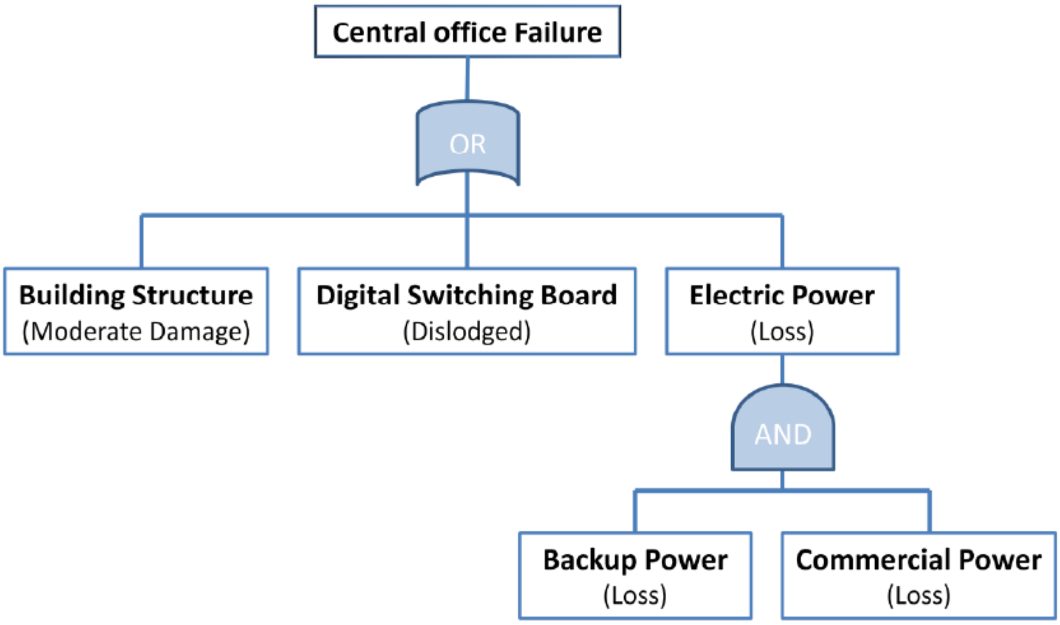


Figure 18: Fault Tree diagram Of Telephone Central Office Building Failure

Central offices and broadcasting stations (including transmission towers) are the only components of the communication system considered in this report as per HAZUS (NIBS-2004) methodology. Therefore, fragility curves are presented for these components only. Other components, such as cables and other lines, usually have enough slack to accommodate ground shaking.

## 3.6 Water and Waste-Water Systems

Water and waste-water systems are on high risk and are susceptible to damage from moderate to severe earthquakes. Past earthquakes show that seismic damage to water system elements can cause extended direct and indirect socio-economic losses with significant environmental impact. This system consists of supply, storage, transmission, and distribution components. All of these components are vulnerable to damage during earthquakes, which may result in a significant disruption to the water utility network. Three components of Water and Waste-Water Systems have been considered in this report, which include water treatment plant, pumping stations and waste-water treatment plant.

### 3.6.1 Water treatment plant

Water treatment plants are complex facilities (Figure 19) that are generally composed of a number of connected physical and chemical unit processes whose role is to improve the water quality. Common components include pre-sedimentation basins, aerators, detention tanks, flocculators, clarifiers, backwash tanks, conduit and channels, coal sand or sand filters, mixing tanks, settling tanks, clear wells, and chemical tanks. Main typology parameters include size, anchorage of sub-components, equipment and backup power.

Figure 19: Water Treatment Plant

### 3.6.2 Pumping Stations

A pumping station (Figure 20) is a facility that boosts water pressure in both transmission and distribution systems. They typically comprise buildings, importation structures, pumps and motor units, pipes, valves and associated electrical and control equipment. Main classification parameters include size, anchorage of sub-components, equipment and backup power.

Figure 20: Pumping Station (PS)

### 3.6.3 Waste-Water treatment plant

Waste-water treatment plants (Figure 21) are complex facilities which include a number of buildings and underground or on-ground reinforced concrete tanks and basins. Common components include trickling filters, clarifiers, chlorine tanks, recirculation and waste-water pumping stations, chlorine storage and handling, tanks and pipelines. Concrete channels are used to convey the waste-water from one location to another within the network. The mechanical, electrical and control equipment (as well as piping and valves) are housed within buildings. Main typology parameters include size, anchorage of sub-components, equipment and backup power, building categorization based on low seismic and advance seismic design.

Figure 21: Waste-Water Treatment Plant

# Chapter 4 – Damage States

In seismic risk assessment, the performance levels of a structure can be defined through damage thresholds called limit states. A limit state defines the boundary between different damage conditions, whereas the damage state defines the damage condition itself. Different damage criteria have been proposed depending on the typology of element at risk and the approach used for the derivation of fragility curves. The degree of damage for building and non-building structures has been estimated by incorporating variant levels of damage proposed by HAZUS in this report (Figure 22). These damage states are slight, moderate, extensive, and complete damage.

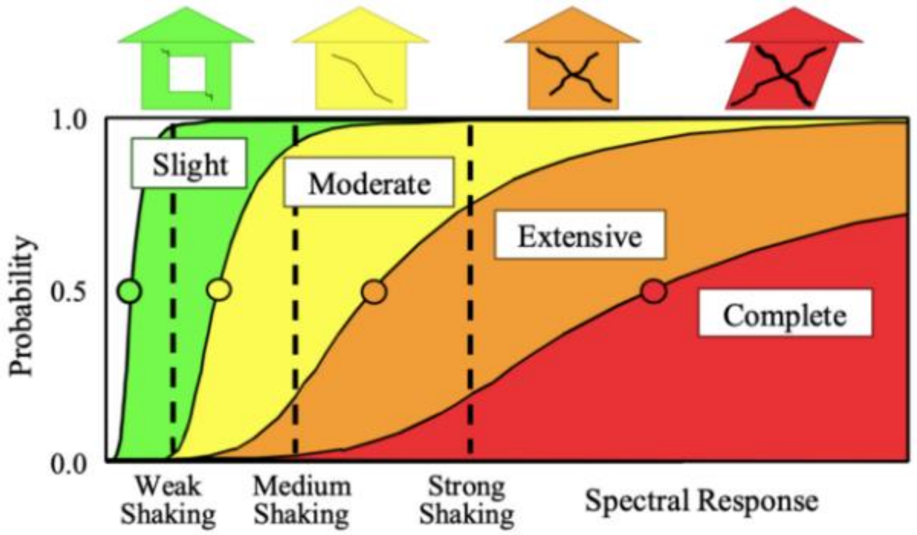


Figure 22: Damage States proposed by HAZUS

# Chapter 5 – Scope of Work

The scope of the work for this report includes development of damage matrices considering probabilistic earthquakes to existing structures in Karachi using knowledge of typologies, classification, and the ground motion intensity measure (i.e., peak ground acceleration-PGA). In this report, damage states (i.e., minor, moderate, extensive or collapse) describing the level of damage to each of the existing structure classification have been employed. Fragility curves are developed for each classification based on empirical or analytical approaches. These curves describe the probability of reaching or exceeding each damage state of a particular level of ground motion. Based on fragility curves, the method for assessing the functionality of each category of structure is presented. Buildings, bridges, electric power network system, harbour system, oil and gas system, telecommunication system and water and waste water systems are included in this report.

The selected building typologies are reinforced and non-reinforced buildings which is further classified into reinforced concrete moment framed (C1), reinforced concrete shear wall framed (C2), reinforced concrete infilled framed (C3), and unreinforced masonry structures (URM). Bridges and flyovers, further classified based upon the types of supporting pier typologies such as single column pier, multiple column pier and wall pier. For an electric power system, the selected components are power grids, generation plants and substations. The power grids are also known as transmission lines and are further divided into low voltage, medium voltage and high voltage transmission lines. The generation plants are further classified into small, medium and large generation plants, whereas the substations typologies are similar to power grids. In harbour system, the components include waterfront structures, cranes and cargo handling facilities, steel tanks and fuel facilities which are further divided into anchored and unanchored components. In an oil and gas system, the considered components are refineries, pumping plants, and tank farms. These components are further classified based on capacities and with anchored or unanchored components. In communication facilities considered the components include building type, switching equipment, backup power and off-site power, further classification based on anchored and unanchored components. In the water and waste water systems, the selected components are treatment plants and pumping stations, which are further classified on the basis of sizes and design considerations.

# Chapter 6 – Methodology

The work is divided into four steps. In the first step, a detailed data collection rubric considering the scope of the project for considered inventory has been developed as shown in Figures 23-29.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Bldg ID** | | | | | | | | |
| **Building Address** | Name | | | Block | House No. | Street No. | District | Colony |
| | | | | | | | | |
| **Coordinates** | Latitude | | | | Longitude | | | |
| **Plan Dimension** | Length | | | | Width | | | |
| **Occupancy** | **I** .Agricultural, Temporary, Minor Storage Facility or with no occupants at most times. | | | | **II** .Residential, Commercial, Small Industry, facilities (occupants < 250) or small clinics (occupants < 50) | | | |
| | **III** .Utility Generation / Transmission, Toxic / Expolosive holding, Educational, Large Public & Private, Large Clinics or High Occupancy facilities | | | | **IV** .Hospitals, Rescue & Emergengy, Disaster Shelter, Airport or National Defense facilities | | | |
| | **Building Use** | | | | | | | |
| **Non - RCC Building Materials** | **Walls & Column** | Brick Masonry | Adobe Masonry | Block Masonry | Wood / bamboo | Reinforced Masonry | Stone Masonry | Other |
| | **Roof** | Cement sheet | Metal Sheet | Cement Tile-beam | Wood / bamboo | Other | | |
| **RCC Buildings Information** | **No. of Stories** | | **Storey Height** | | **B. Wall Height** | | **Gate Height** | |
| | | | | | | | | |
| | **Boundary Wall type** | | | | **Entrance Gate** | | | |
| | Front | 2 Sided | Grilled | None | Solid | | Grilled | |
| **Physical Condition** | **Building Initial Condition - Damage Grade** | | | | | | | |
| | Grade - 0 | None | No Structural and Non Structural Damage | | | | | |
| | Grade - 1 | Slight | Hairline cracks in walls, plaster broken, seepage (all non structura). | | | | | |
| | Grade - 2 | Moderate | Cracks in beams / columns, reinforcement exposed, concrete deterioration (all structural in addition to non-structural) | | | | | |
| **Comments** | | | | | | | | |

Figure 23: Building Stock data rubric

| | | | | | |
|---|---|---|---|---|---|
| Structure ID | | | | | |
| Structure Address | Name | Block | District | Colony | |
| | | | | | |
| Coordinates | Latitude | | Longitude | | |
| Plan dimension | | | | | |
| | | | | | |
| | | | | | |
| Typology | Wall Pier | Bent Pier | Single Column Pier | | |
| Fixity | Anchored | Anchored | Anchored | | |
| | Unanchored | Unanchored | Unanchored | | |
| Physical Codition | Structure Condition-Damage Grade | | | | |
| | Grade-0 | None | | | |
| | Grade-1 | Slight | | | |
| | Grade-2 | Moderate | | | |
| Comments | | | | | |

Figure 24: Bridges and Flyovers data rubric

| | | | | |
|---|---|---|---|---|
| Structure ID | | | | |
| Structure Address | Name | Block | District | Colony |
| | | | | |
| Coordinates | Latitude | | Longitude | |
| Plan dimension | | | | |
| | | | | |

| Typology | Analysis level | Element code |
|---|---|---|
| Electric power grid | Network | EPN01 |
| Generation plant | Station | EPN02 |
| Substation | Station | EPN03 |

| | | | | |
|---|---|---|---|---|
| Typology | EPN-01 | EPN-02 | EPN-03 | |
| | HV > 350KV | Small <200MW | Low <150KV | |
| | MV (350 KV to 150KV) | Medium/large >200MV | Medium (150KV to 350KV) | |
| | LV < 150KV | | High >350KV | |
| | | | | |
| Fixity | | Anchored | Anchored | |
| | | Unanchored | Unanchored | |
| Physical Codition | Structure Condition-Damage Grade | | | |
| | Grade-0 | None | | |
| | Grade-1 | Slight | | |
| | Grade-2 | Moderate | | |
| Comments | | | | |

Figure 25: Electric power network data rubric

| | | | | | |
|---|---|---|---|---|---|
| Structure ID | | | | | |
| Structure Address | Name | Block | District | Colony | |
| Coordinates | Latitude | | Longitude | | |
| Plan dimension | | | | | |
| Typology | Water Front Structure | | | | |
| | H< 10 m with Vs =250m/s | Cranes | Tanks | Other Cargo Facilities | Fuel Facilities |
| | H< 10 m with Vs =500m/s | | | | Low Seismic |
| | H> 10 m with Vs =250m/s | stationary | | stationary | Moderate Seismic |
| | H> 10 m with Vs =500m/s | rail mounted | | rail mounted | High Seismic |
| Fixity | | | Anchored | | Anchored |
| | | | Unanchored | | Unanchored |
| Physical Codition | Structure Condition-Damage Grade | | | | |
| | Grade-0 | None | | | |
| | Grade-1 | Slight | | | |
| | Grade-2 | Moderate | | | |
| Comments | | | | | |

Figure 26: Harbor System data rubric

| | | | | |
|---|---|---|---|---|
| Structure ID | | | | |
| Structure Address | Name | Block | District | Colony |
| | | | | |
| Coordinates | Latitude | | Longitude | |
| Plan dimension | | | | |
| | | | | |
| | | | | |
| Typology | Refineries | | Pumping Plants | Tank Farm |
| | Small < 100000 BPD | | Low Seismic | |
| | Medium/Large > 100000 BPD | | High Seismic | |
| | | | | |
| Fixity | Anchored | | Anchored | Anchored |
| | Unanchored | | Unanchored | Unanchored |
| Physical Codition | Structure Condition-Damage Grade | | | |
| | Grade-0 | None | | |
| | Grade-1 | Slight | | |
| | Grade-2 | Moderate | | |
| Comments | | | | |

Figure 27: Oil and Gas System data rubric

| | | | | | |
|---|---|---|---|---|---|
| Structure ID | | | | | |
| Structure Address | Name | Block | District | Colony | |
| | | | | | |
| Coordinates | Latitude | | Longitude | | |
| Plan dimension | | | | | |
| | | | | | |
| | | | | | |
| Typology | Exchange Buildings | Transmission Tower | | | |
| | | | | | |
| Fixity | Anchored | Anchored | | | |
| | Unanchored | Unanchored | | | |
| Physical Codition | Structure Condition-Damage Grade | | | | |
| | Grade-0 | None | | | |
| | Grade-1 | Slight | | | |
| | Grade-2 | Moderate | | | |
| Comments | | | | | |

Figure 28: Telecommunication network data rubric

| | | | | |
|---|---|---|---|---|
| Structure ID | | | | |
| Structure Address | Name | Block | District | Colony |
| | | | | |
| Coordinates | Latitude | | Longitude | |
| Plan dimension | | | | |
| | | | | |
| | | | | |
| Typology | Waste-Water treatment Plant | | Water Treatment Plant | Pumping station |
| | Low rise low seismic | | | Small <10mgd |
| | Low rise advance seism | | | Medium/Large > 10mgd |
| | | | | |
| Fixity | Anchored | | Anchored | Anchored |
| | Unanchored | | Unanchored | Unanchored |
| Physical Codition | Structure Condition-Damage Grade | | | |
| | Grade-0 | None | | |
| | Grade-1 | Slight | | |
| | Grade-2 | Moderate | | |
| Comments | | | | |

Figure 29: Water and Waste-Water Systems data rubric

In the second step, Geographic information system (GIS) mapping has been employed based on the typology classification for different existing structures shown in Figures 30-39. Also, the collected sample database shown in Tables 1-19.

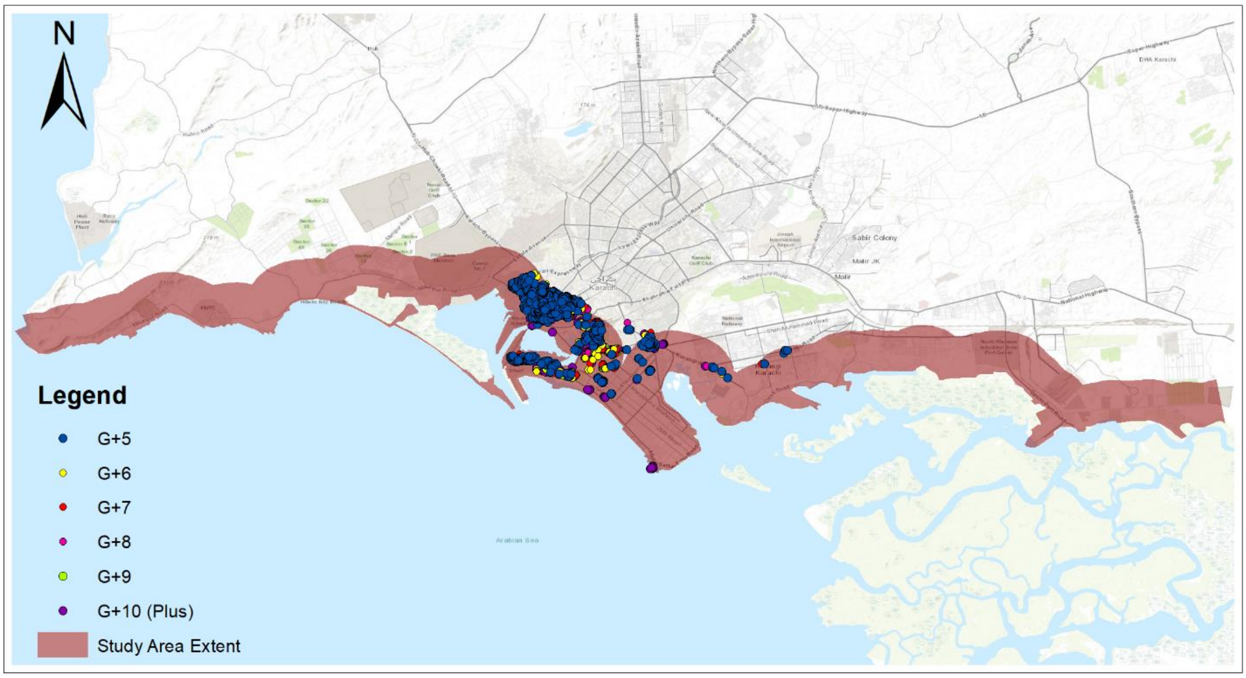


Figure 30: Reinforced Concrete Building Stock in Case-study Area

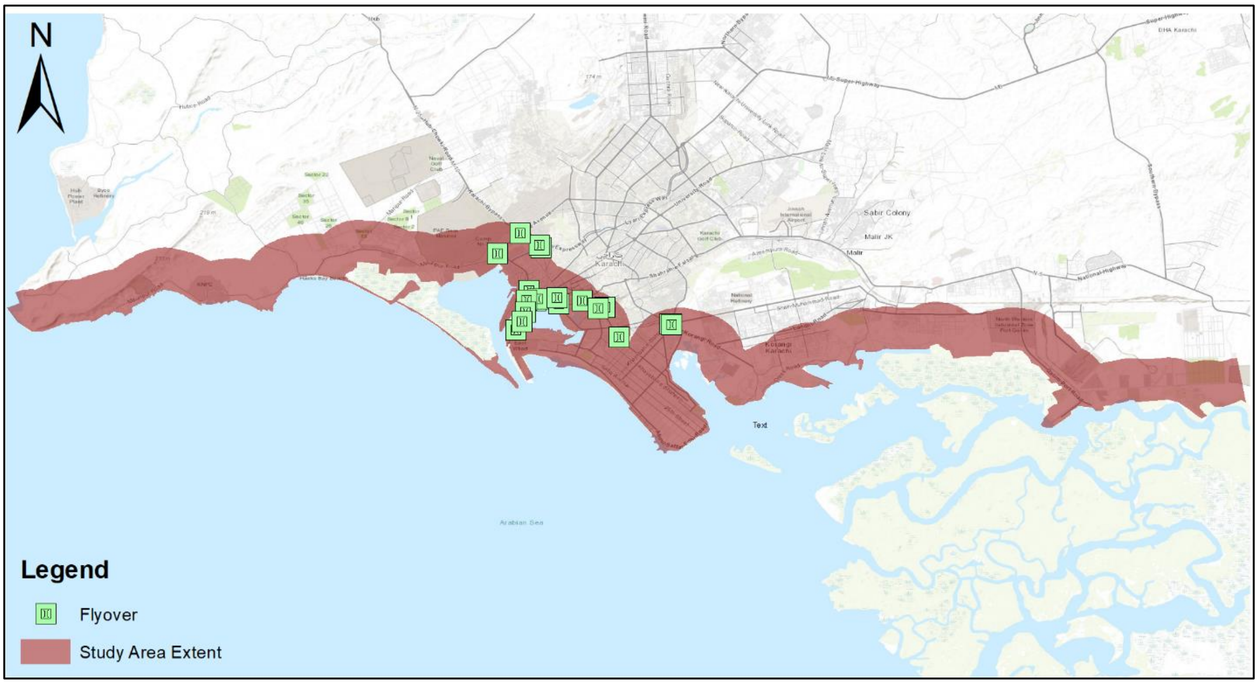


Figure 31: Identified flyovers in the case-study area

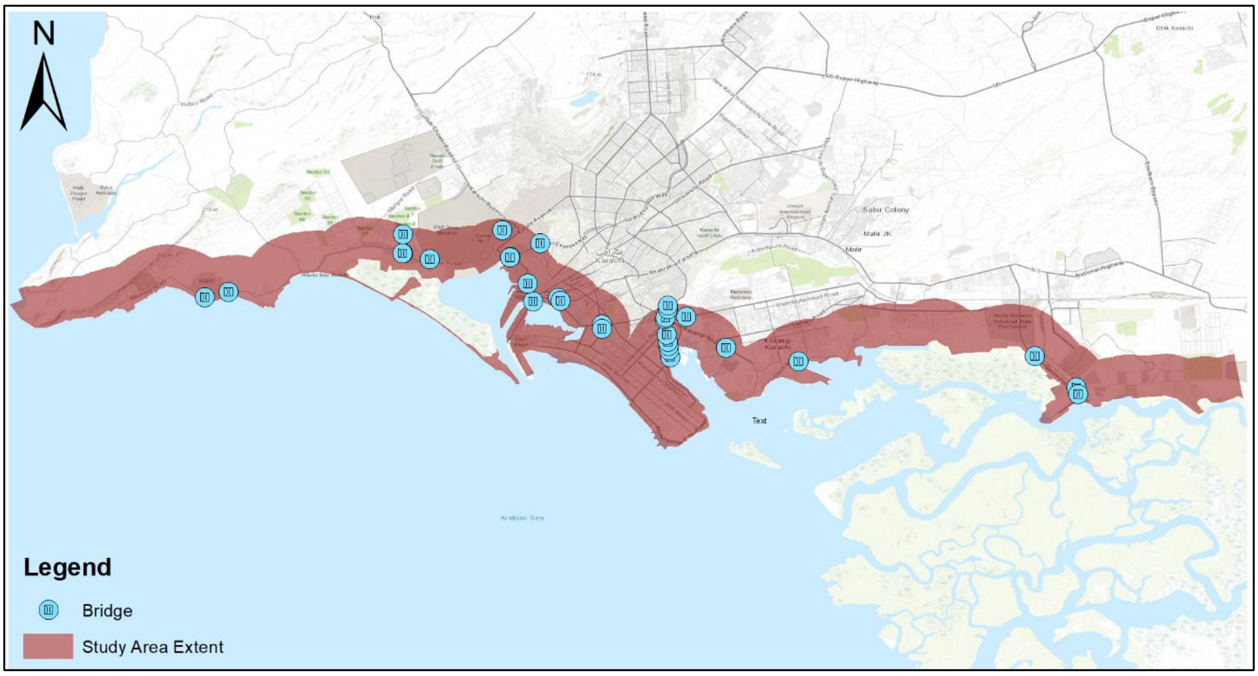


Figure 32: Identified bridges in the case-study area

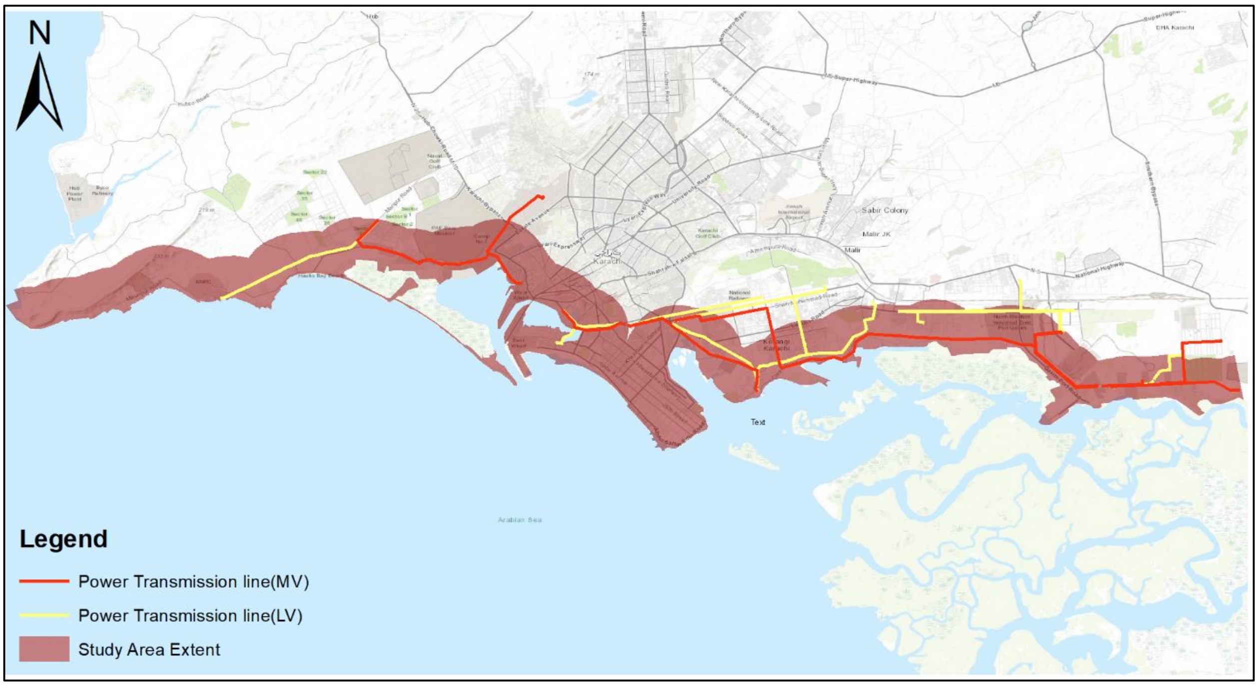


Figure 33: Power Grid-EPN-01

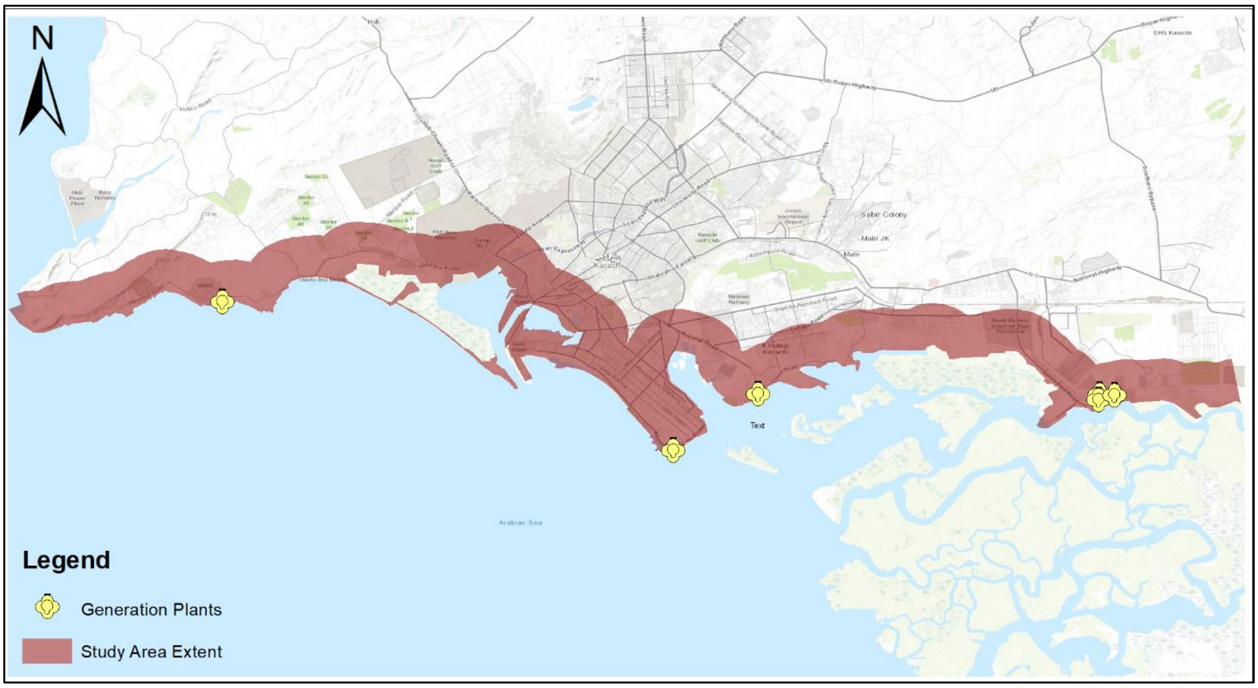


Figure 34: Generation Plant-EPN-02

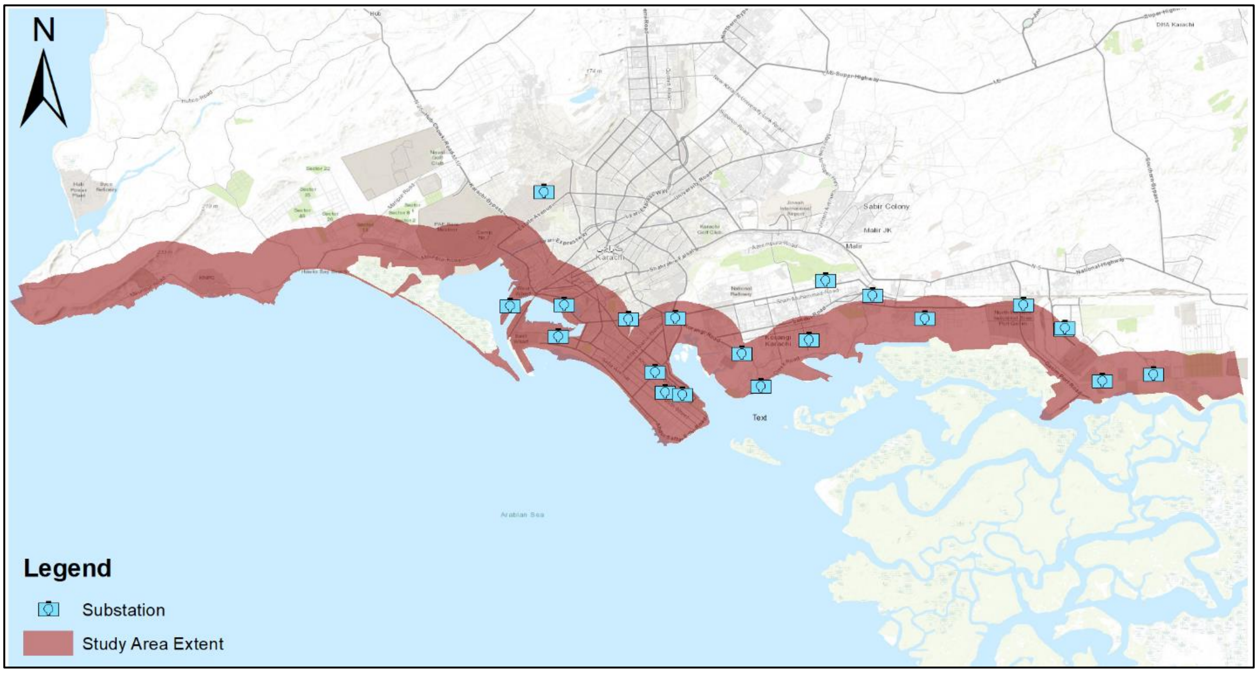


Figure 35: Substations-EPN-03

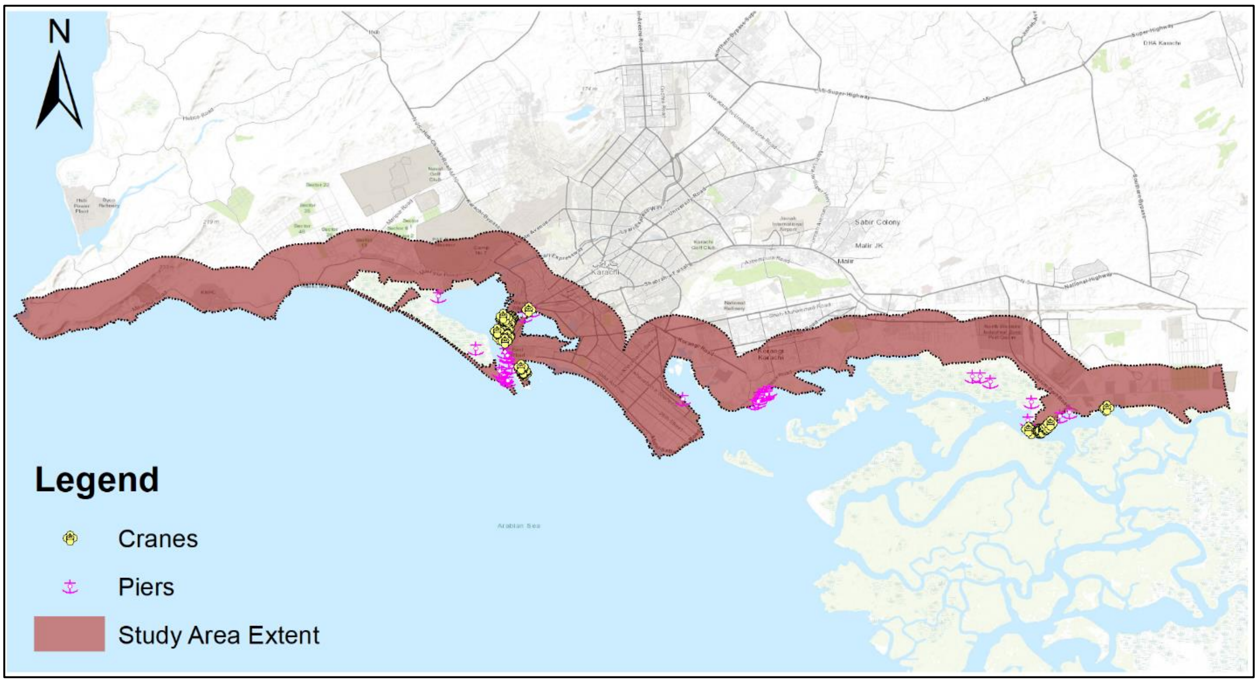


Figure 36: Waterfront Structures, Cranes and Fuel Facilities

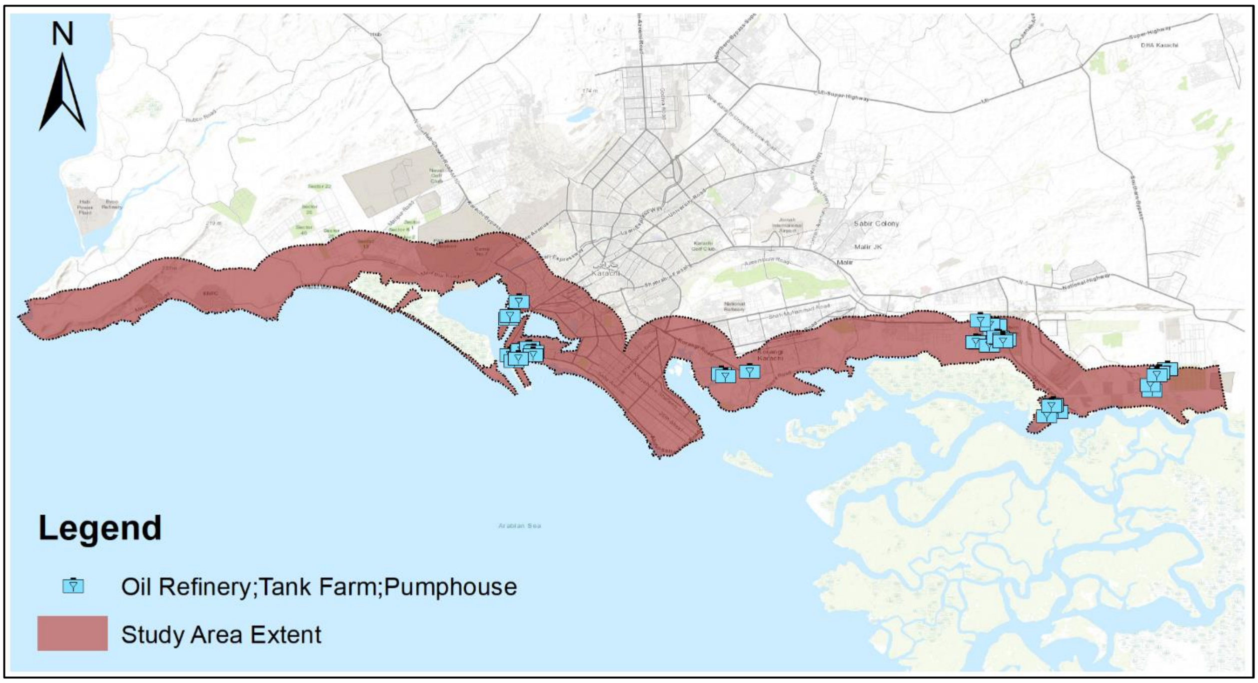


Figure 37: Refineries, Pumping Plants and Tank Farms

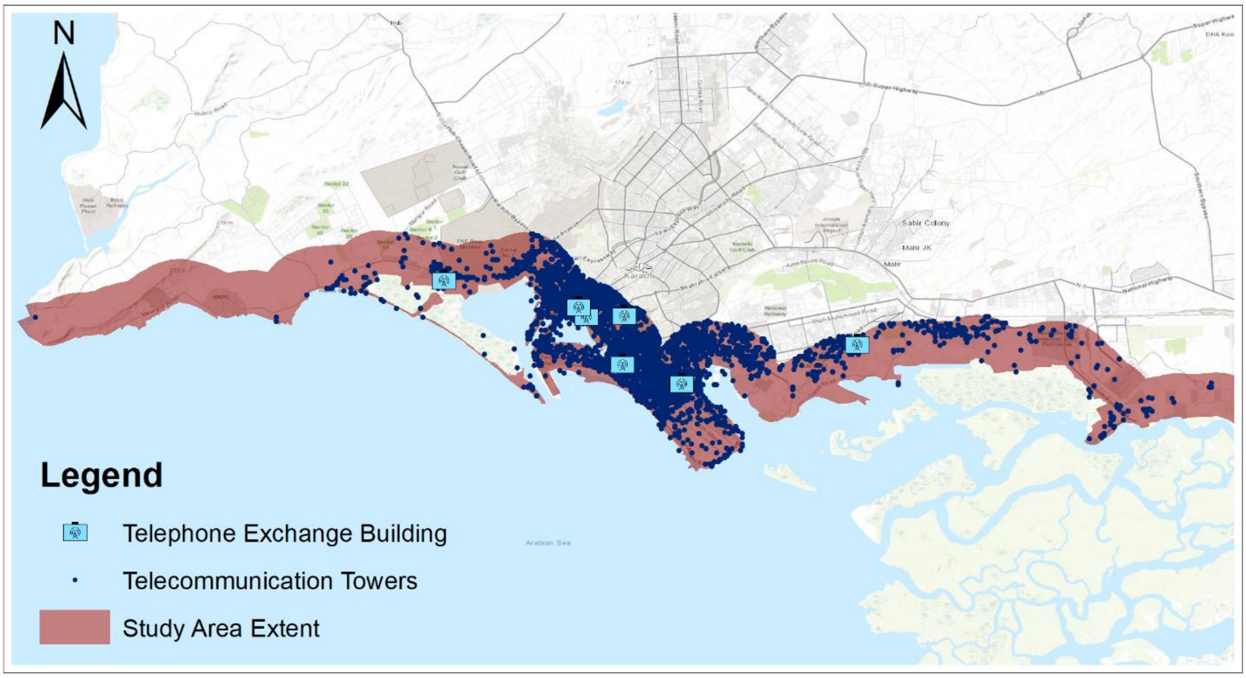


Figure 38: Telephone Exchange Buildings and Transmission Towers

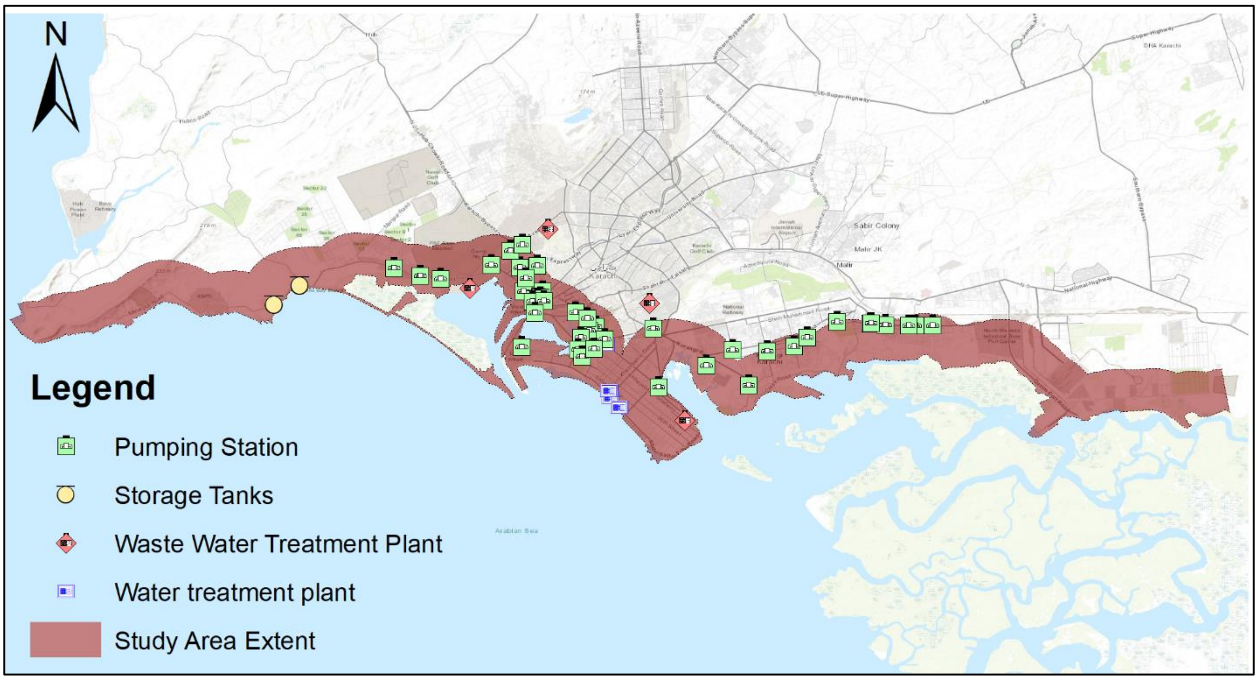


Figure 39: Water treatment plant, Waste-water treatment plant and Pumping stations

Table 1: Ground plus Five Story Reinforced Concrete Buildings

| S.No | Objectid | Location | Stoery | Building Type | Longitude | Latitude |
|---|---|---|---|---|---|---|
| 1 | 8 | Korangi | 5 | RCC | 67.11277848 | 24.81620518 |
| 2 | 9 | Korangi | 5 | RCC | 67.11253342 | 24.81715338 |
| 3 | 10 | Korangi | 5 | RCC | 67.11343886 | 24.81642365 |
| 4 | 12 | Korangi | 5 | RCC | 67.12253902 | 24.80961462 |
| 5 | 13 | Korangi | 5 | RCC | 67.11845615 | 24.81380873 |
| 6 | 23 | Korangi | 5 | RCC | 67.14676254 | 24.81894782 |
| 7 | 28 | Korangi | 5 | RCC | 67.15981704 | 24.82608301 |
| 8 | 32 | Korangi | 5 | RCC | 67.16062797 | 24.82779414 |
| 9 | 33 | Korangi | 5 | RCC | 67.16086577 | 24.82782788 |
| 10 | 36 | Korangi | 5 | RCC | 67.1618926 | 24.82809204 |

Table 2: Ground plus Six Storeyed Reinforced Concrete Building

| S.No | Objectid | Location | Stoery | Building Type | Longitude | Latitude |
|---|---|---|---|---|---|---|
| 1 | 18 | Korangi | 6 | RCC | 67.11903532 | 24.81229 |
| 2 | 26 | Korangi | 6 | RCC | 67.14698993 | 24.8193 |
| 3 | 62 | Clifton | 6 | RCC | 67.03199123 | 24.83947 |
| 4 | 71 | Clifton | 6 | RCC | 67.02423376 | 24.82876 |
| 5 | 76 | Clifton | 6 | RCC | 67.03343144 | 24.83282 |
| 6 | 79 | Clifton | 6 | RCC | 67.03305869 | 24.83484 |
| 7 | 90 | Clifton | 6 | RCC | 67.0236973 | 24.83337 |
| 8 | 101 | Clifton | 6 | RCC | 67.02515405 | 24.83222 |
| 9 | 102 | Clifton | 6 | RCC | 67.02545056 | 24.83223 |
| 10 | 119 | Clifton | 6 | RCC | 67.02919081 | 24.8345 |

Table 3: Bent pier supported flyovers

| S.No | Longitude | Latitude | Flyover name | Column Type |
|---|---|---|---|---|
| 1 | 67.00714 | 24.84346 | Mai Kalochi Flyover | Bent Pier |
| 2 | 66.99553 | 24.8798 | Liyari Flyover | Bent Pier |
| 3 | 66.99435 | 24.88159 | Liyari Flyovere | Bent Pier |
| 4 | 67.03259 | 24.84092 | Clifton Flyover | Bent Pier |
| 5 | 66.98228 | 24.88925 | SherShah Flyover | Bent Pier |
| 6 | 66.96745 | 24.87594 | Gulbai Flyover | Bent Pier |
| 7 | 66.98334 | 24.83189 | Napier Mole Flyover | Bent Pier |

Table 4: Single column/Hammerhead pier supported flyovers

| S.No | Longitude | Latitude | Flyover name | Column Type |
|---|---|---|---|---|
| 1 | 66.99232 | 24.84559 | MT khan flyover | Single Column Pier |
| 2 | 66.99354 | 24.84681 | Jinnah Flyover | Single Column Pier |
| 3 | 67.08029 | 24.83062 | Qayyumabad Interchange | Single Column Pier |
| 4 | 67.07919 | 24.83056 | Qayyumabad Interchange | Single Column Pier |
| 5 | 67.08026 | 24.83009 | Qayyumabad Interchange | Single Column Pier |
| 6 | 67.04619 | 24.82208 | Gizri Flyover | Single Column Pier |

Table 5: Wall pier supported bridges

| S.No | Latitude | Longitude | Bridge name | Column Type |
|---|---|---|---|---|
| 1 | 24.83789 | 67.07787 | Manzoor Colony Street Road Bridge 1 | Wall Pier |
| 2 | 24.8401 | 67.07794 | Manzoor Colony Street Road Bridge 2 | Wall Pier |
| 3 | 24.80738 | 67.31679 | Qasim Port Road Bridge 1 | Wall Pier |

Table 6: List of Low Voltage Transmission line-EPN-01

| S.No | Longitude | Latitude | Capacity | Fixity |
|---|---|---|---|---|
| 1 | 67.41255 | 24.81442 | LV<150KV | Unanchored |
| 2 | 67.41238 | 24.81102 | LV<150KV | Unanchored |
| 3 | 67.41227 | 24.81301 | LV<150KV | Unanchored |
| 4 | 67.41214 | 24.81513 | LV<150KV | Unanchored |
| 5 | 67.41203 | 24.81723 | LV<150KV | Unanchored |
| 6 | 67.41191 | 24.81932 | LV<150KV | Unanchored |
| 7 | 67.4125 | 24.80894 | LV<150KV | Unanchored |
| 8 | 67.41221 | 24.80857 | LV<150KV | Unanchored |
| 9 | 67.41364 | 24.79515 | LV<150KV | Unanchored |
| 10 | 67.39195 | 24.79023 | LV<150KV | Unanchored |

Table 7: List of Medium Voltage Transmission line-EPN-01

| S.No | Longitude | Latitude | Capacity | Fixity |
|---|---|---|---|---|
| 1 | 67.4373 | 24.81871 | MV (350 KV to 150 KV) | Unanchored |
| 2 | 67.43735 | 24.81763 | MV (350 KV to 150 KV) | Unanchored |

| | | | | |
|---|---|---|---|---|
| 3 | 67.43602 | 24.81758 | MV (350 KV to 150 KV) | Unanchored |
| 4 | 67.43372 | 24.81745 | MV (350 KV to 150 KV) | Unanchored |
| 5 | 67.43133 | 24.81732 | MV (350 KV to 150 KV) | Unanchored |
| 6 | 67.42895 | 24.81722 | MV (350 KV to 150 KV) | Unanchored |
| 7 | 67.42657 | 24.8171 | MV (350 KV to 150 KV) | Unanchored |
| 8 | 67.42419 | 24.81699 | MV (350 KV to 150 KV) | Unanchored |
| 9 | 67.42181 | 24.81688 | MV (350 KV to 150 KV) | Unanchored |
| 10 | 67.41943 | 24.81677 | MV (350 KV to 150 KV) | Unanchored |

Table 8: List of Generation Plants-EPN-02

| S.No | Name | Capacity | Fixity | Latitude | Longitude |
|---|---|---|---|---|---|
| 1 | K-Electric BQPS I | Small <200MW | Anchored | 24.785 | 67.36 |
| 2 | K-Electric BQPS II | Medium/large >200MV | Anchored | 24.782 | 67.36 |
| 3 | Port Qasim Power Plant | Medium/large >200MV | Anchored | 24.785 | 67.37 |
| 4 | Karachi Nuclear Power Complex | Medium/large >200MV | Anchored | 24.845 | 66.789 |
| 5 | DHA Cogen Ltd - DCL Power | Small <200MW | Anchored | 24.749 | 67.083 |
| 6 | KE KTPS (CCPP) | Medium/large >200MV | Anchored | 24.786 | 67.138 |

Table 9: List of Substations-EPN-03

| S.No | Name | Longitude | Latitude | Capacity | Fixity |
|---|---|---|---|---|---|
| 1 | Korangi South Grid Station | 67.1694 | 24.8154 | Low<150KV | Anchored |
| 2 | K-Electric EPZ Grid Station | 67.2449 | 24.8295 | Low<150KV | Anchored |
| 3 | PRL Grid Station | 67.1258 | 24.8065 | Low<150KV | Anchored |
| 4 | Defence Grid Station | 67.0693 | 24.7945 | Low<150KV | Anchored |
| 5 | KE DHA 1 Grid station | 67.0758 | 24.7815 | Low<150KV | Anchored |
| 6 | Korangi Creek Grid Station | 67.0826 | 24.8297 | Medium (150KV to 350KV) | Anchored |
| 7 | Gizri Grid Station | 67.0521 | 24.8290 | Medium (150KV to 350KV) | Anchored |
| 8 | KE KTPS Grid Station | 67.1382 | 24.7852 | Low<150KV | Anchored |
| 9 | KE Lalazar Grid Station | 67.0102 | 24.8381 | Medium (150KV to 350KV) | Anchored |
| 10 | Creek City Grid Station | 67.0870 | 24.7800 | Low<150KV | Anchored |

Table 10: Waterfront Structures and Cranes

| S.No | Name | Latitude | Longitude | Piers | Cranes |
|---|---|---|---|---|---|
| 1 | Boat Wharf | 24.84087 | 66.98674 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 2 | P.N.S Himalaya Pier | 24.8192 | 66.95452 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 3 | K.P.T. Crew Pier | 24.8003 | 66.97409 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |

| | | | | | |
|---|---|---|---|---|---|
| 4 | K.P.T. Officer Pier (Pilots) | 24.79971 | 66.97453 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 5 | K.P.T. Workshop Pier | 24.80314 | 66.97183 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 6 | Passenger Pier | 24.80059 | 66.97366 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 7 | Pak-Naval Academy Pier | 24.80124 | 66.97332 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 8 | Pier for public boats | 24.80431 | 66.97038 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 9 | Qasim Pier | 24.79808 | 66.97584 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 10 | Oil Pier I | 24.80717 | 66.97852 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 11 | Oil Pier II | 24.81031 | 66.97642 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 12 | Oil Pier III | 24.81371 | 66.9751 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 13 | Karachi Yacht Club Pier | 24.81458 | 66.97559 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 14 | Kemari Jetty | 24.81678 | 66.97382 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 15 | Port Grand Pier | 24.84411 | 66.99176 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 16 | FOTCO Jetty | 24.79707 | 67.29423 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 17 | Progas Jetty | 24.80079 | 67.28767 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 18 | Jetty | 24.80088 | 67.28233 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 19 | Pak-Steel Terminal (IOCB) | 24.78388 | 67.3213 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 20 | MVTJ Jetty | 24.77179 | 67.3191 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 21 | Service Jetty | 24.77715 | 67.34651 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 22 | LCT Pier | 24.77439 | 67.34028 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 23 | PAF Jetty | 24.78321 | 67.13867 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 24 | Jetty | 24.79161 | 67.14861 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 25 | Jetty | 24.79027 | 67.14704 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 26 | Jetty | 24.78909 | 67.14646 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 27 | Jetty | 24.79016 | 67.14452 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 28 | Jetty | 24.78858 | 67.14385 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 29 | Jetty | 24.78829 | 67.14302 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 30 | Jetty | 24.78777 | 67.14165 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 31 | Jetty | 24.78603 | 67.14194 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 32 | Jetty | 24.78421 | 67.14128 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 33 | DHA Creek Pier | 24.78589 | 67.09134 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |
| 34 | P. M. A Boat Jetty | 24.85389 | 66.92987 | H> 10m and Vs = 250m/sec | Stationery/Rail Mounted |

Table 11: Cargo Handling Facilities, Steel Tanks and Fuel Facilities

| S. No | Name | Cargo Handling Facilities | Tanks | Fuel Facilities |
|---|---|---|---|---|
| 1 | Boat Wharf | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 2 | P.N.S Himalaya Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 3 | K.P.T. Crew Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 4 | K.P.T. Officer Pier (Pilots) | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 5 | K.P.T. Workshop Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 6 | Passenger Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 7 | Pakistan Naval Academy Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 8 | Pier for public boats | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 9 | Qasim Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 10 | Oil Pier I | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 11 | Oil Pier II | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 12 | Oil Pier III | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 13 | Karachi Yacht Club Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 14 | Kemari Jetty | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 15 | Port Grand Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 16 | FOTCO Jetty | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 17 | Progas Jetty | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 18 | Jetty | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 19 | Pakistan Steel Terminal | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 20 | MVTJ Jetty | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 21 | Service Jetty | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |
| 22 | LCT Pier | Stationery/Rail Mounted | Anchored | High Seismic (Unanchored) |

Table 12: List of Oil Refineries

| S.No | Name | Latitude | Longitude | Typology | Fixity |
|---|---|---|---|---|---|
| 1 | Khalis Oil refinery | 24.80596 | 67.412752 | Small | Anchored |
| 2 | HM Extraction | 24.79174 | 67.402762 | Small | Anchored |
| 3 | Mujahid Oil Refinery | 24.7777 | 67.340117 | Small | Anchored |
| 4 | Farooq Enterprises | 24.80342 | 67.407858 | Small | Anchored |
| 5 | M.M. Oil Mills | 24.77477 | 67.332679 | Small | Anchored |
| 6 | Unity Foods Ltd Portqasim Refinery Edible Oil | 24.79504 | 67.401417 | Small | Anchored |
| 7 | Shujabad Agro Industries | 24.83265 | 67.297126 | Small | Anchored |
| 8 | Gamalux Oleochemicals (PVT.) LTD.Director Number | 24.83471 | 67.299155 | Small | Anchored |
| 9 | Total Lube Pakistan (Lubricant Plant) | 24.82348 | 67.287395 | Small | Anchored |
| 10 | PARCO Bin Qasim | 24.82526 | 67.305529 | Medium/Large | Anchored |

| | | | | | |
|---|---|---|---|---|---|
| 11 | Al-Makka Oil Refinery | 24.80198 | 67.405823 | Small | Anchored |
| 12 | Mapak Edible Oils (Pvt.) Limited | 24.78227 | 67.337145 | Small | Anchored |
| 13 | Engineer's Lubricant (Lube Oil Plant) | 24.82384 | 67.285775 | Small | Anchored |
| 14 | PRL | 24.80264 | 67.11685 | Small | Anchored |
| 15 | PARCO KEAMARI TERMINAL | 24.81543 | 66.989558 | Medium/Large | Anchored |
| 16 | Faisalabad Oil Refinery | 24.83518 | 67.294843 | Small | Anchored |
| 17 | WR Edible Oil Refinery | 24.83814 | 67.288583 | Small | Anchored |
| 18 | Pakistan Refinery Limited | 24.80115 | 67.119441 | Small | Anchored |
| 19 | PARCO Corporate Headquarters | 24.80415 | 67.135644 | Small | Anchored |
| 20 | Bosicor Pakistan Ltd Refinery | 24.81681 | 66.98455 | Small | Anchored |
| 21 | IFFCO Pakistan | 24.78134 | 67.335677 | Small | Anchored |
| 22 | PSO Terminal"C" | 24.81802 | 66.989849 | Small | Anchored |
| 23 | Chevron Pakistan Lubricants Pvt. Ltd | 24.83936 | 66.97586 | Small | Anchored |
| 24 | International Tank Terminals (Pvt.) Ltd | 24.8411 | 66.976782 | Small | Anchored |
| 25 | Haroon Oils Ltd | 24.85056 | 66.982685 | Small | Anchored |
| 26 | Chevron Oil Company | 24.81938 | 66.988206 | Small | Anchored |
| 27 | Byco Terminal Pakistan Ltd | 24.81587 | 66.988166 | Medium/Large | Anchored |
| 28 | Al Raheem Oil Terminal | 24.81625 | 66.991014 | Small | Anchored |
| 29 | Shell L O B P (Lubricant Oil Blending Plant) | 24.81525 | 66.97677 | Small | Anchored |
| 30 | Al Abbas Tank Terminal Kemari | 24.81122 | 66.979332 | Small | Anchored |
| 31 | Pakistan Molasses Company (pvt) Ltd. | 24.81767 | 66.983308 | Small | Anchored |
| 32 | Burshane Petroleum Pvt Limited | 24.81779 | 66.984496 | Small | Anchored |
| 33 | Pakistan State Oil (PSO) - Kemari Terminal A | 24.81871 | 66.984715 | Small | Anchored |
| 34 | Pak Grease Manufacturing Co (Pvt) Ltd | 24.81845 | 66.984214 | Small | Anchored |
| 35 | Total Parco Pakistan Ltd. | 24.82014 | 66.989499 | Small | Anchored |
| 36 | ZY & Co. Bulk Terminal (Pvt) LTD | 24.81705 | 66.992214 | Small | Anchored |
| 37 | Al Noor Terminal | 24.81511 | 66.991895 | Small | Anchored |
| 38 | F&B Terminal | 24.81278 | 66.982258 | Small | Anchored |
| 39 | Hascol Vito Terminal | 24.82133 | 67.294688 | Small | Anchored |
| 40 | Bakri Energy Oil Terminal | 24.82665 | 67.301409 | Small | Anchored |
| 41 | Bakri Energy MOGAS Terminal | 24.82701 | 67.299676 | Small | Anchored |
| 42 | Bakri Energy Oil Terminal 1 | 24.82546 | 67.303746 | Small | Anchored |
| 43 | Hascol Petroleum Limited IPTL | 24.82425 | 67.303715 | Small | Anchored |

Table 13: List of Pumping Plants

| S.No | Name | Latitude | Longitude | Typology | Fixity |
|---|---|---|---|---|---|
| 1 | Khalis Oil refinery | 24.80596 | 67.412752 | High Seismic | Anchored |
| 2 | HM Extraction | 24.79174 | 67.402762 | High Seismic | Anchored |
| 3 | Mujahid Oil Refinery | 24.7777 | 67.340117 | High Seismic | Anchored |
| 4 | Farooq Enterprises | 24.80342 | 67.407858 | High Seismic | Anchored |

| | | | | | |
|---|---|---|---|---|---|
| 5 | M.M. Oil Mills | 24.77477 | 67.332679 | High Seismic | Anchored |
| 6 | Unity Foods Ltd Portqasim Refinery2 Edible Oil | 24.79504 | 67.401417 | High Seismic | Anchored |
| 7 | Shujabad Agro Industries | 24.83265 | 67.297126 | High Seismic | Anchored |
| 8 | Gamalux Oleochemicals (PVT.) LTD.Director Number | 24.83471 | 67.299155 | High Seismic | Anchored |
| 9 | Total Lube Pakistan (Lubricant Plant) | 24.82348 | 67.287395 | High Seismic | Anchored |
| 10 | PARCO Bin Qasim | 24.82526 | 67.305529 | High Seismic | Anchored |
| 11 | Al-Makka Oil Refinery | 24.80198 | 67.405823 | High Seismic | Anchored |
| 12 | Mapak Edible Oils (Pvt.) Limited | 24.78227 | 67.337145 | High Seismic | Anchored |
| 13 | Engineer's Lubricant (Lube Oil Plant) | 24.82384 | 67.285775 | High Seismic | Anchored |
| 14 | PRL | 24.80264 | 67.11685 | High Seismic | Anchored |
| 15 | PARCO KEAMARI TERMINAL | 24.81543 | 66.989558 | High Seismic | Anchored |
| 16 | Faisalabad Oil Refinery | 24.83518 | 67.294843 | High Seismic | Anchored |
| 17 | WR Edible Oil Refinery | 24.83814 | 67.288583 | High Seismic | Anchored |
| 18 | Pakistan Refinery Limited | 24.80115 | 67.119441 | High Seismic | Anchored |
| 19 | PARCO Corporate Headquarters | 24.80415 | 67.135644 | High Seismic | Anchored |
| 20 | Bosicor Pakistan Ltd Refinery | 24.81681 | 66.98455 | High Seismic | Anchored |
| 21 | IFFCO Pakistan | 24.78134 | 67.335677 | High Seismic | Anchored |
| 22 | PSO Terminal"C" | 24.81802 | 66.989849 | High Seismic | Anchored |
| 23 | Chevron Pakistan Lubricants Pvt. Ltd | 24.83936 | 66.97586 | High Seismic | Anchored |
| 24 | International Tank Terminals (Pvt.) Ltd | 24.8411 | 66.976782 | High Seismic | Anchored |
| 25 | Haroon Oils Ltd | 24.85056 | 66.982685 | High Seismic | Anchored |
| 26 | Chevron Oil Company | 24.81938 | 66.988206 | High Seismic | Anchored |
| 27 | Byco Terminal Pakistan Ltd | 24.81587 | 66.988166 | High Seismic | Anchored |
| 28 | Al Raheem Oil Terminal | 24.81625 | 66.991014 | High Seismic | Anchored |
| 29 | Shell L O B P (Lubricant Oil Blending Plant) | 24.81525 | 66.97677 | High Seismic | Anchored |
| 30 | Al Abbas Tank Terminal Kemari | 24.81122 | 66.979332 | High Seismic | Anchored |
| 31 | Pakistan Molasses Company (pvt) Ltd. | 24.81767 | 66.983308 | High Seismic | Anchored |
| 32 | Burshane Petroleum Pvt Limited | 24.81779 | 66.984496 | High Seismic | Anchored |
| 33 | Pakistan State Oil (PSO) - Kemari Terminal A | 24.81871 | 66.984715 | High Seismic | Anchored |
| 34 | Pak Grease Manufacturing Co (Pvt) Ltd | 24.81845 | 66.984214 | High Seismic | Anchored |
| 35 | Total Parco Pakistan Ltd. | 24.82014 | 66.989499 | High Seismic | Anchored |
| 36 | ZY & Co. Bulk Terminal (Pvt) LTD | 24.81705 | 66.992214 | High Seismic | Anchored |
| 37 | Al Noor Terminal | 24.81511 | 66.991895 | High Seismic | Anchored |
| 38 | F&B Terminal | 24.81278 | 66.982258 | High Seismic | Anchored |
| 39 | Hascol Vito Terminal | 24.82133 | 67.294688 | High Seismic | Anchored |
| 40 | Bakri Energy Oil Terminal | 24.82665 | 67.301409 | High Seismic | Anchored |
| 41 | Bakri Energy MOGAS Terminal | 24.82701 | 67.299676 | High Seismic | Anchored |
| 42 | Bakri Energy Oil Terminal 1 | 24.82546 | 67.303746 | High Seismic | Anchored |
| 43 | Hascol Petroleum Limited IPTL | 24.82425 | 67.303715 | High Seismic | Anchored |

Table 14: Tank Farms

| S.No | Name | Latitude | Longitude | Fixity |
|---|---|---|---|---|
| 1 | Khalis Oil refinery | 24.80596 | 67.412752 | Anchored |
| 2 | HM Extraction | 24.79174 | 67.402762 | Anchored |
| 3 | Mujahid Oil Refinery | 24.7777 | 67.340117 | Anchored |
| 4 | Farooq Enterprises | 24.80342 | 67.407858 | Anchored |
| 5 | M.M. Oil Mills | 24.77477 | 67.332679 | Anchored |
| 6 | Unity Foods Ltd Portqasim Refinery2 Edible Oil | 24.79504 | 67.401417 | Anchored |
| 7 | Shujabad Agro Industries | 24.83265 | 67.297126 | Anchored |
| 8 | Gamalux Oleochemicals (PVT.) LTD.Director Number | 24.83471 | 67.299155 | Anchored |
| 9 | Total Lube Pakistan (Lubricant Plant) | 24.82348 | 67.287395 | Anchored |
| 10 | PARCO Bin Qasim | 24.82526 | 67.305529 | Anchored |
| 11 | Al-Makka Oil Refinery | 24.80198 | 67.405823 | Anchored |
| 12 | Mapak Edible Oils (Pvt.) Limited | 24.78227 | 67.337145 | Anchored |
| 13 | Engineer's Lubricant (Lube Oil Plant) | 24.82384 | 67.285775 | Anchored |
| 14 | PRL | 24.80264 | 67.11685 | Anchored |
| 15 | PARCO KEAMARI TERMINAL | 24.81543 | 66.989558 | Anchored |
| 16 | Faisalabad Oil Refinery | 24.83518 | 67.294843 | Anchored |
| 17 | WR Edible Oil Refinery | 24.83814 | 67.288583 | Anchored |
| 18 | Pakistan Refinery Limited | 24.80115 | 67.119441 | Anchored |
| 19 | PARCO Corporate Headquarters | 24.80415 | 67.135644 | Anchored |
| 20 | Bosicor Pakistan Ltd Refinery | 24.81681 | 66.98455 | Anchored |
| 21 | IFFCO Pakistan | 24.78134 | 67.335677 | Anchored |
| 22 | PSO Terminal"C" | 24.81802 | 66.989849 | Anchored |
| 23 | Chevron Pakistan Lubricants Pvt. Ltd | 24.83936 | 66.97586 | Anchored |
| 24 | International Tank Terminals (Pvt.) Ltd | 24.8411 | 66.976782 | Anchored |
| 25 | Haroon Oils Ltd | 24.85056 | 66.982685 | Anchored |
| 26 | Chevron Oil Company | 24.81938 | 66.988206 | Anchored |
| 27 | Byco Terminal Pakistan Ltd | 24.81587 | 66.988166 | Anchored |
| 28 | Al Raheem Oil Terminal | 24.81625 | 66.991014 | Anchored |
| 29 | Shell L O B P (Lubricant Oil Blending Plant) | 24.81525 | 66.97677 | Anchored |
| 30 | Al Abbas Tank Terminal Kemari | 24.81122 | 66.979332 | Anchored |
| 31 | Pakistan Molasses Company (pvt) Ltd. | 24.81767 | 66.983308 | Anchored |
| 32 | Burshane Petroleum Pvt Limited | 24.81779 | 66.984496 | Anchored |
| 33 | Pakistan State Oil (PSO) - Kemari Terminal A | 24.81871 | 66.984715 | Anchored |
| 34 | Pak Grease Manufacturing Co (Pvt) Ltd | 24.81845 | 66.984214 | Anchored |
| 35 | Total Parco Pakistan Ltd. | 24.82014 | 66.989499 | Anchored |
| 36 | ZY & Co. Bulk Terminal (Pvt) LTD | 24.81705 | 66.992214 | Anchored |
| 37 | Al Noor Terminal | 24.81511 | 66.991895 | Anchored |
| 38 | F&B Terminal | 24.81278 | 66.982258 | Anchored |
| 39 | Hascol Vito Terminal | 24.82133 | 67.294688 | Anchored |

| | | | | |
|---|---|---|---|---|
| 40 | Bakri Energy Oil Terminal | 24.82665 | 67.301409 | Anchored |
| 41 | Bakri Energy MOGAS Terminal | 24.82701 | 67.299676 | Anchored |
| 42 | Bakri Energy Oil Terminal 1 | 24.82546 | 67.303746 | Anchored |
| 43 | Hascol Petroleum Limited IPTL | 24.82425 | 67.303715 | Anchored |

Table 15: Telephone Exchange Buildings

| S.No | Name | Latitude | Longitude | Fixity |
|---|---|---|---|---|
| 1 | Telephone Exchange | 24.826262 | 67.176839 | Anchored |
| 2 | Maripur Telephone Exchange | 24.866197 | 66.917705 | Anchored |
| 3 | Clifton Telephone Exchange | 24.813771 | 67.029837 | Anchored |
| 4 | PTCL Misri Shah Telephone Exchange | 24.801364 | 67.066752 | Anchored |
| 5 | Karachi Telephone Exchange | 24.844178 | 67.030615 | Anchored |
| 6 | PTCL Telephone Exchange | 24.843297 | 67.006948 | Anchored |
| 7 | PTCL, Telephone Exchange | 24.849667 | 67.002288 | Anchored |

Table 16: List of Transmission Towers

| Tower-No | Latitude | Longitude | Fixity |
|---|---|---|---|
| 1 | 24.828807 | 67.060841 | Anchored |
| 2 | 24.830647 | 67.06192 | Anchored |
| 3 | 24.78447 | 67.346878 | Anchored |
| 4 | 24.78447 | 67.346878 | Anchored |
| 5 | 24.78447 | 67.346878 | Anchored |
| 6 | 24.821548 | 67.065353 | Anchored |
| 7 | 24.821548 | 67.065353 | Anchored |
| 8 | 24.821548 | 67.065353 | Anchored |
| 9 | 24.833908 | 67.066727 | Anchored |
| 10 | 24.833908 | 67.066727 | Anchored |

Table 17: Water Treatment Plant

| S.No | Name | Fixity | Latitude | Longitude |
|---|---|---|---|---|
| 1 | Bahria Foundation Water Purification Plant | Anchored | 24.82436 | 67.04179 |
| 2 | CBC Water Purification Plant 02 | Anchored | 24.78944 | 67.04507 |
| 3 | CBC Water Purification Plant 01 | Anchored | 24.78324 | 67.05071 |
| 4 | CBC Water Purification Plant 03 | Anchored | 24.79395 | 67.04409 |

Table 18: Waste-Water Treatment Plant

| S.No | Name | Latitude | Longitude | Typology | Fixity |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| 1 | TP-3 | 24.86111 | 66.95222 | Low Rise Advance Seismic | Anchored |
| 2 | TP-1 | 24.90023 | 67.00367 | Low Rise Advance Seismic | Anchored |
| 3 | TP-2 | 24.85122 | 67.07043 | Low Rise Advance Seismic | Anchored |
| 4 | DHA Waste Water TP | 24.77421 | 67.09344 | Low Rise Advance Seismic | Anchored |

Table 19: List of Pumping Stations (PS)

| S.No | Name | Latitude | Longitude | Typology | Fixity |
|---|---|---|---|---|---|
| 1 | Gulbai PS | 24.876665 | 66.966431 | Small | Anchored |
| 2 | Bihar Colony PS | 24.874931 | 66.985255 | Small | Anchored |
| 3 | Chakawara PS | 24.876154 | 66.996614 | Small | Anchored |
| 4 | Peoples Play Ground PS | 24.859232 | 66.987508 | Small | Anchored |
| 5 | Khajoor Bazar PS | 24.859281 | 67.00035 | Small | Anchored |
| 6 | Shah Waliullah PS | 24.854119 | 66.994556 | Small | Anchored |
| 7 | Gao Gall PS | 24.855253 | 66.998491 | Small | Anchored |
| 8 | Musa Lane PS | 24.854429 | 66.996966 | Small | Anchored |
| 9 | Jafar Uddin PS | 24.852528 | 66.993567 | Small | Anchored |
| 10 | Bombay Bazar PS | 24.852808 | 67.001027 | Small | Anchored |

In the third step, PGA has been extracted from the hazard analysis presented in a separate report, which has been reproduced in Figure 40. The extracted PGA obtained at bed-rock level is further amplified on the basis of site amplification factors (Table 20) considering the typical soil characteristics (i.e., Soil type SD of UBC-97) in the case study area (Figure 41). The calculated soil amplification factor used in this report is 1.4 and is based on the calculated mean value of peak ground acceleration for different probability of exceedance (Table 21).

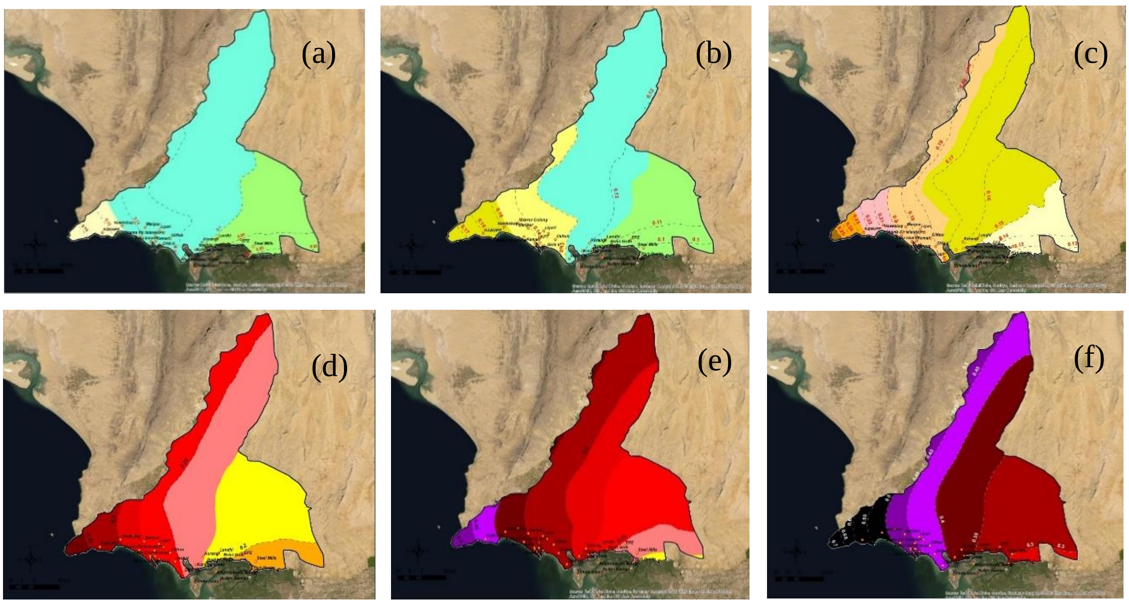


Figure 40: Spatial Distribution for annual probability of exceedance of the ground motion in terms of PGA-intensity measure in 50 years (a) 70 percent probability of exceedance (53 YRP) (b) 50 percent probability of

exceedance (80 YRP) (c) 25 percent probability of exceedance (178 YRP) (d) 10 percent probability of exceedance (476 YRP) (e) 5 percent probability of exceedance (976 YRP) (f) 2 percent probability of exceedance (2475 YRP)

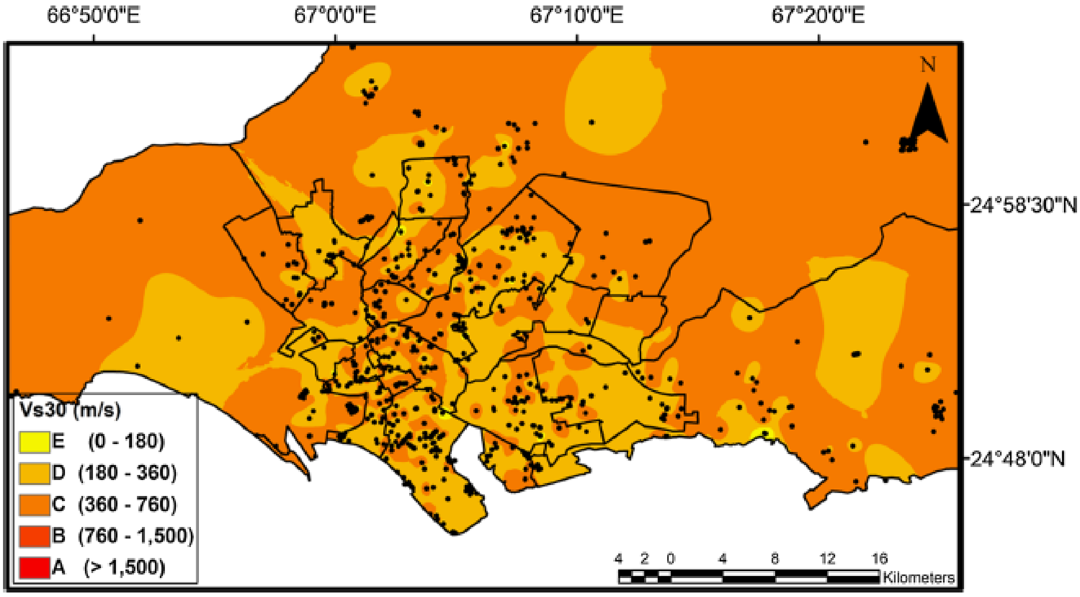


Figure 41: Vs30 values in Case-study area (Kumar et al., 2015)

Table 20: Soil Amplification Factors as per UBC-97

| Soil Profile Type | *Coefficient $C_a$* | | | | |
|---|---|---|---|---|---|
| | Z=0.075 | Z=0.15 | Z=0.2 | Z=0.3 | Z=0.4 |
| $S_A$ | 0.06 | 0.12 | 0.16 | 0.24 | $0.32N_a$ |
| $S_B$ | 0.08 | 0.15 | 0.20 | 0.30 | $0.40N_a$ |
| $S_C$ | 0.09 | 0.18 | 0.24 | 0.33 | $0.40N_a$ |
| $S_D$ | 0.12 | 0.22 | 0.28 | 0.36 | $0.44N_a$ |
| $S_E$ | 0.19 | 0.30 | 0.34 | 0.36 | $0.36N_a$ |
| | *Coefficient $C_V$* | | | | |
| | Z=0.075 | Z=0.15 | Z=0.2 | Z=0.3 | Z=0.4 |
| $S_A$ | 0.06 | 0.12 | 0.16 | 0.24 | $0.32N_v$ |
| $S_B$ | 0.08 | 0.15 | 0.20 | 0.30 | $0.40N_v$ |
| $S_C$ | 0.13 | 0.25 | 0.32 | 0.45 | $0.56N_v$ |
| $S_D$ | 0.18 | 0.32 | 0.40 | 0.54 | $0.64N_v$ |
| $S_E$ | 0.26 | 0.50 | 0.64 | 0.84 | $0.96N_v$ |

Table 21: Calculated Mean value of Intensity Measure-PGA for Different Return Periods

| **Return Period (years)** | **53** | **80** | **178** | **476** | **976** | **2475** |
|---|---|---|---|---|---|---|
| **Probability of exceedance (POE) (%)** | 70% | 50% | 25% | 10% | 5% | 2% |
| **PGA (g)** | 0.166 | 0.197 | 0.268 | 0.377 | 0.474 | 0.623 |

In the fourth and final step, the suitable fragility curves are identified from the literature and the corresponding damage matrices for different structures have been plotted. The fragility functions proposed by FEMA loss estimation methodology for earthquake models (FEMA-HAZUS Technical manual-2003) have been used in this report for damage estimates in all building type except for low-rise C3 and low-rise URM buildings Kumar et al., 2017 and Naveed et al., 2014 proposed fragility functions have been employed. To estimate the damage in bridges and flyovers for study area Khan et al., 2015 proposed fragility functions are employed. For electric power network system, the fragility functions proposed by FEMA loss estimation methodology for earthquake models (FEMA-HAZUS Technical manual-2003) have been employed.

The empirical fragility curves describing the earthquake induced damage in port structures proposed by HAZUS (NIBS-2004) methodology have been employed. Damage functions for waterfront structures were established based on damageability of subcomponents, namely, piers, seawalls, and wharf. Fault tree logic and the lognormal best fitting technique were used in developing these fragility curves. For cranes and cargo handling equipment, a distinction is made between stationary and rail-mounted cranes. Similar to waterfront structures, damage functions for fuel facilities were established based on damageability of subcomponents, namely, building structure (high seismic/low seismic), tanks (anchored/unanchored), and backup power (with/without). Fault-tree logic and the lognormal best fitting technique were used in developing these fragility curves. For oil refineries, the employed fragility curves are based on the probabilistic combination of subcomponent damage functions using Boolean expressions to describe the relationship of subcomponents. For pumping plants, the fragility function proposed by the Risk-UE Project (Alexoudi and Petilakis, 2003) for anchored and unanchored components have been used. Finally, the fragility functions proposed by HAZUS (NIBS 2004) are employed for the vulnerability assessment of tank farms. These fragility functions are based on fault-tree analysis (Figure 42) accounting also the fragility of the equipment (electric power, tanks, elevated pipes, electrical and mechanical components) needed for the tank facility to function properly.

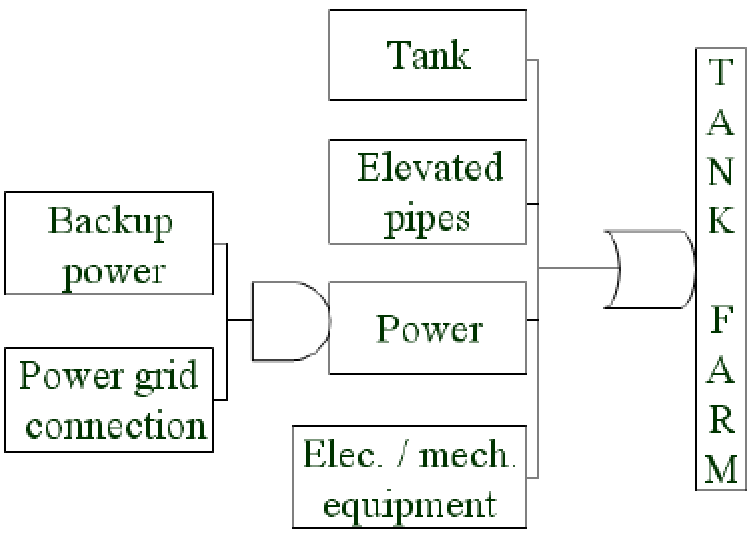


Figure 42: Fault-tree analysis proposed by HAZUS (NIBS 2004) for tank farms

The fragility functions from SRM-LIFE (2007) (Seismic Risk Assessment and Management of Lifelines, Utilities and Infrastructures) are employed for the vulnerability assessment of water and waste-water system. They were derived through fault-tree analysis, using the fault-tree and the fragility curves of sub-components proposed by HAZUS (NIBS 2004). The general framework of the methodology adopted in SRM-LIFE (2007) is illustrated in Figure 43. The vulnerability of buildings and lifeline systems is assessed for different seismic scenarios (Pitilakis et al., 2006a,b; Pitilakis et al., 2007a,b; Argyroudis et al., 2005).

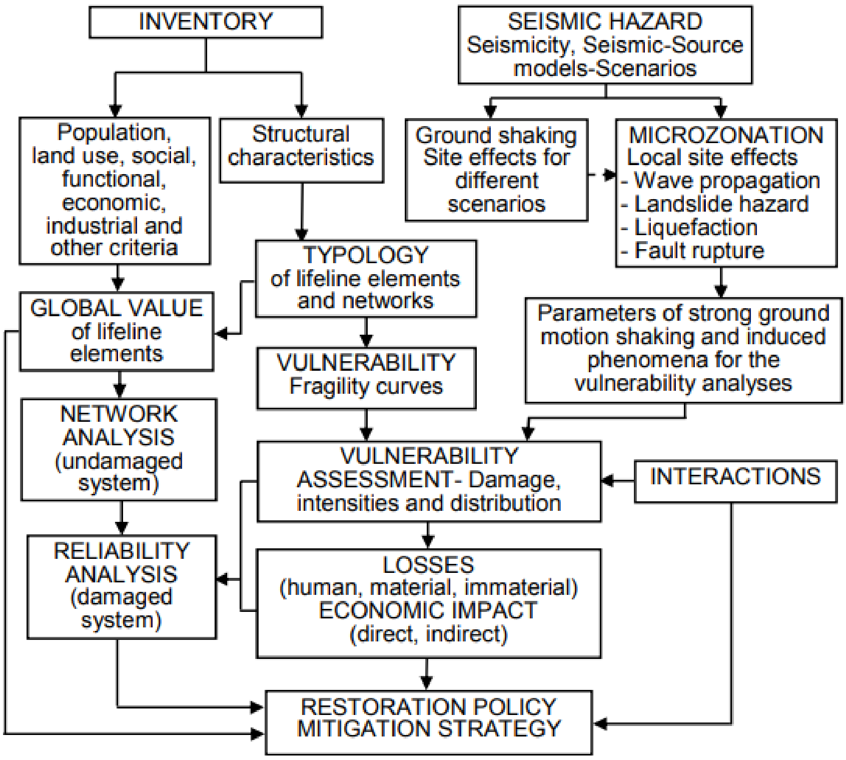


Figure 43: Seismic Risk Mitigation approach for lifelines and infrastructures

In this report, to develop the damage matrices for different inventories generally HAZUS methodology has been employed. The HAZUS-MH Earthquake Model provides estimates of damage and loss to buildings, essential facilities, transportation lifelines, utility lifelines, and population based on scenario or probabilistic earthquakes. The HAZUS model employs both earthquake hazard and structural fragility terms to calculate damage ratios and estimate damage costs (Figure 44).

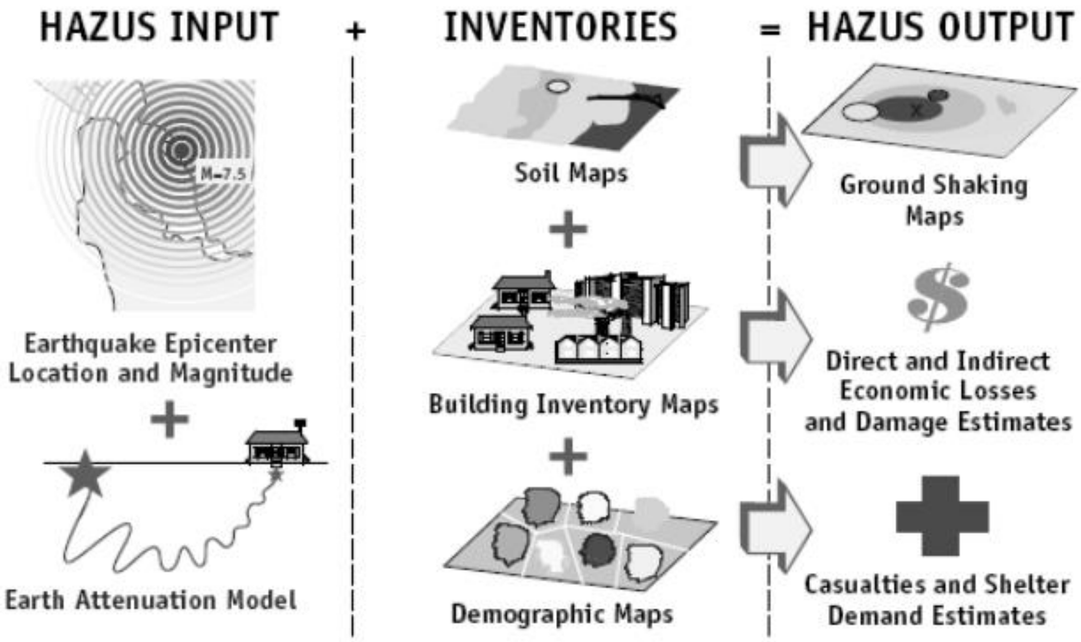


Figure 44: Earthquake Loss estimation Methodology (FEMA-HAZUS Technical manual-2003)

# Chapter 7 – Results and Discussion

The fragility functions for C1 building are plotted (Figures 45-47) for low-rise (C1L- number of floors three), mid-rise (C1M-number of floors four to eight) and high-rise (C1H- number of floors more than eight) building stock in terms of intensity measure (IM) PGA. Results are presented in terms of damage matrices in Figures 48-50. These show that at 10% probability of exceedance event, for low-rise structures 13% slight, 34% moderate, 31% extensive and 13% collapse limit states exceeding. For mid-rise structures 13% slight, 48% moderate, 25% extensive and 9% collapse limit states exceeding. In case of high-rise structures, 10% slight, 43% moderate, 30% extensive and 14% collapse limit states exceeding. The detailed damage matrices for different probability of exceedance are shown in Tables 22-24 for the low-rise, mid-rise and high-rise moment resisting framed buildings.

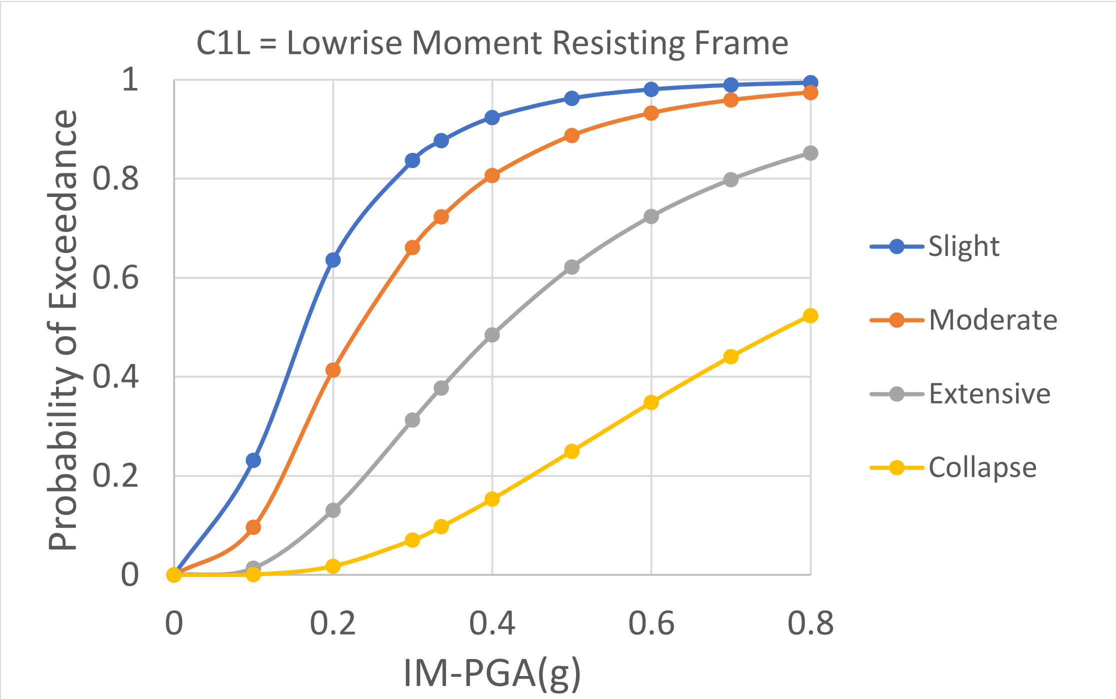


Figure 45: Fragility Curves for Low-rise Reinforced Concrete Moment Frame (C1L)

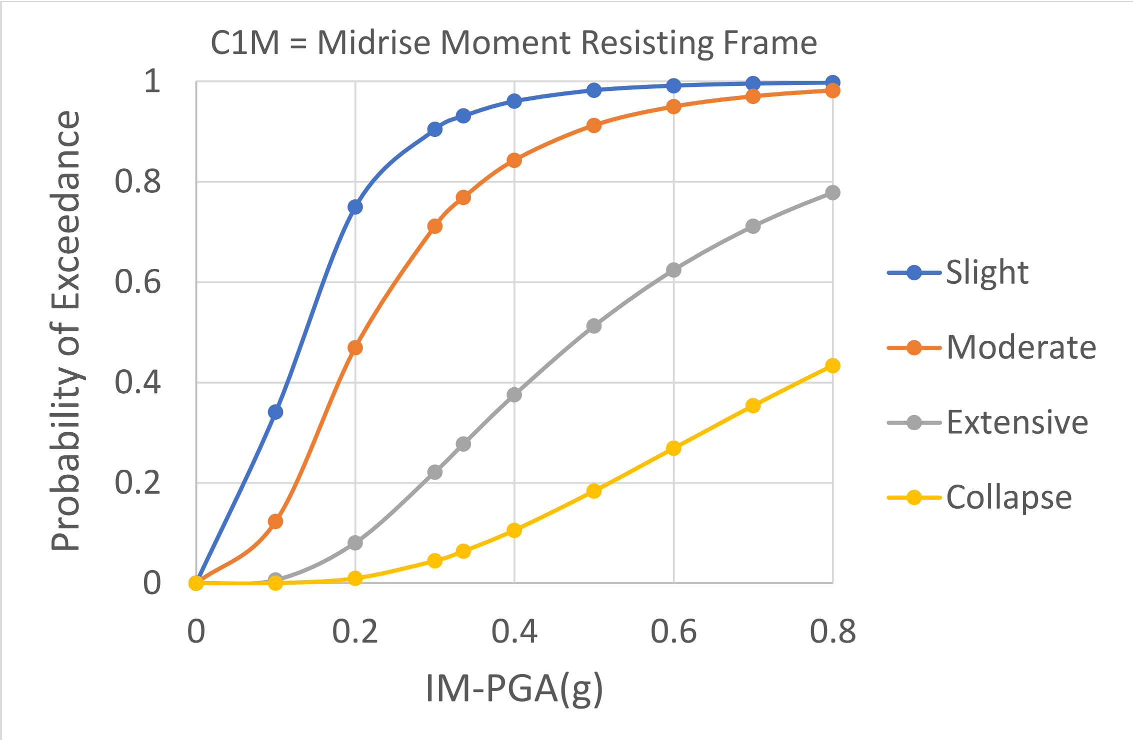


Figure 46: Fragility Curves for Mid-rise Reinforced Concrete Moment Frame (C1M)

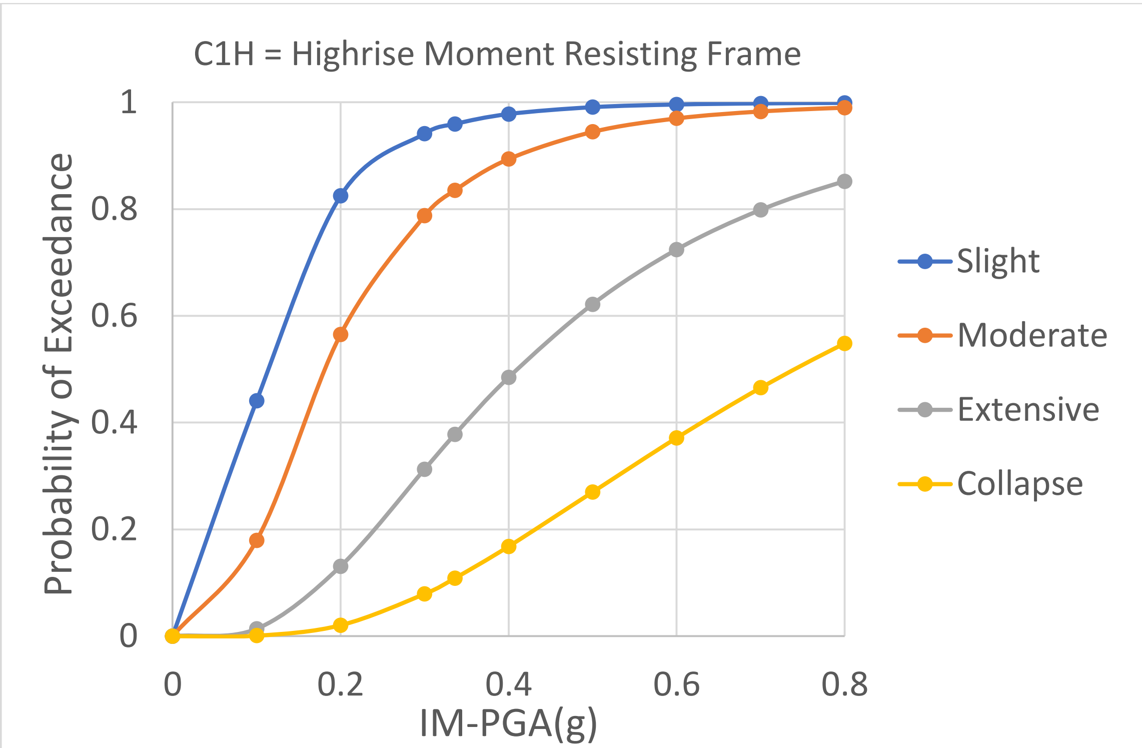


Figure 47: Fragility Curves for High-rise Reinforced Concrete Moment Frame (C1H)

Table 22: Damage Matrix for Low-rise Concrete Moment Resisting Framed Buildings (C1L)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 48 | 21 | 23 | 7 | 1 | 100 |
| **80** | 37 | 23 | 27 | 11 | 2 | 100 |
| **178** | 21 | 19 | 34 | 21 | 5 | 100 |
| **476** | 9 | 13 | 34 | 31 | 13 | 100 |
| **976** | 4 | 9 | 28 | 37 | 22 | 100 |
| **2475** | 2 | 4 | 20 | 37 | 37 | 100 |

Table 23: Damage Matrix for Mid-rise Concrete Moment Resisting Framed Buildings (C1M)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 36 | 29 | 31 | 4 | 0 | 100 |
| **80** | 26 | 28 | 38 | 7 | 1 | 100 |
| **178** | 13 | 22 | 47 | 15 | 3 | 100 |
| **476** | 5 | 13 | 48 | 25 | 9 | 100 |
| **976** | 2 | 8 | 42 | 32 | 16 | 100 |
| **2475** | 1 | 3 | 31 | 36 | 29 | 100 |

Table 24: Damage Matrix for High-rise Concrete Moment Resisting Framed Buildings (C1H)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 26 | 29 | 37 | 7 | 1 | 100 |
| **80** | 18 | 26 | 43 | 11 | 2 | 100 |
| **178** | 8 | 18 | 48 | 20 | 6 | 100 |
| **476** | 3 | 10 | 43 | 30 | 14 | 100 |
| **976** | 1 | 6 | 34 | 35 | 24 | 100 |
| **2475** | 0 | 3 | 23 | 35 | 39 | 100 |

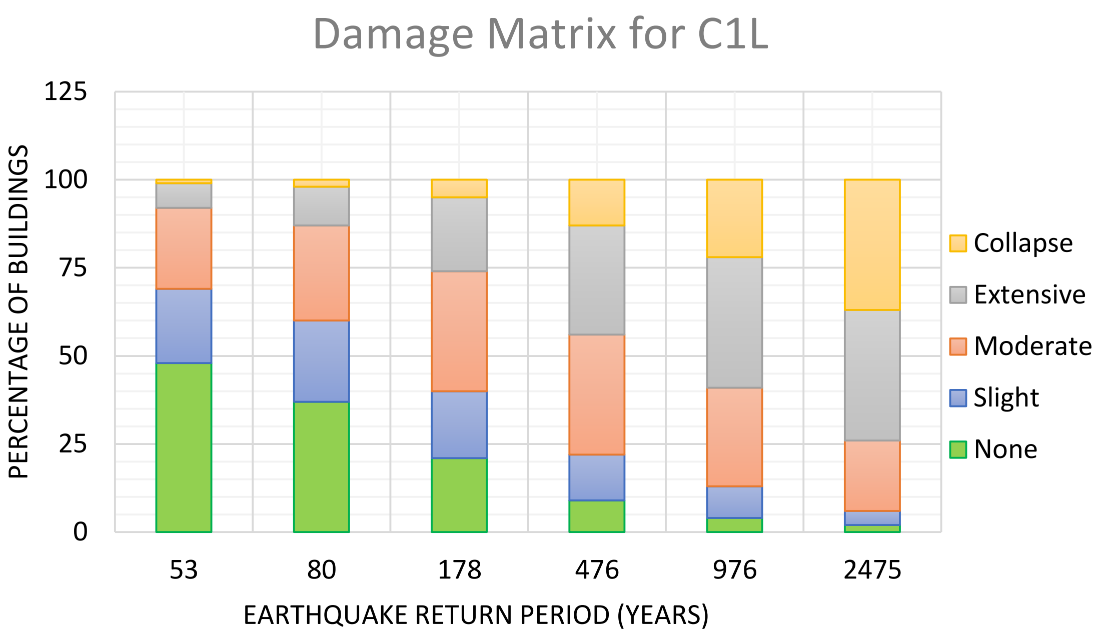


Figure 48: Low-rise Concrete Moment Resisting Framed Buildings (C1L)

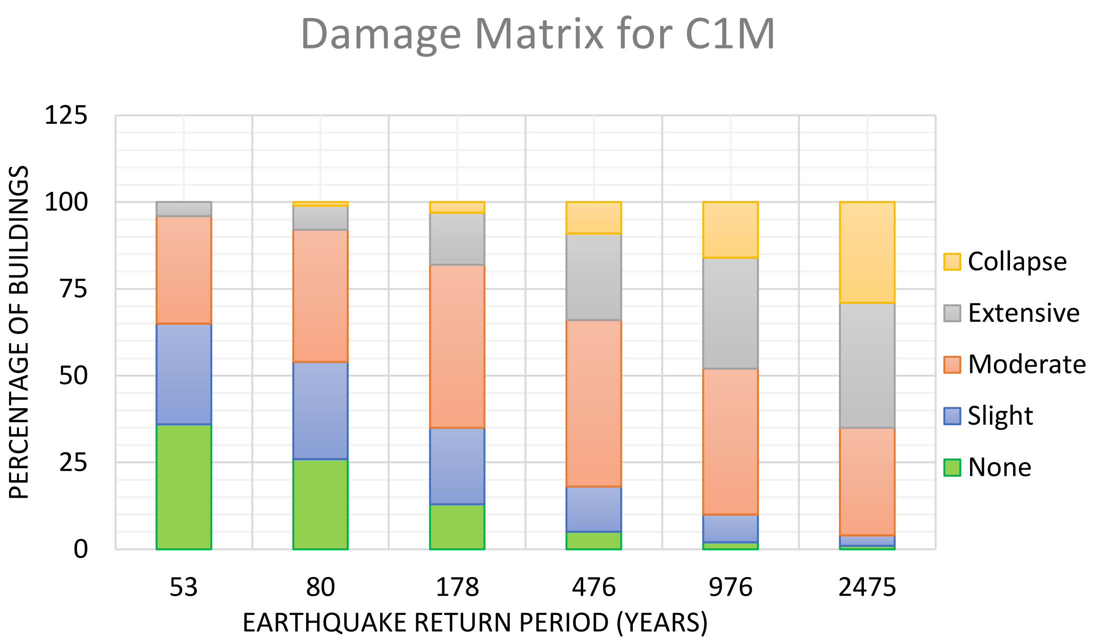


Figure 49: Mid-rise Concrete Moment Resisting Framed Buildings (C1M)

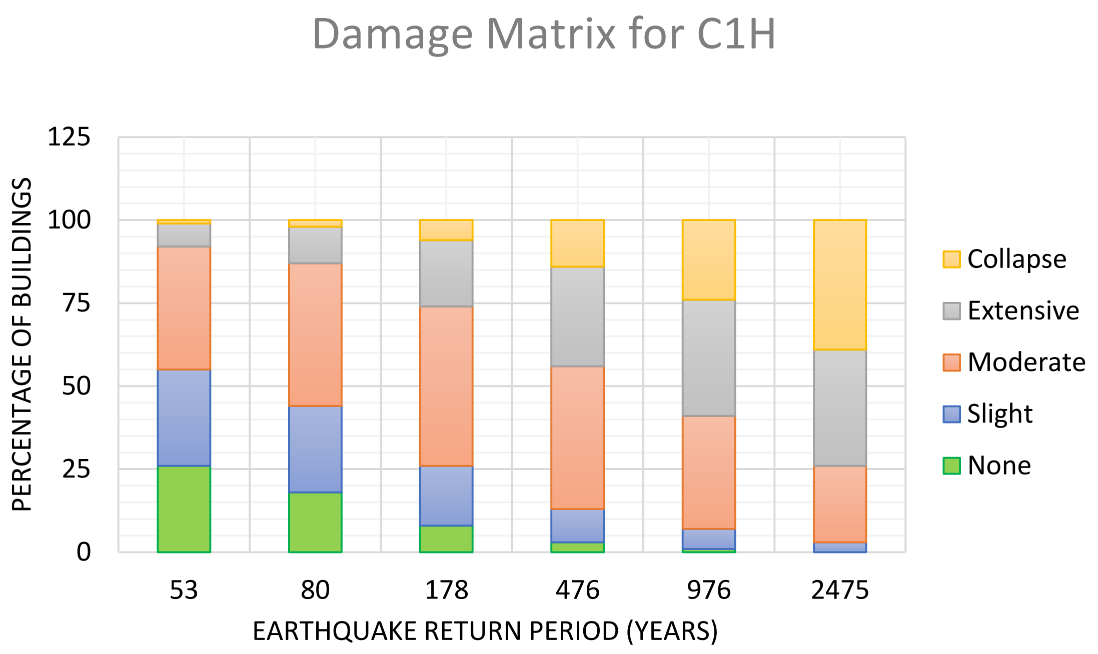


Figure 50: High-rise Concrete Moment Resisting Framed Buildings (C1H)

The fragility functions for C2 buildings are plotted (Figures 51-53) for low-rise (C2L- number of floors three), mid-rise (C2M-number of floors four to eight) and high-rise (C2H- number of floors more than eight) building stock in terms of intensity measure PGA. Results are presented in terms of damage matrices in Figures 54-56. These show that at 10% probability of exceedance event, for low-rise structures 24% slight, 29% moderate, 25% extensive and 9% collapse limit states exceeding. For mid-rise structures 20% slight, 45% moderate, 21% extensive and 6% collapse limit states exceeding. In case of high-rise structures, 18% slight, 52% moderate, 21% extensive and 5% collapse limit states exceeding. The detailed damage matrices for different probability of exceedance are shown in Tables 25-27 for the low-rise, mid-rise and high-rise shear wall framed buildings.

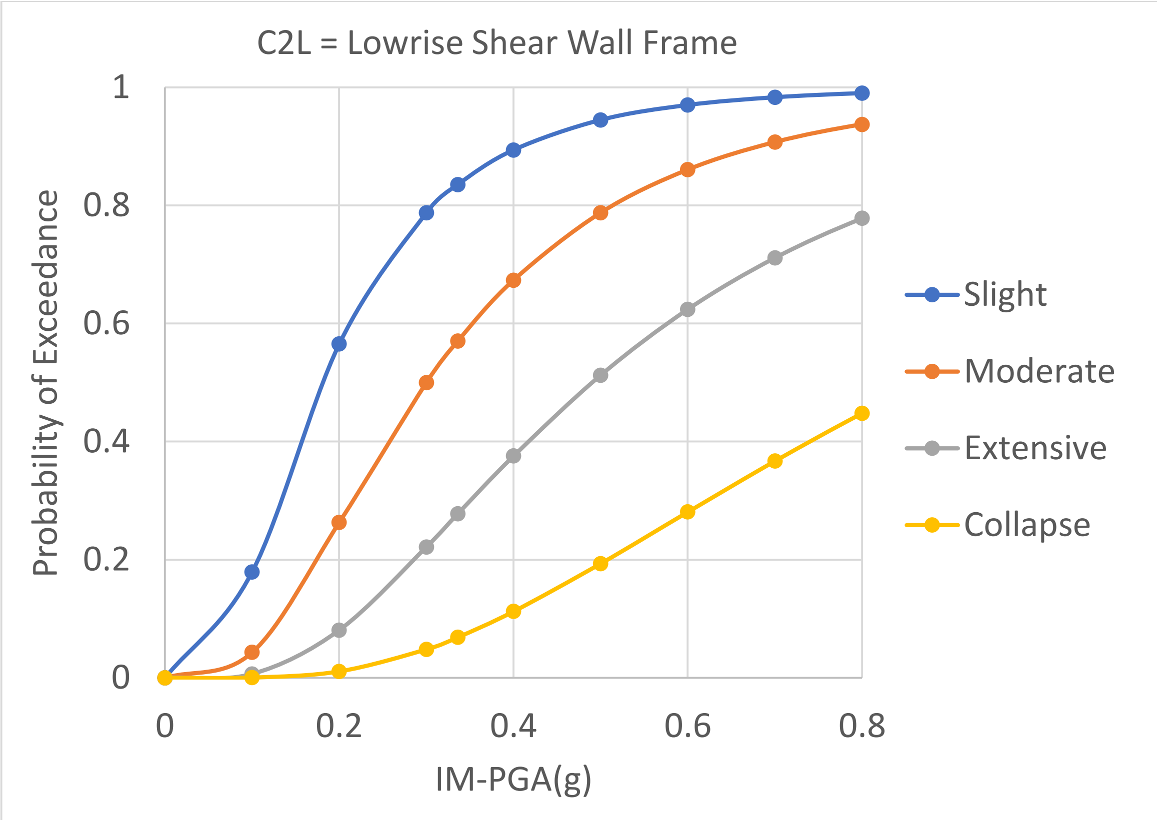


Figure 51: Fragility Functions for Low-rise Shear Wall Framed Building (C2L)

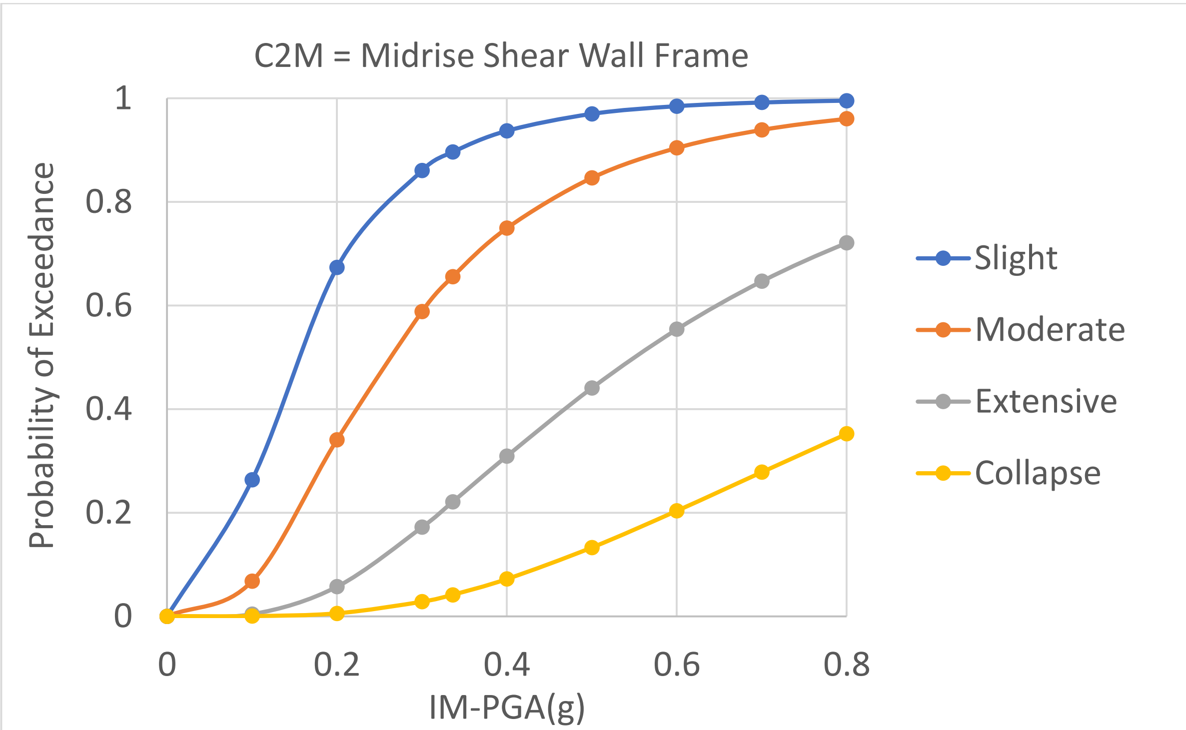


Figure 52: Fragility Functions for Mid-rise Shear Wall Framed Building (C2M)

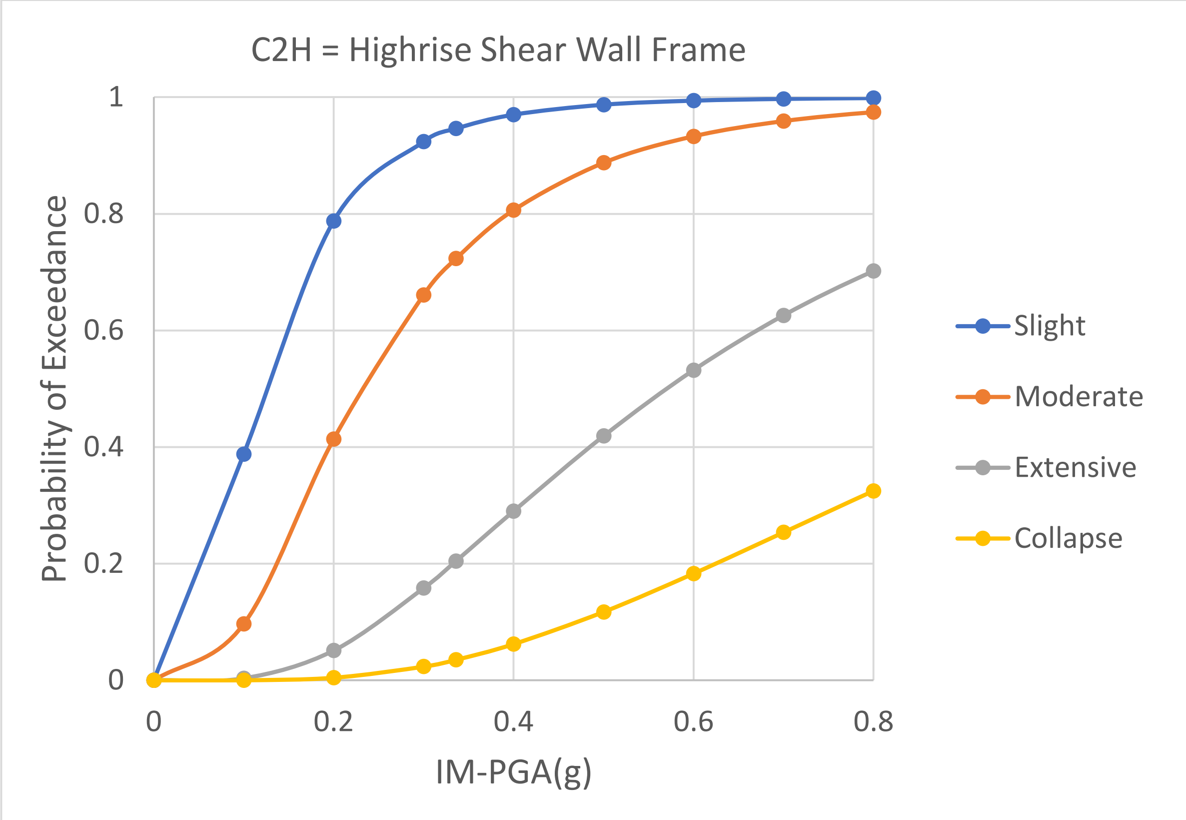


Figure 53: Fragility Functions for High-rise Shear Wall Framed Building (C2H)

Table 25: Damage Matrix for Low-rise Shear Wall Framed Buildings (C2L)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 55 | 27 | 13 | 5 | 0 | 100 |
| **80** | 44 | 30 | 18 | 7 | 1 | 100 |
| **178** | 26 | 31 | 25 | 15 | 3 | 100 |
| **476** | 13 | 24 | 29 | 25 | 9 | 100 |
| **976** | 7 | 17 | 28 | 31 | 17 | 100 |
| **2475** | 3 | 10 | 22 | 35 | 30 | 100 |

Table 26: Damage Matrix for Mid-rise Shear Wall Framed Buildings (C2M)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 44 | 32 | 21 | 3 | 0 | 100 |
| **80** | 34 | 33 | 28 | 4 | 1 | 100 |
| **178** | 18 | 30 | 39 | 11 | 2 | 100 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **476** | 8 | 20 | 45 | 21 | 6 | 100 |
| **976** | 4 | 13 | 42 | 29 | 12 | 100 |
| **2475** | 1 | 8 | 33 | 36 | 22 | 100 |

Table 27: Damage Matrix for High-rise Shear Wall Framed Buildings (C2H)

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 31 | 38 | 28 | 3 | 0 | 100 |
| **80** | 22 | 38 | 35 | 5 | 0 | 100 |
| **178** | 10 | 30 | 48 | 10 | 2 | 100 |
| **476** | 4 | 18 | 52 | 21 | 5 | 100 |
| **976** | 2 | 11 | 48 | 29 | 10 | 100 |
| **2475** | 0 | 6 | 38 | 36 | 20 | 100 |

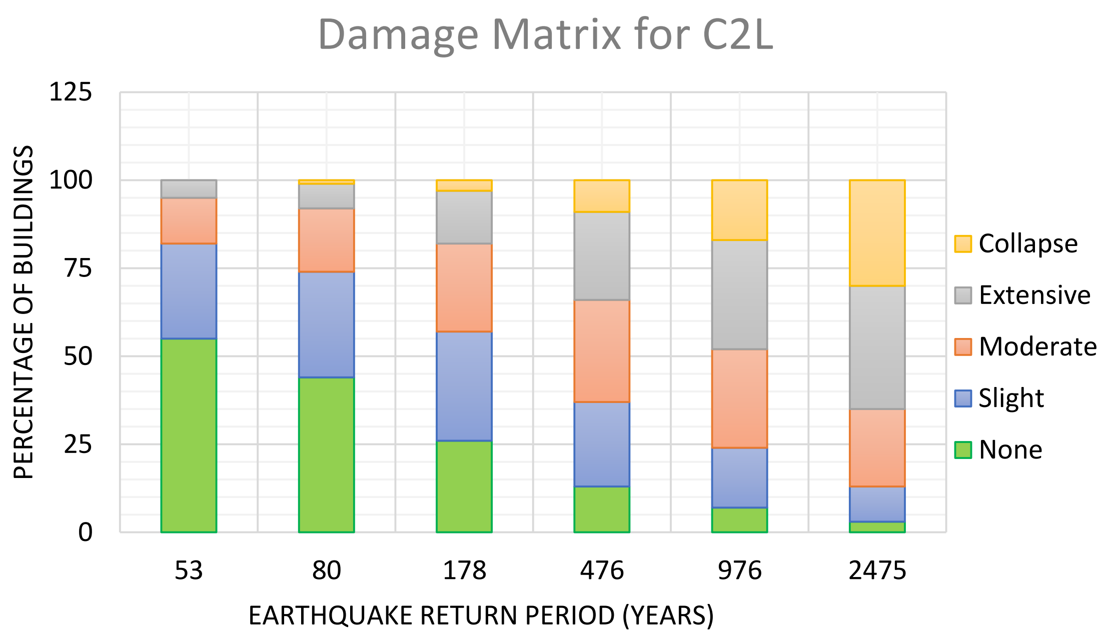


Figure 54: Damage Matrix for Low-rise Shear Wall Framed Building (C2L)

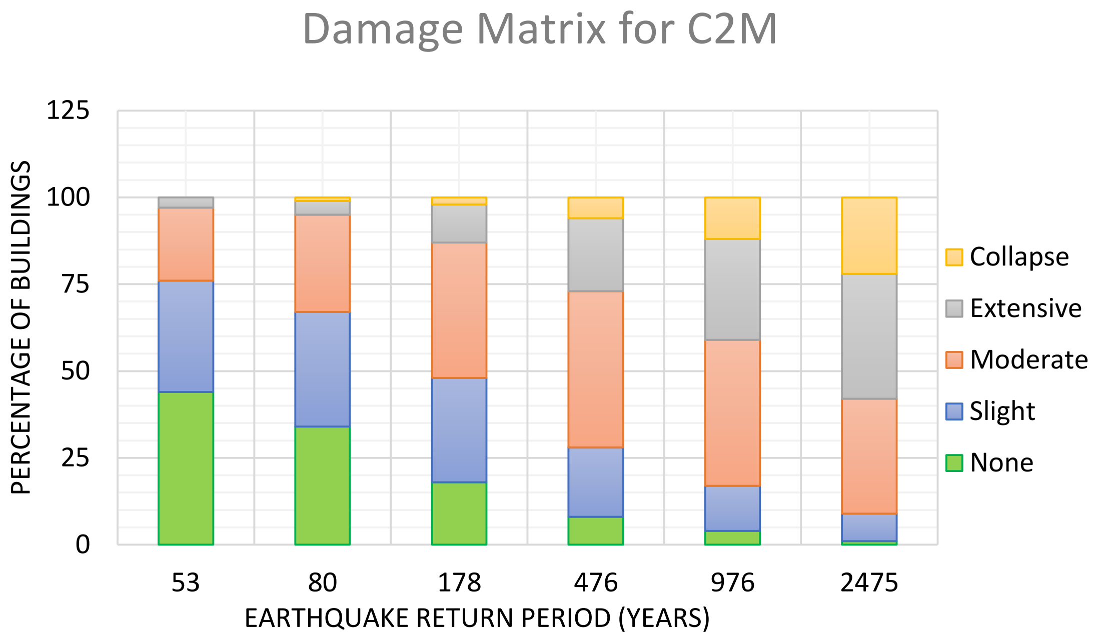


Figure 55: Damage Matrix for Mid-rise Shear Wall Framed Building (C2M)

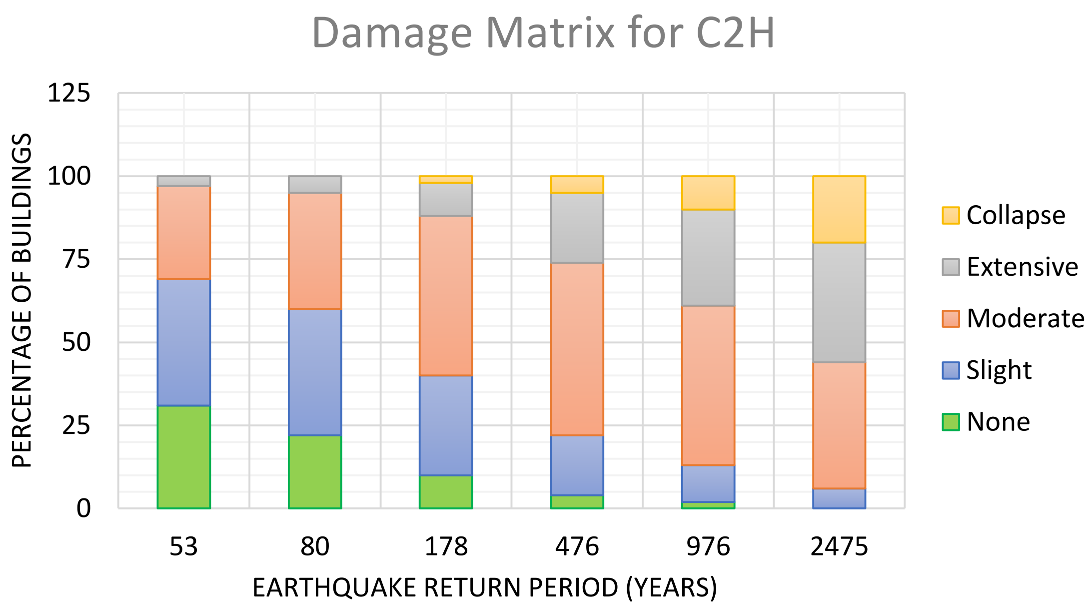


Figure 56: Damage Matrix for High-rise Shear Wall Framed Building (C2H)

The fragility functions (Figures 57-59) corresponding to C3 buildings are plotted for low-rise (C3L- number of floors three), mid-rise (C3M-number of floors four to eight) and high-rise (C3H- number of floors more than eight) building stock. Results are presented in terms of damage matrices in Figures 60-62. These show that at 10% probability of exceedance event, for low-rise structures 2% slight, 3% moderate, 7% extensive and 85% collapse limit states exceeding. For mid-rise structures 5% slight, 20% moderate, 30% extensive and 44% collapse limit states exceeding. In case of high-rise structures, 4% slight, 26% moderate, 28% extensive and 41% collapse limit states exceeding. The detailed damage matrices for different probability of exceedance are shown in Tables 28-30 for the low-rise, mid-rise and high-rise infilled framed buildings.

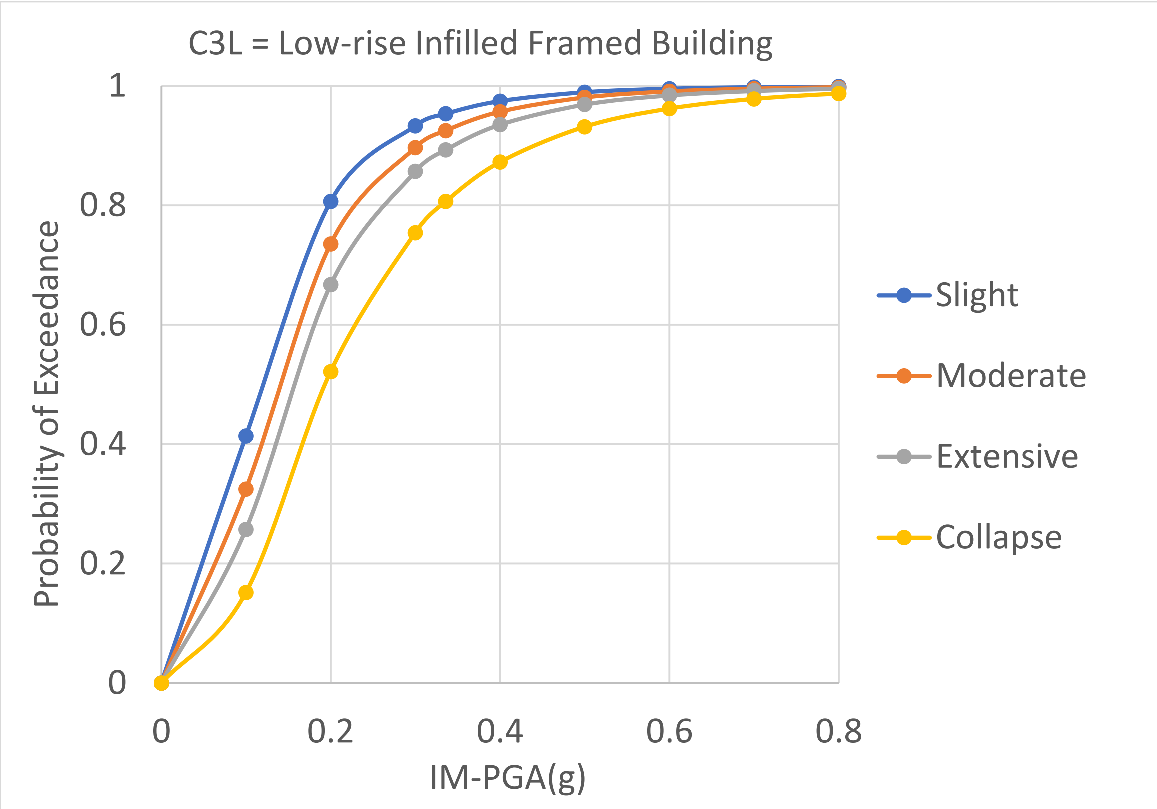


Figure 57: Fragility Functions for Low-rise Infilled Framed Building (C3L)

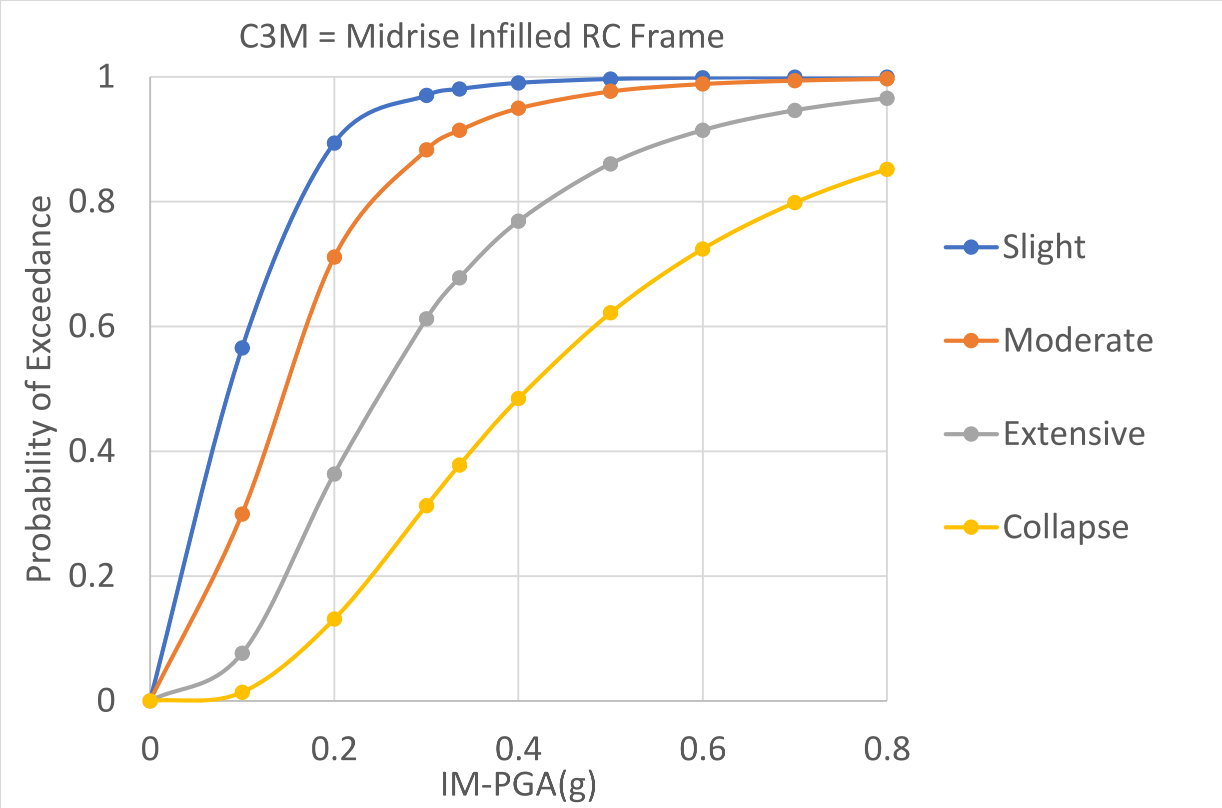


Figure 58: Fragility Functions for Mid-rise Infilled Framed Building (C3M)

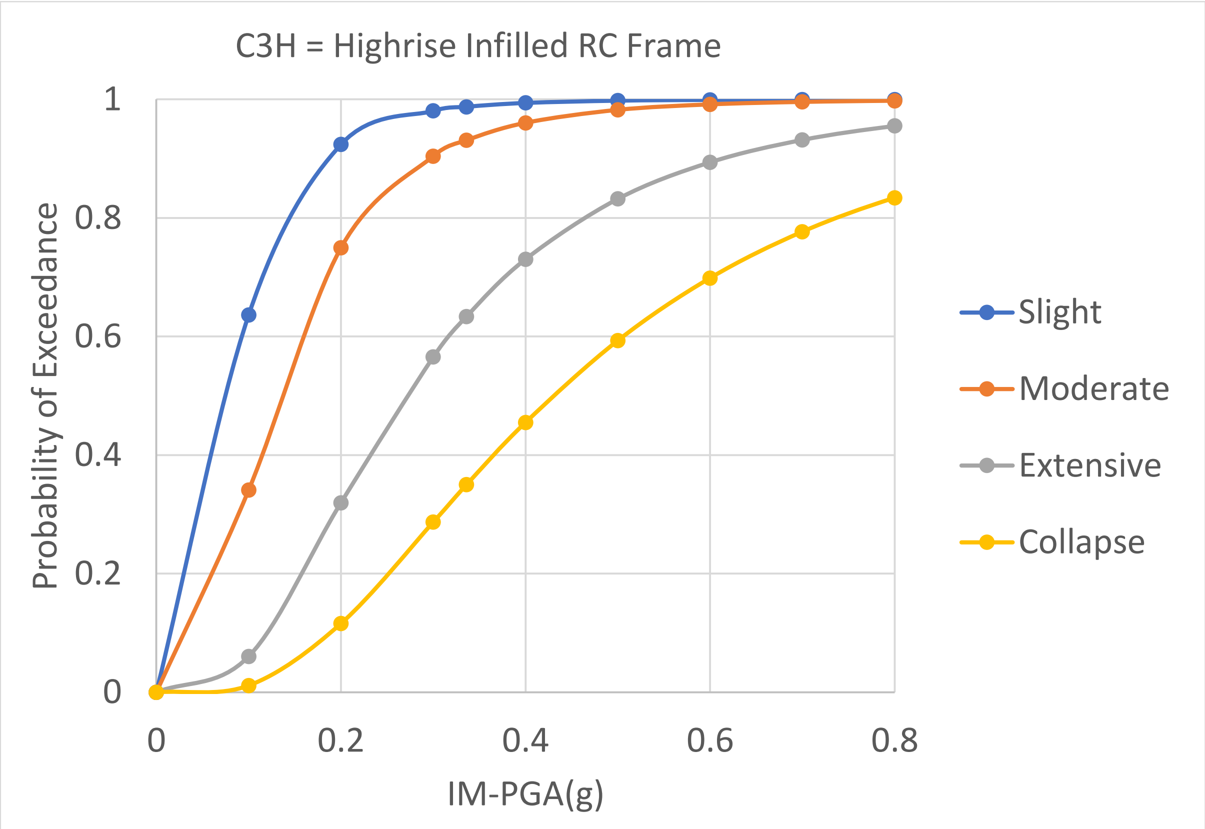


Figure 59: Fragility Functions for High-rise Infilled Framed Building (C3H)

Table 28: Damage Matrix for Low-rise Infilled Framed Buildings (C3L)

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 28 | 9 | 7 | 15 | 41 | 100 |
| **80** | 20 | 7 | 7 | 15 | 51 | 100 |
| **178** | 9 | 5 | 4 | 12 | 70 | 100 |
| **476** | 3 | 2 | 3 | 7 | 85 | 100 |
| **976** | 1 | 1 | 2 | 4 | 92 | 100 |
| **2475** | 0 | 1 | 0 | 2 | 97 | 100 |

Table 29: Damage Matrix for Mid-rise Infilled Framed Buildings (C3M)

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 17 | 23 | 34 | 18 | 8 | 100 |
| **80** | 11 | 19 | 35 | 22 | 13 | 100 |
| **178** | 4 | 11 | 30 | 29 | 26 | 100 |
| **476** | 1 | 5 | 20 | 30 | 44 | 100 |
| **976** | 0 | 3 | 13 | 25 | 59 | 100 |
| **2475** | 0 | 1 | 7 | 18 | 74 | 100 |

Table 30: Damage Matrix for High-rise Infilled Framed Buildings (C3H)

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 13 | 22 | 43 | 15 | 7 | 100 |
| **80** | 8 | 18 | 43 | 20 | 11 | 100 |
| **178** | 3 | 10 | 37 | 27 | 23 | 100 |
| **476** | 1 | 4 | 26 | 28 | 41 | 100 |
| **976** | 0 | 2 | 17 | 25 | 56 | 100 |
| **2475** | 0 | 1 | 9 | 18 | 72 | 100 |

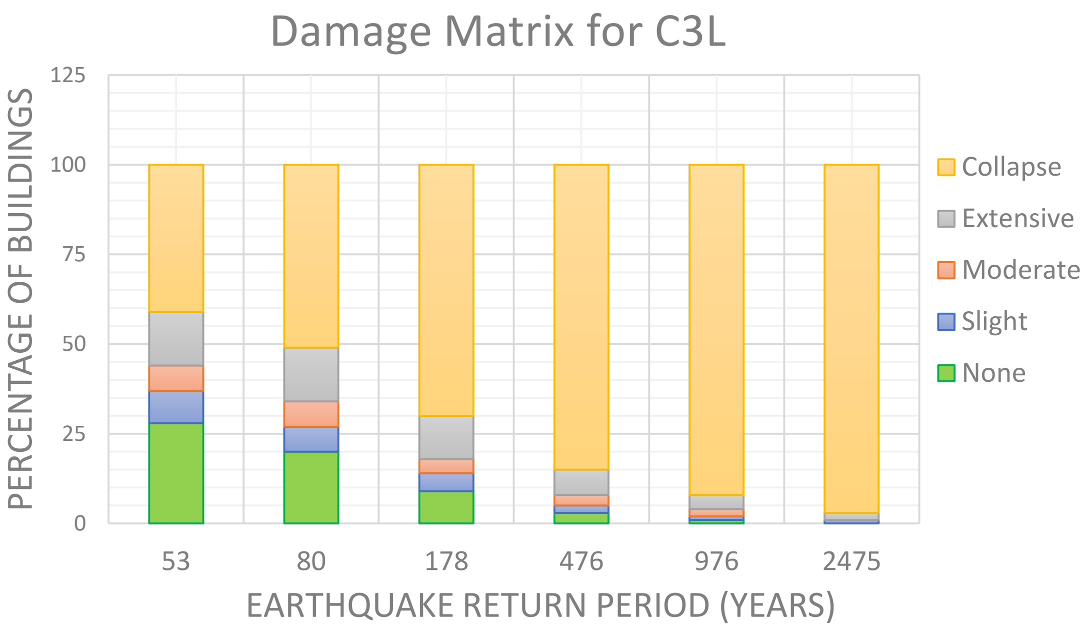


Figure 60: Damage Matrix for Low-rise Infilled Framed Building (C3L)

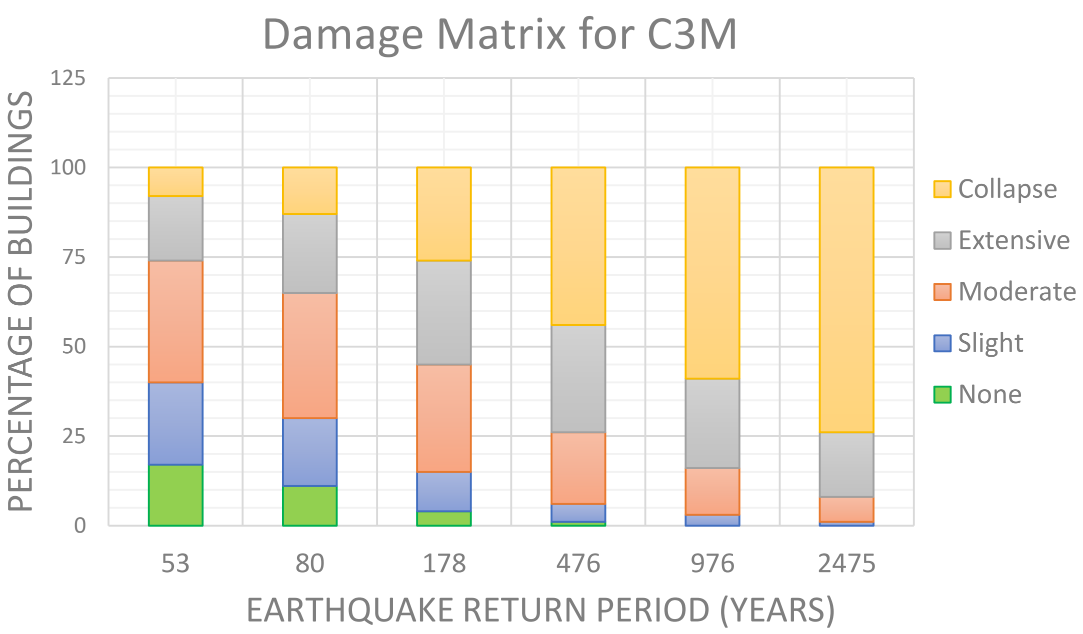


Figure 61: Damage Matrix for Mid-rise Infilled Framed Building (C3M)

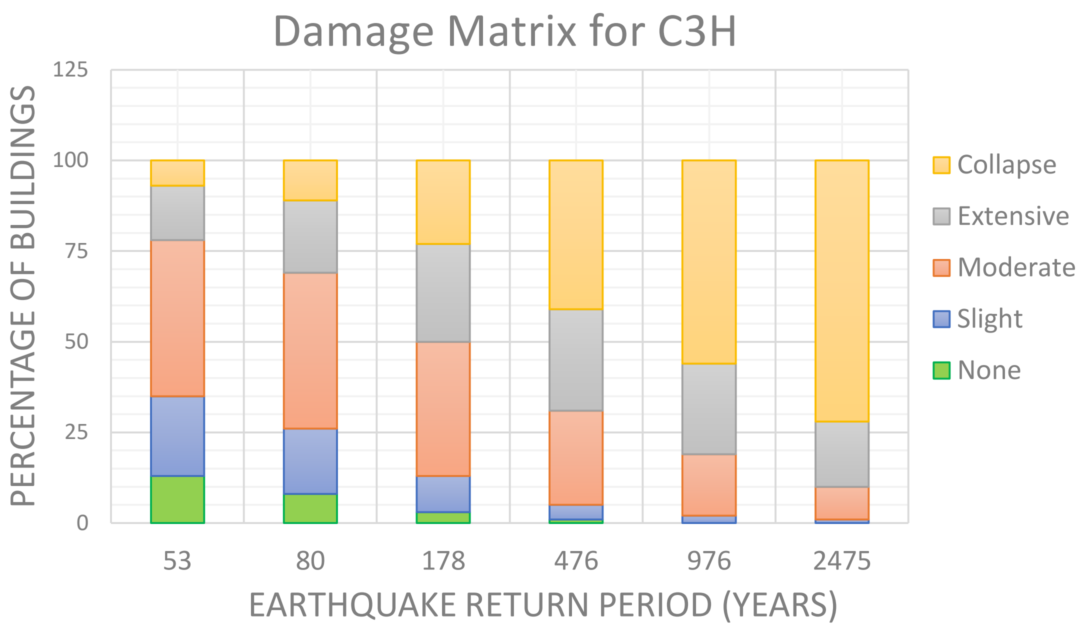


Figure 62: Damage Matrix for High-rise Infilled Framed Building (C3H)

The fragility functions (Figures 63-64) for URM buildings are plotted for unreinforced stone masonry (Cst) and unreinforced block masonry (Cbl) building stock. Results are presented in terms of damage matrices in Figures 65-67. These show that at 10% probability of exceedance event, for stone masonry structures 8% slight, 20% moderate, 38% extensive and 33% collapse limit states exceeding. For block masonry structures 13% slight, 23% moderate, 39% extensive and 23% collapse limit states exceeding. The detailed damage matrices for different probability of exceedance are shown in Tables 31-32 for the stone masonry and block masonry buildings.

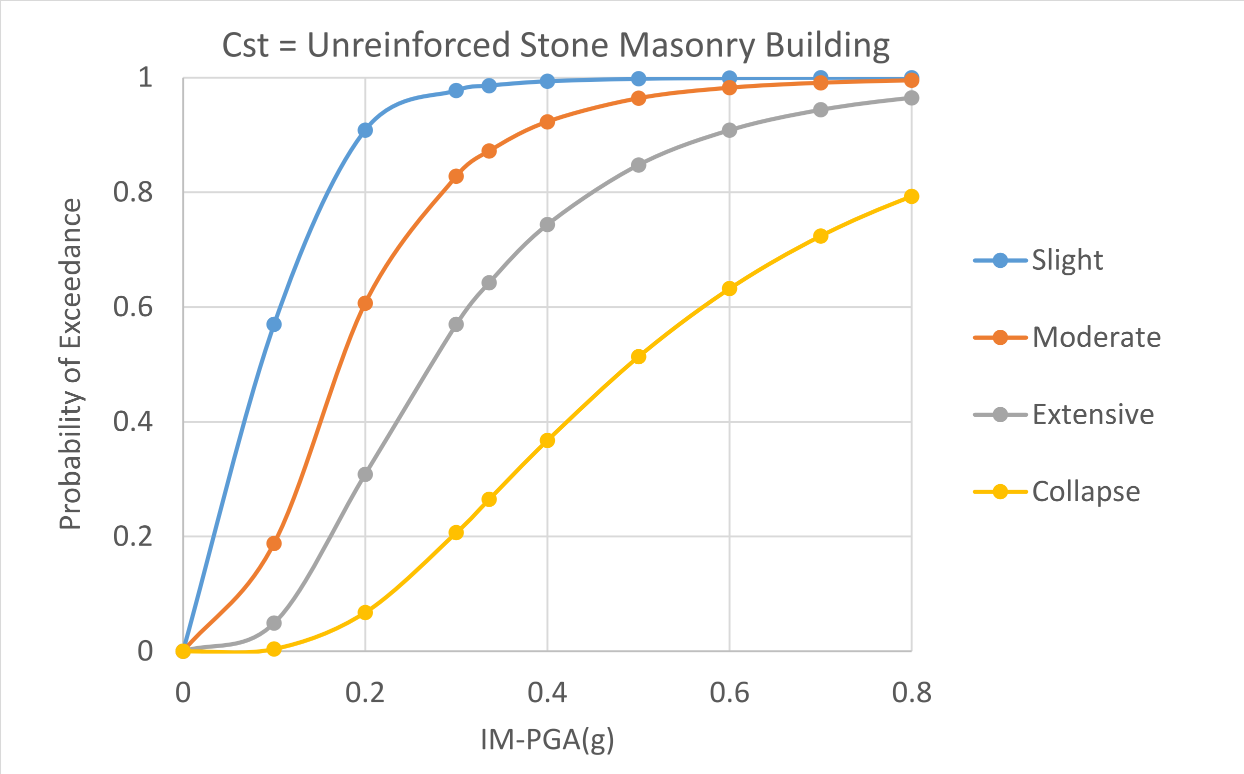


Figure 63: Fragility Functions for Unreinforced Stone Masonry Building (Cst)

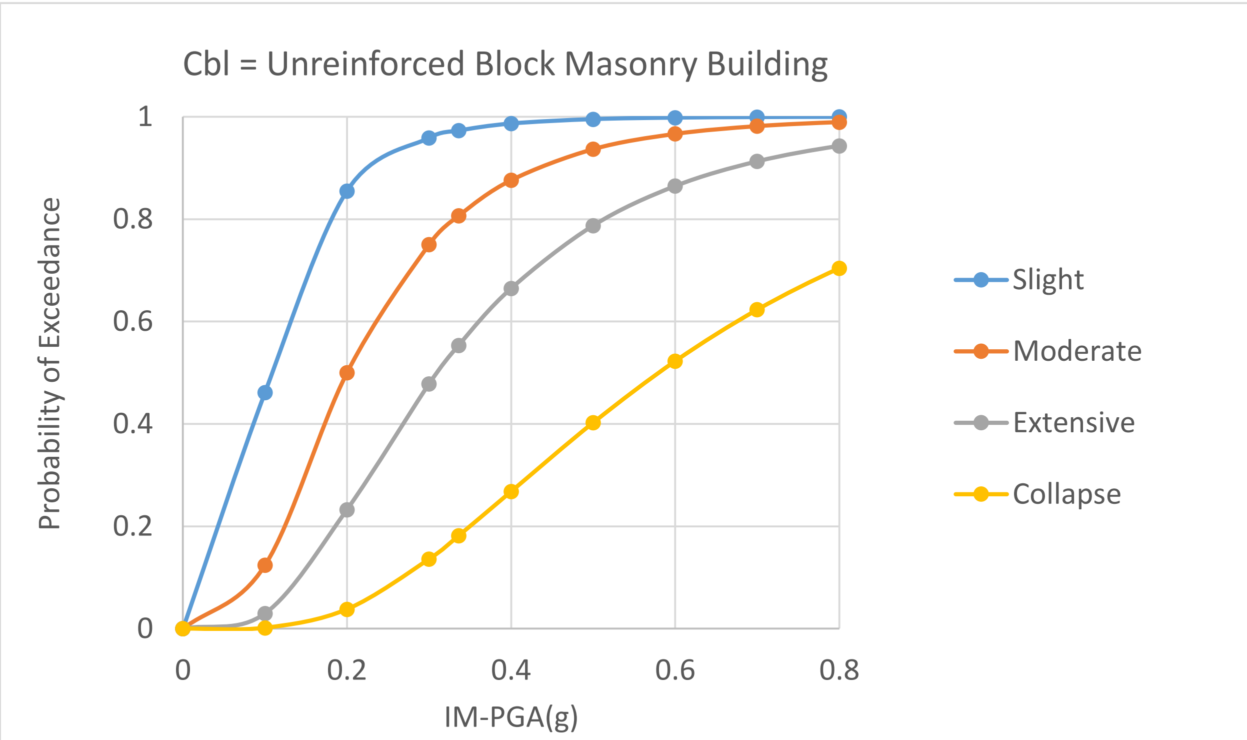


Figure 64: Fragility Functions for Unreinforced Block Masonry Building (Cbl)

Table 31: Damage Matrix for Unreinforced Stone Masonry Buildings (Cst)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 15 | 37 | 27 | 17 | 4 | 100 |
| **80** | 10 | 30 | 30 | 24 | 6 | 100 |
| **178** | 3 | 19 | 28 | 34 | 16 | 100 |
| **476** | 1 | 8 | 20 | 38 | 33 | 100 |
| **976** | 0 | 4 | 13 | 35 | 48 | 100 |
| **2475** | 0 | 2 | 6 | 26 | 66 | 100 |

Table 32: Damage Matrix for Unreinforced Block Masonry Buildings (Cbl)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 23 | 39 | 23 | 13 | 2 | 100 |
| **80** | 15 | 36 | 27 | 18 | 4 | 100 |
| **178** | 6 | 25 | 28 | 31 | 10 | 100 |
| **476** | 2 | 13 | 23 | 39 | 23 | 100 |
| **976** | 1 | 7 | 16 | 39 | 37 | 100 |
| **2475** | 0 | 3 | 9 | 33 | 55 | 100 |

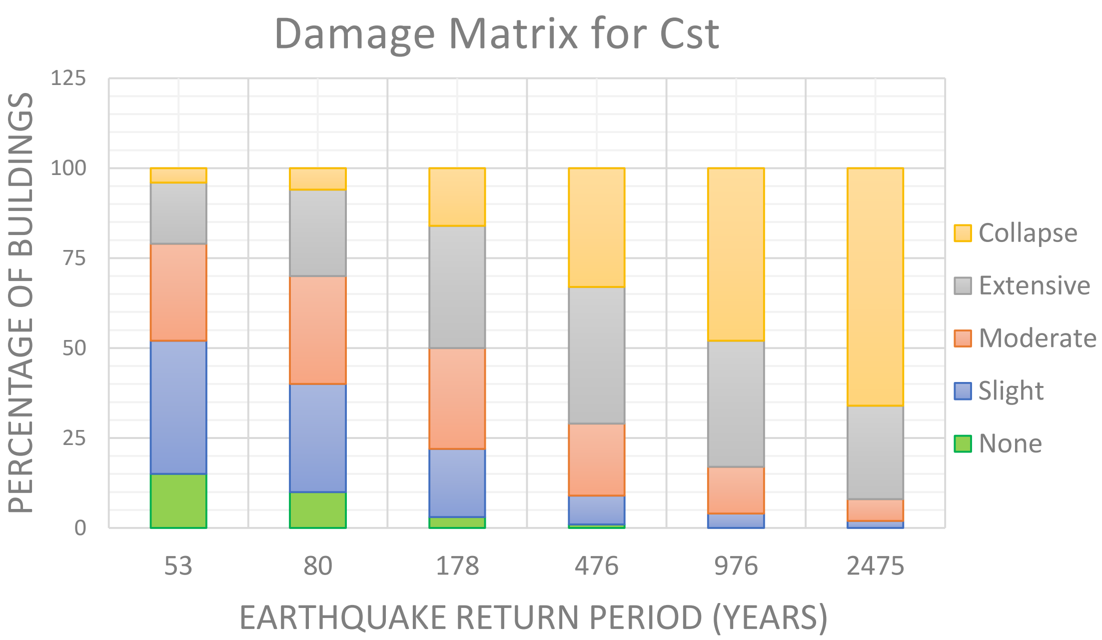


Figure 65: Damage Matrix for Unreinforced Stone Masonry Buildings

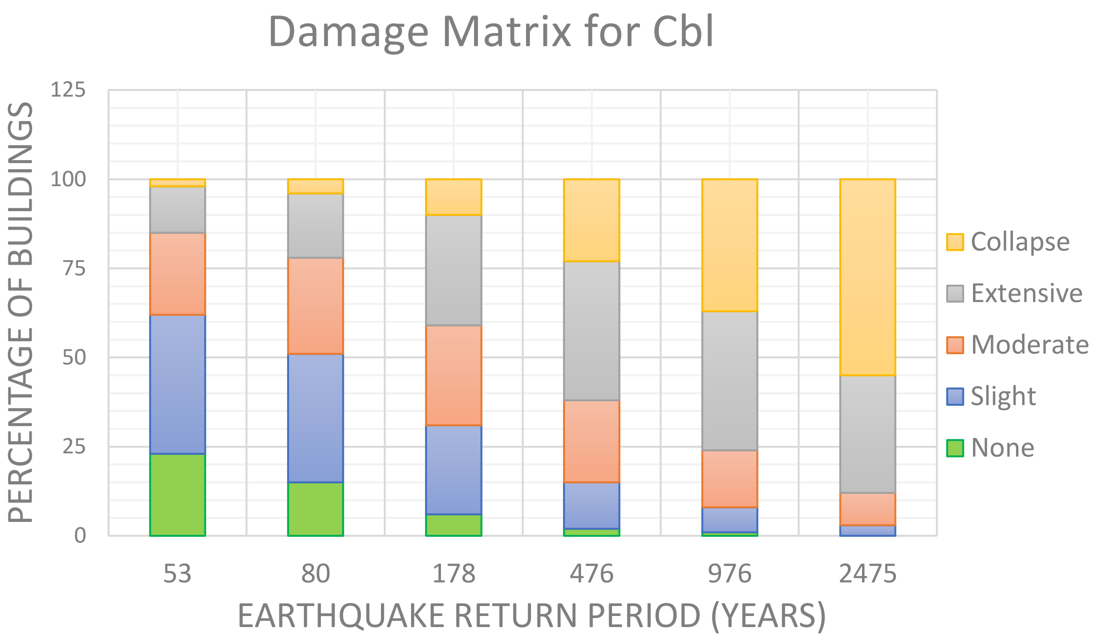


Figure 66: Damage Matrix for Unreinforced Block Masonry Buildings

Bridges and flyovers are classified on the basis of pier typologies in this report. The fragility curves presented by Khan et al. (2015) are employed for the vulnerability assessment of these structures. These were derived through pushover analysis at component levels. Four different damage states such as slight, moderate, extensive and collapse are considered herein and their corresponding fragility curves are presented in Figures 67-69. Results are presented in terms of damage matrices in Figures 70-72. These show that 13% slight, 13% moderate, 18% extensive and 55% collapse limit states may exceed in single column pier supported structures at 10% probability of exceedance event. Similarly, 18% slight, 4% moderate, 14% extensive and 61% collapse limit states may exceed in multiple columns/bent pier supported structures at 10% probability of exceedance. Finally, at the same probability of exceedance 30% slight, 13% moderate, 14% extensive and 15% collapse limit states may exceed in the wall pier supported structures. The detailed damage matrices for different probability of exceedance are shown in Tables 33-35 for the single column pier, multiple column pier and wall pier bridges.

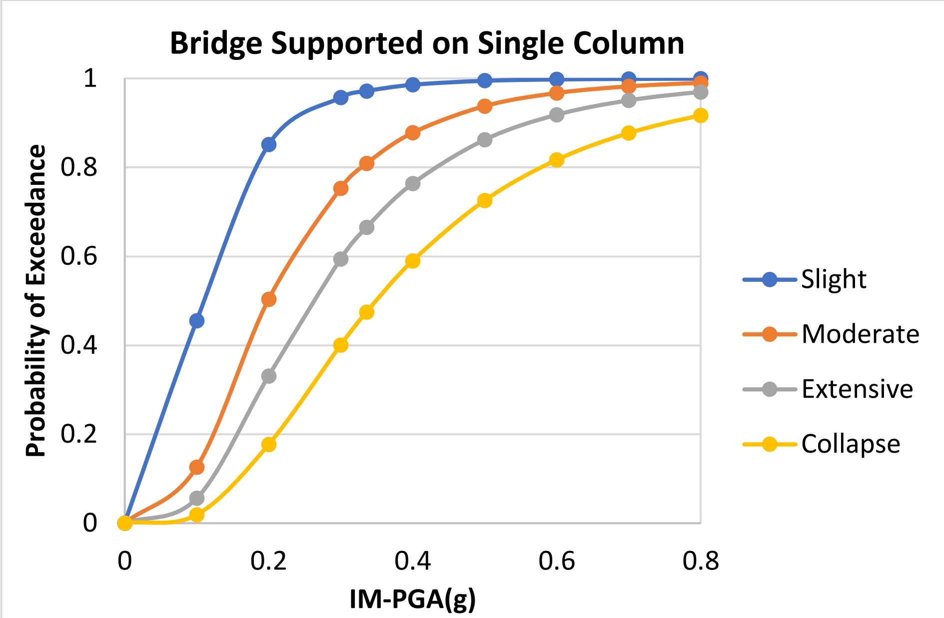


Figure 67: Fragility Functions for Single Column Pier

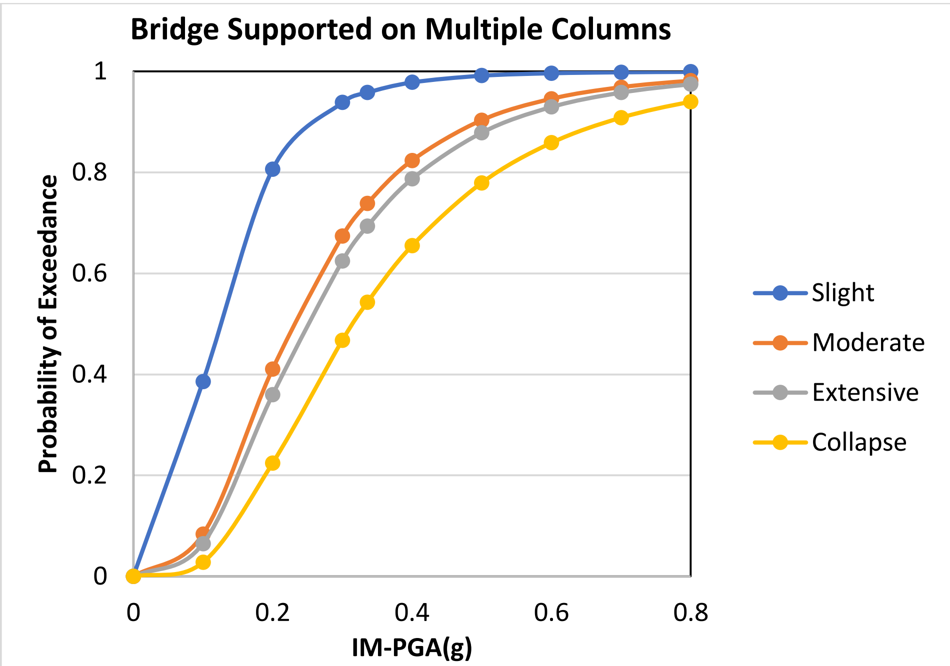


Figure 68: Fragility Functions for Multiple Columns Pier

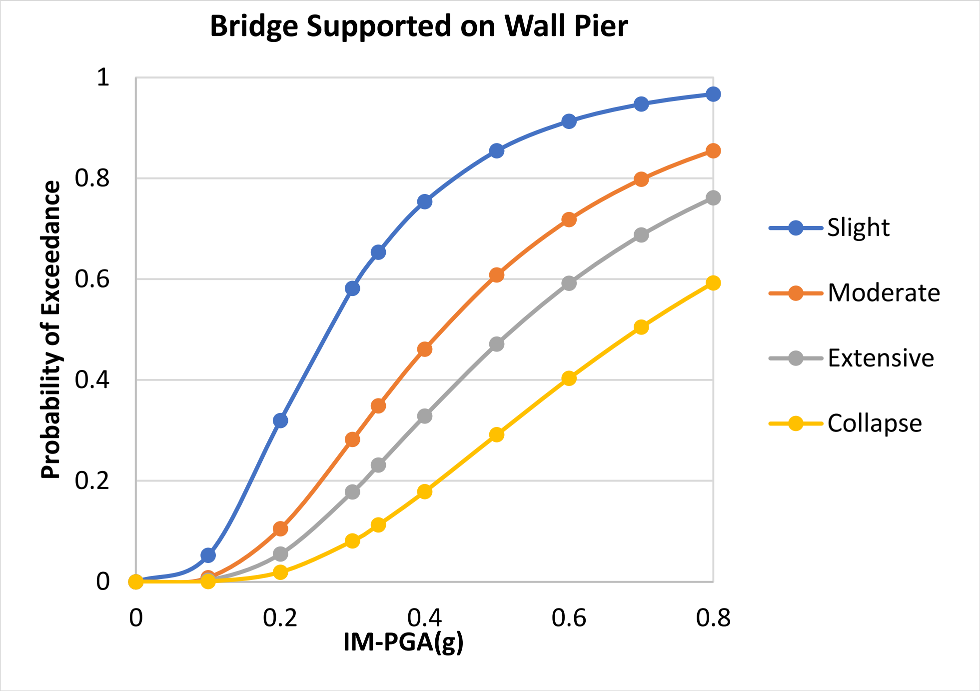


Figure 69: Fragility Functions for Wall Pier

Table 33: Damage Matrix for Single Column Pier

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 23 | 39 | 15 | 12 | 11 | 100 |
| **80** | 15 | 35 | 17 | 15 | 17 | 100 |
| **178** | 6 | 24 | 17 | 19 | 33 | 100 |
| **476** | 2 | 13 | 13 | 18 | 55 | 100 |
| **976** | 1 | 7 | 8 | 15 | 70 | 100 |
| **2475** | 0 | 3 | 4 | 9 | 83 | 100 |

Table 34: Damage Matrix for Multiple Columns Pier

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 29 | 41 | 4 | 11 | 14 | 100 |
| **80** | 20 | 40 | 5 | 13 | 22 | 100 |
| **178** | 9 | 31 | 5 | 16 | 40 | 100 |
| **476** | 3 | 18 | 4 | 14 | 61 | 100 |
| **976** | 1 | 10 | 3 | 11 | 75 | 100 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **2475** | 0 | 4 | 1 | 7 | 87 | 100 |

Table 35: Damage Matrix for Wall Pier

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 78 | 16 | 3 | 2 | 1 | 100 |
| **80** | 69 | 21 | 5 | 3 | 2 | 100 |
| **178** | 49 | 29 | 9 | 8 | 6 | 100 |
| **476** | 28 | 30 | 13 | 14 | 15 | 100 |
| **976** | 17 | 26 | 14 | 17 | 26 | 100 |
| **2475** | 8 | 18 | 12 | 19 | 43 | 100 |

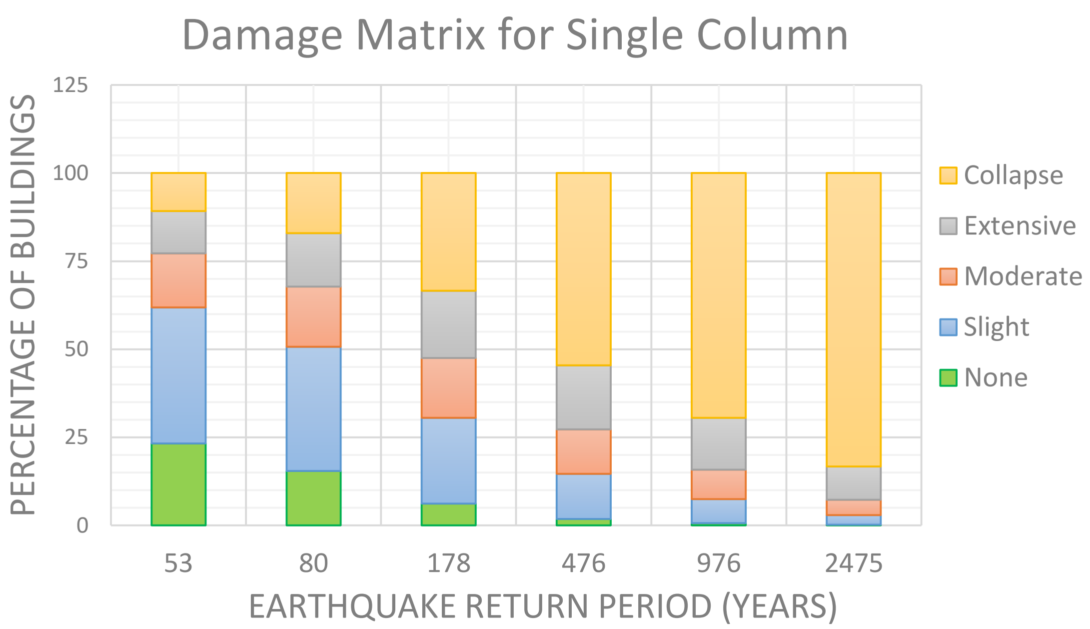


Figure 70: Damage Matrix for Single Column Pier

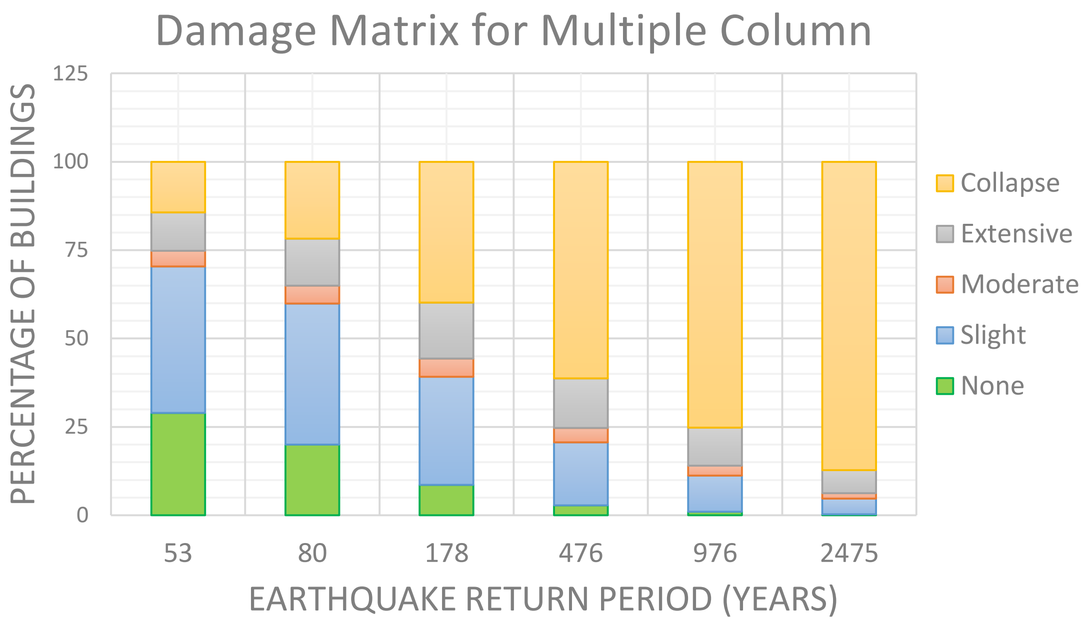


Figure 71: Damage Matrix for Multiple Columns Pier

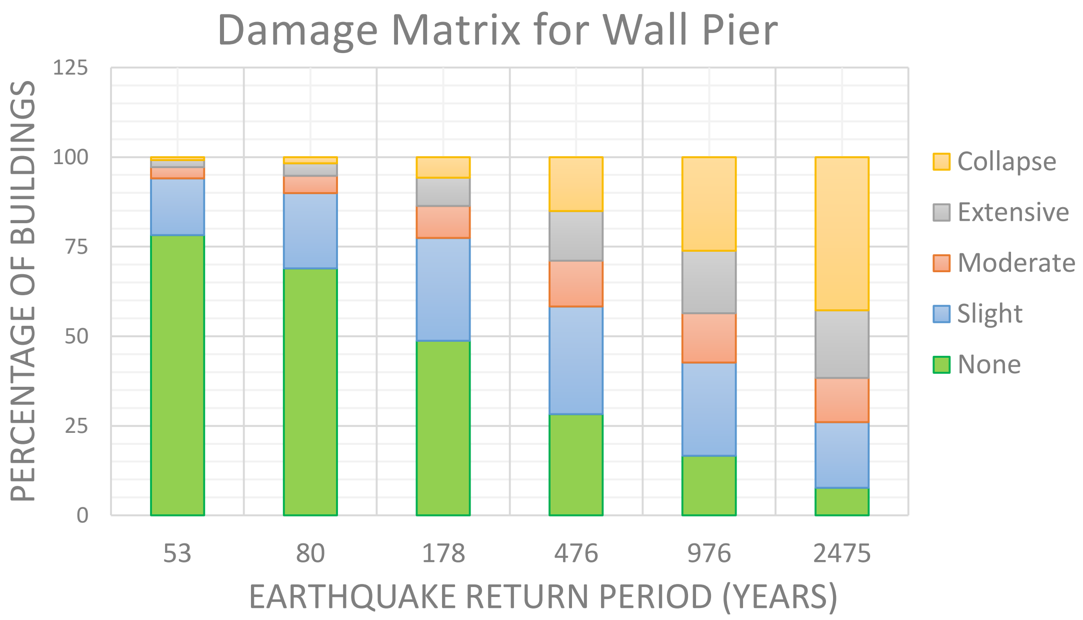


Figure 72: Damage Matrix for Wall Pier

The fragility functions for EPN-01 are plotted for two cases; (1) for collapse limit state (Figure 73) and (2) for functionality or connectivity loss (Figure 77). These fragility curves are based on empirical approach proposed by Osorio et al., 2007. Results are presented in terms of damage matrices in Figures 74-76. These show that for collapse limit state around 34% low voltage, 56% medium voltage and 96% high voltage transmission lines will be damaged at 10% probability of exceedance event. The detailed damage matrix for different probability of exceedance is shown in Table 36 for the low voltage, medium voltage and high voltage transmission lines. Fragility functions based on functionality loss show that 100% probability of 80% connectivity loss in all three types of transmission lines (Figures 78-80) at 10% probability of exceedance event. The detailed damage matrix for different probability of exceedance is shown in Table 37 for the 20%, 50% and 80% functionality loss.

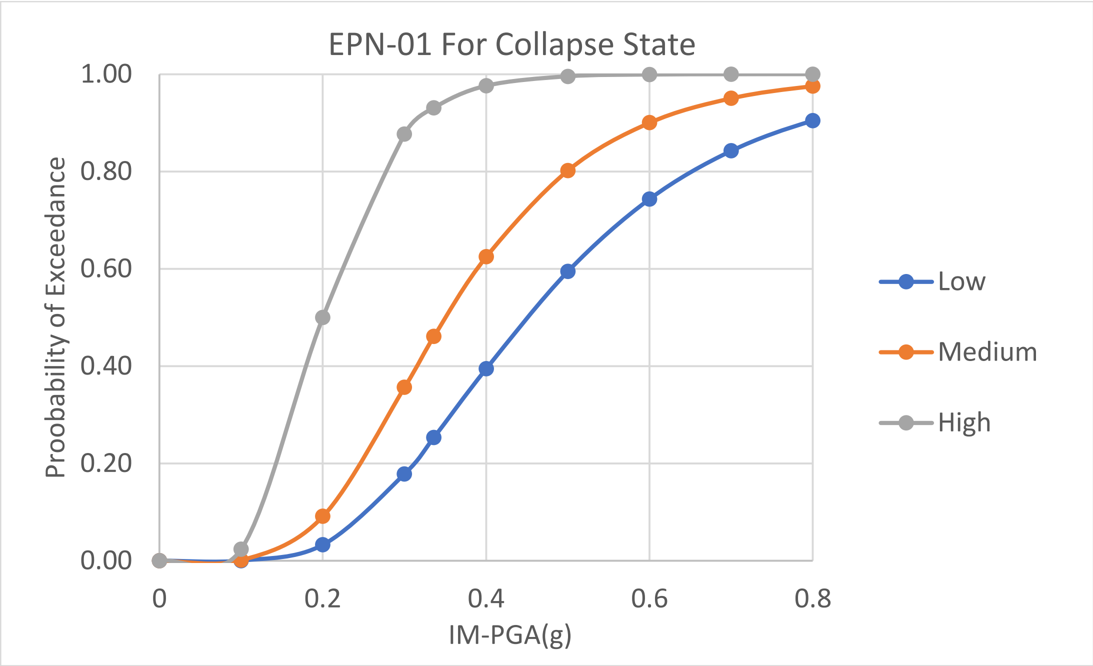


Figure 73: Collapse limit state for EPN-01

Table 36: Damage Matrix for Collapse limit state (EPN-01)

| **Return Period** | **Low Voltage** | | **Medium Voltage** | | **High Voltage** | |
|---|---|---|---|---|---|---|
| | None | Collapse | None | Collapse | None | Collapse |
| **Years** | % | % | % | % | % | % |
| **53** | 99 | 1 | 96 | 4 | 70 | 30 |
| **80** | 97 | 3 | 91 | 9 | 52 | 48 |
| **178** | 88 | 12 | 73 | 27 | 20 | 80 |
| **476** | 66 | 34 | 44 | 56 | 4 | 96 |
| **976** | 45 | 55 | 24 | 76 | 1 | 99 |
| **2475** | 23 | 77 | 8 | 92 | 0 | 100 |

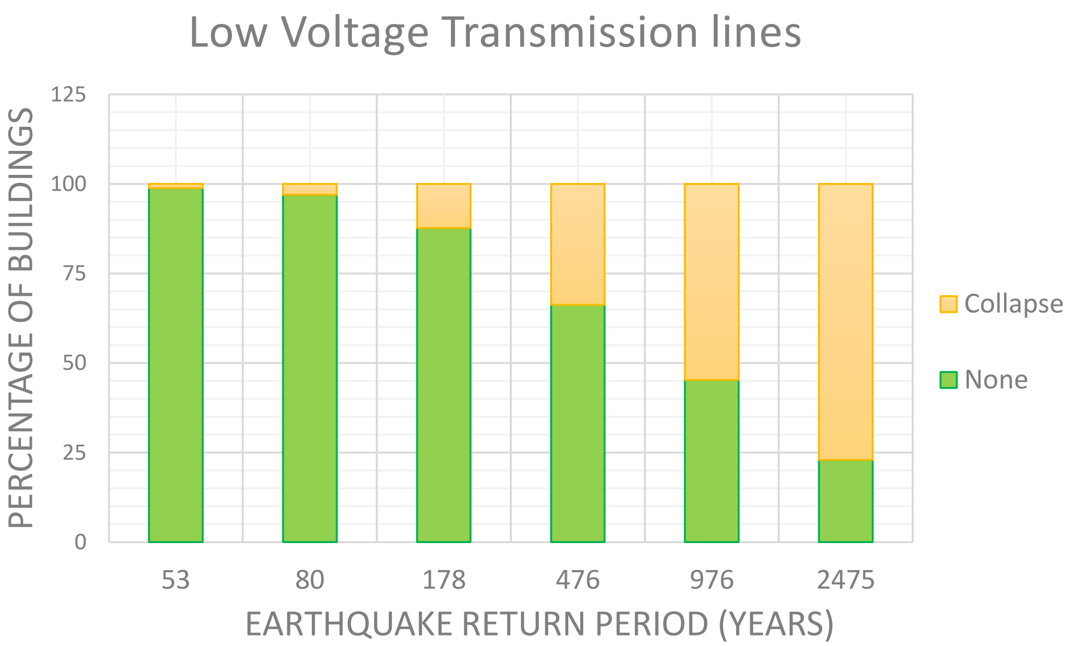


Figure 74: Damage Matrix for Collapse limit state for EPN-01 with Low Voltage Transmission lines

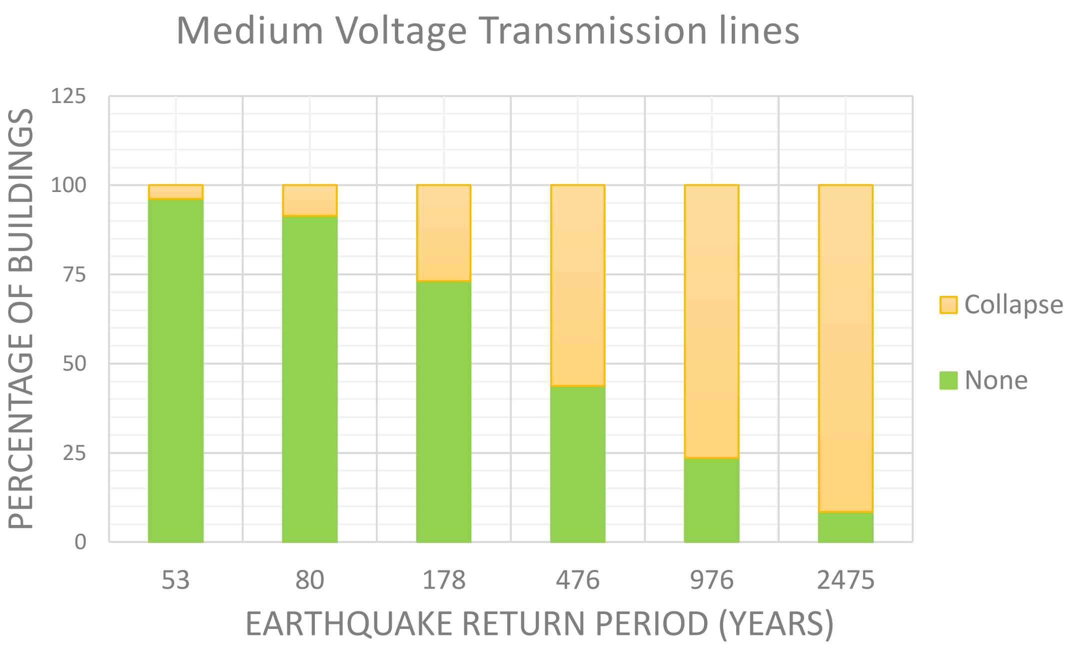


Figure 75: Damage Matrix for Collapse limit state for EPN-01 with Medium Voltage Transmission lines

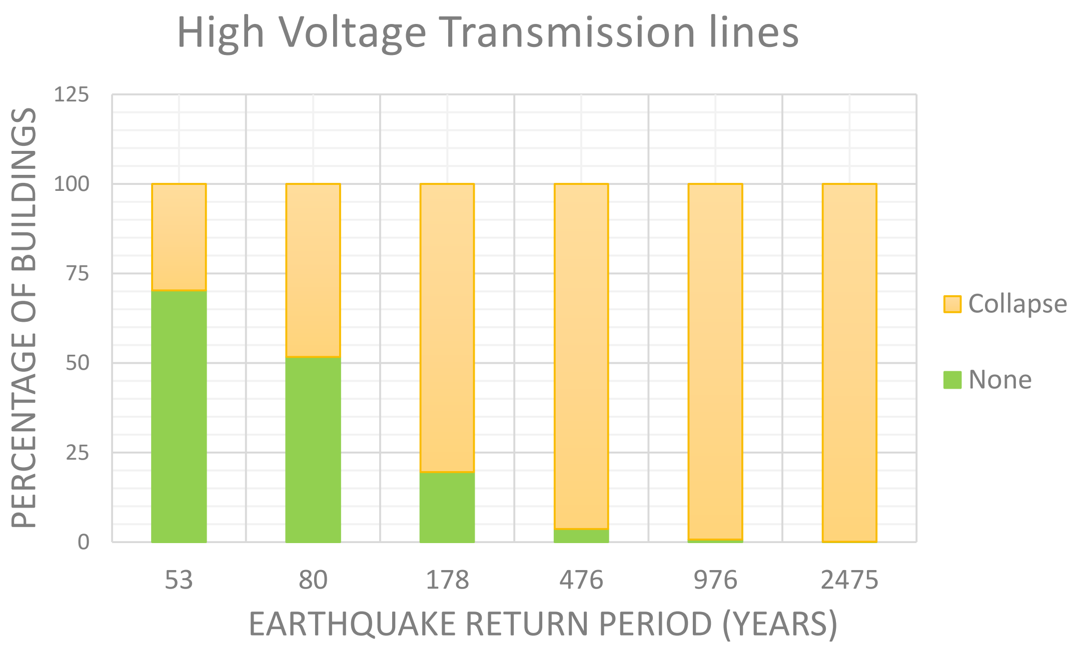


Figure 76: Damage Matrix for Collapse limit state for EPN-01 with High Voltage Transmission lines

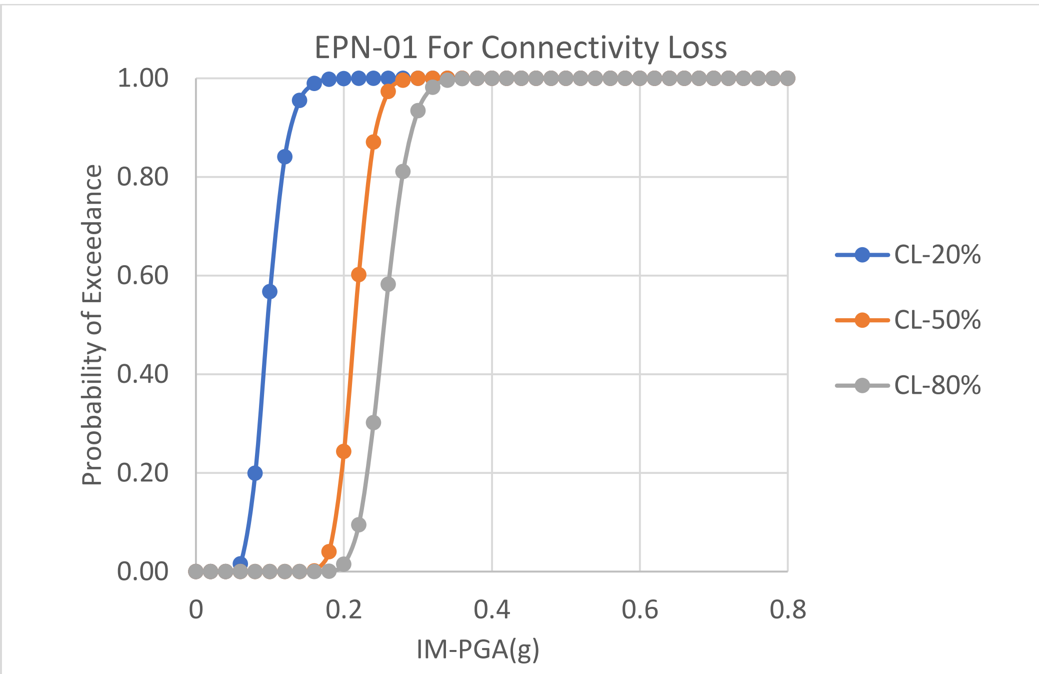


Figure 77: Fragility Functions in terms of Connectivity Loss (EPN-01)

Table 37: Damage Matrix for Connectivity Loss (EPN-01)

| **Return Period** | **20% CL** | | **50% CL** | | **80% CL** | |
|---|---|---|---|---|---|---|
| | None | Collapse | None | Collapse | None | Collapse |
| **Years** | % | % | % | % | % | % |
| **53** | 1 | 99 | 99 | 1 | 100 | 0 |
| **80** | 0 | 100 | 80 | 20 | 99 | 1 |
| **178** | 0 | 100 | 1 | 99 | 29 | 71 |
| **476** | 0 | 100 | 0 | 100 | 0 | 100 |
| **976** | 0 | 100 | 0 | 100 | 0 | 100 |
| **2475** | 0 | 100 | 0 | 100 | 0 | 100 |

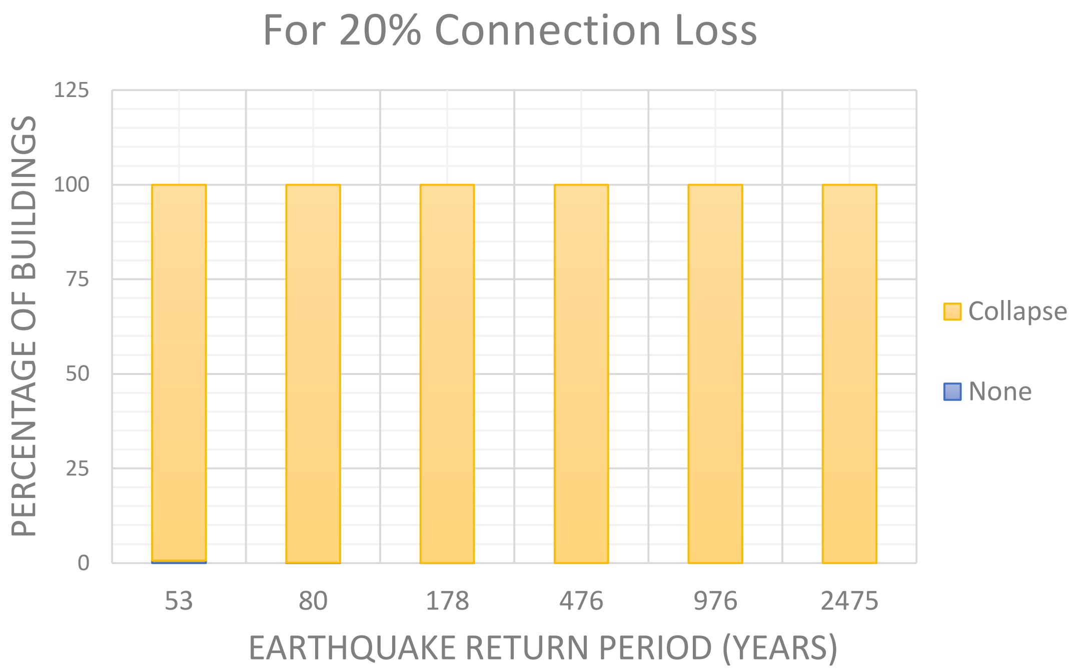


Figure 78: Damage Matrix in terms of 20% Connectivity Loss (EPN-01)

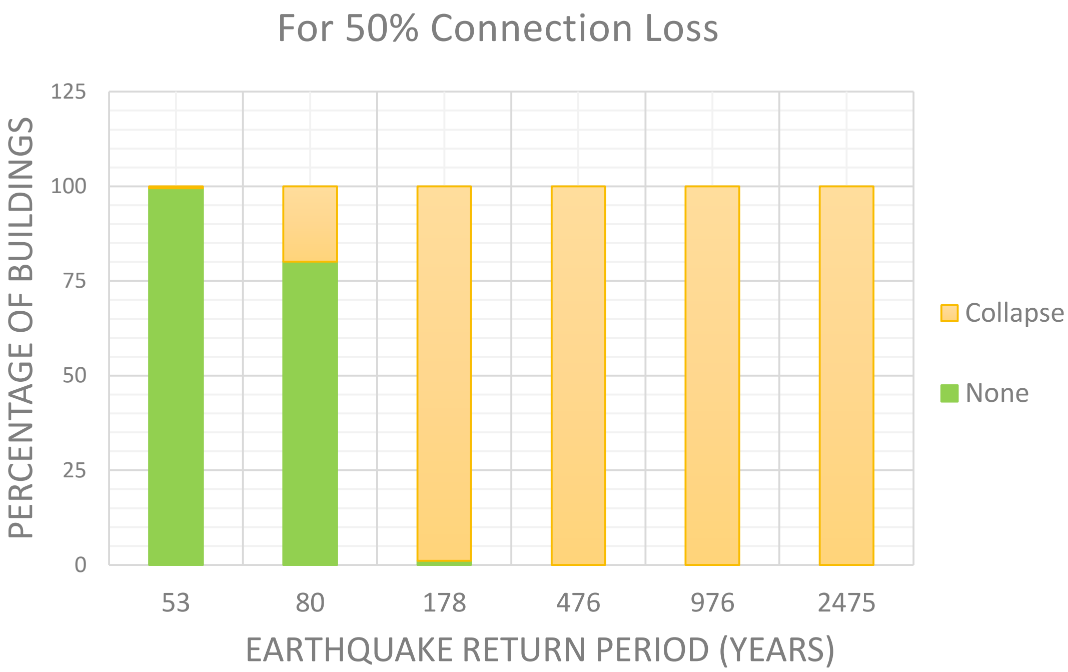


Figure 79: Damage Matrix in terms of 50% Connectivity Loss (EPN-01)

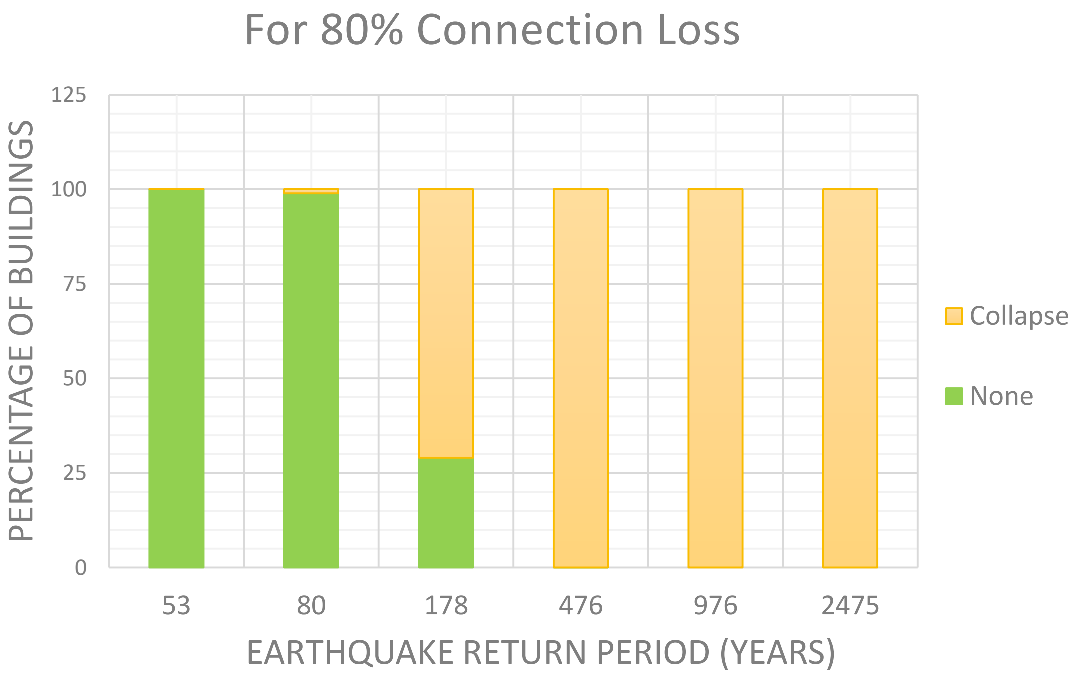


Figure 80: Damage Matrix in terms of 80% Connectivity Loss (EPN-01)

Generation plants (EPN-02) are classified into small and medium/large generation plants. The fragility curves for EPN-02 are presented for damage states i.e., slight, moderate, extensive and collapse limit states (Figures 81-82). These fragility curves are based on numerical method and proposed by FEMA-HAZUS technical manual in 2003. Results are presented in terms of damage matrix in Figure 83 and show that anchored small generation plants exceeding 14% slight, 54% moderate, 24% extensive and 7% collapse limit states at 10% probability of exceedance event. Similarly, for anchored medium/large generation plants show that (Figure 84) 24% slight, 47% moderate, 22% extensive and 5% collapse limit states exceeding at 10% probability of exceedance. The detailed damage matrices for variant probability of exceedance are shown in Tables 38-39 for the anchored small, medium and large generation plants.

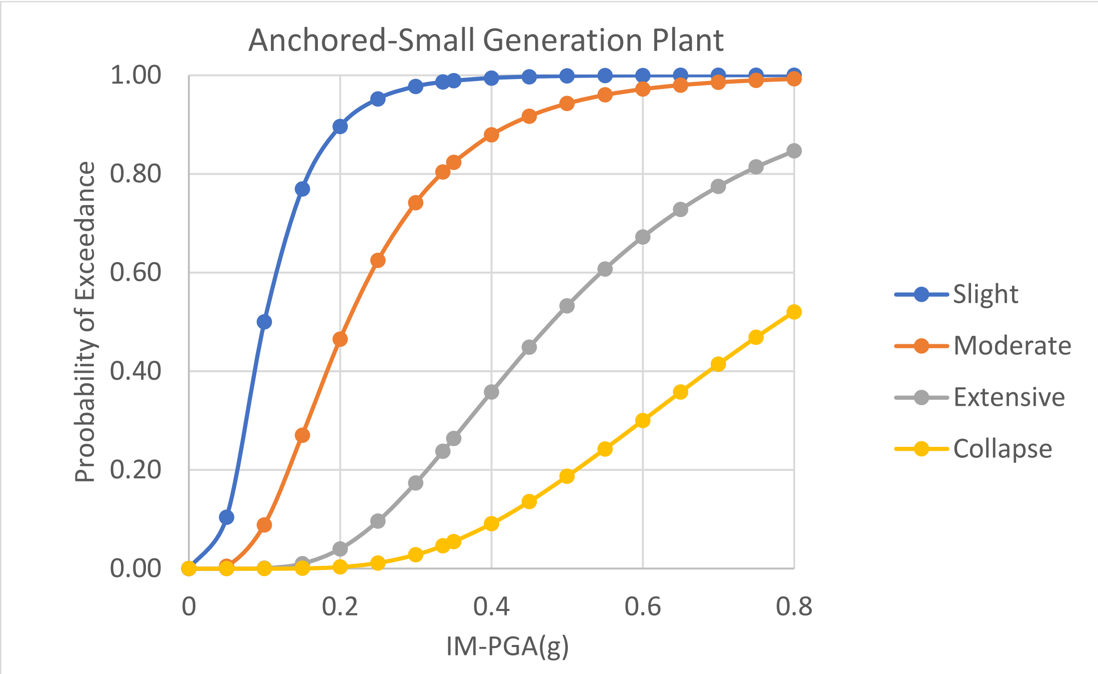


Figure 81: Fragility Functions for Anchored-Small Generation Plant (EPN-02)

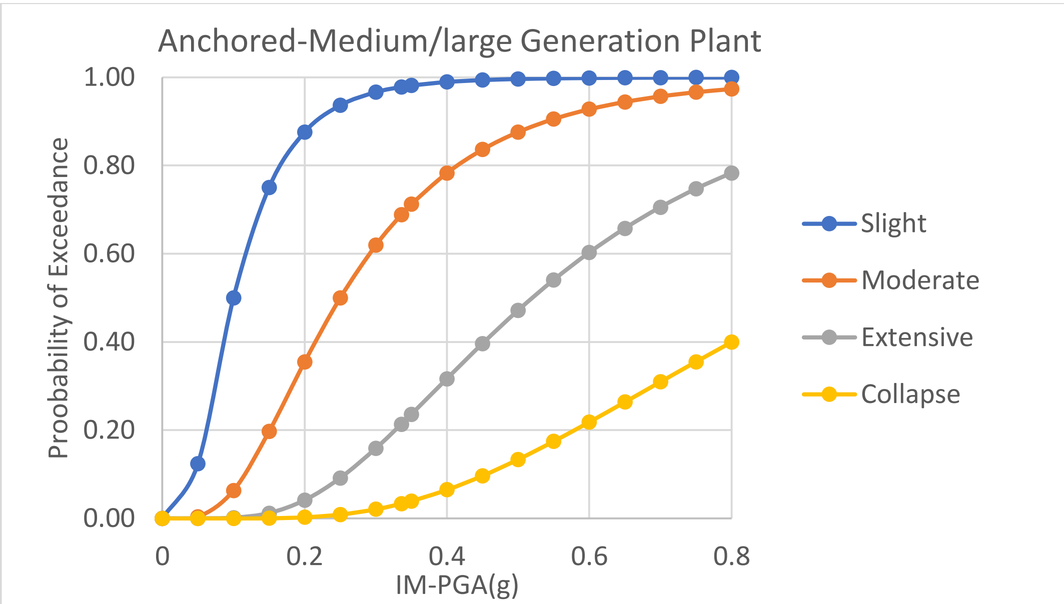


Figure 82: Fragility Functions for Anchored-Medium/Large Generation Plant (EPN-02)

Table 38: Damage Matrix for Anchored Small Generation Plant (EPN-02)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 18 | 49 | 32 | 2 | 0 | 100 |
| **80** | 11 | 44 | 42 | 3 | 0 | 100 |
| **178** | 4 | 29 | 55 | 11 | 2 | 100 |
| **476** | 1 | 14 | 54 | 24 | 7 | 100 |
| **976** | 0 | 7 | 44 | 33 | 16 | 100 |
| **2475** | 0 | 2 | 28 | 37 | 33 | 100 |

Table 39: Damage Matrix for Anchored Medium/Large Generation Plant (EPN-02)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 20 | 55 | 23 | 2 | 0 | 100 |
| **80** | 13 | 53 | 31 | 4 | 0 | 100 |
| **178** | 5 | 40 | 43 | 10 | 1 | 100 |
| **476** | 1 | 24 | 47 | 22 | 5 | 100 |
| **976** | 0 | 14 | 42 | 32 | 11 | 100 |
| **2475** | 0 | 6 | 31 | 39 | 24 | 100 |

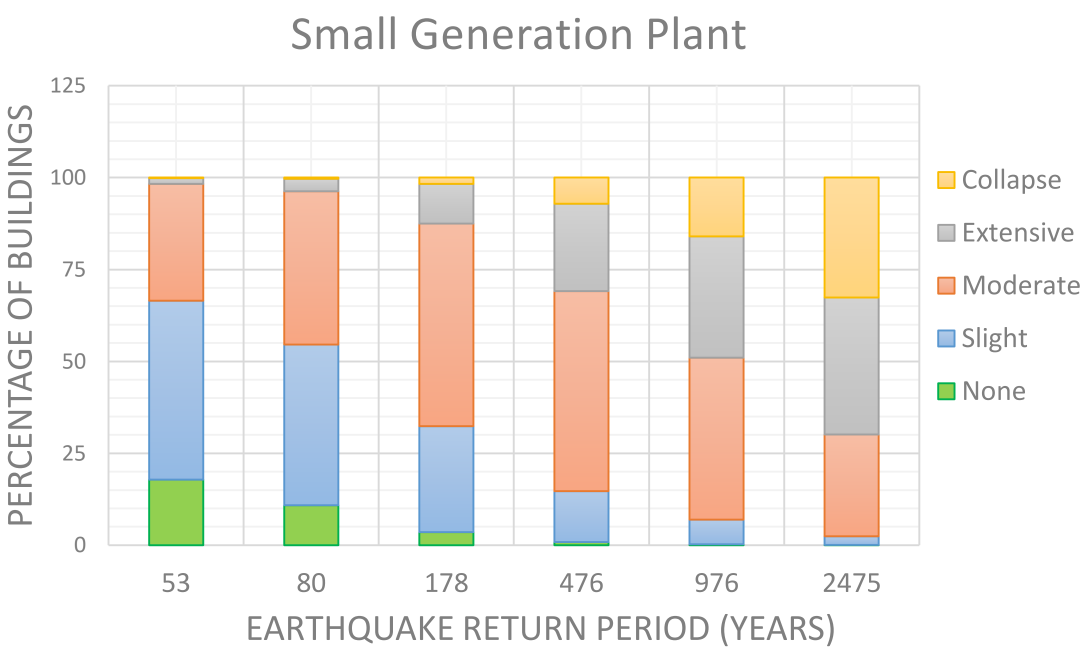


Figure 83: Fragility Functions for Anchored Small Generation Plant (EPN-02)

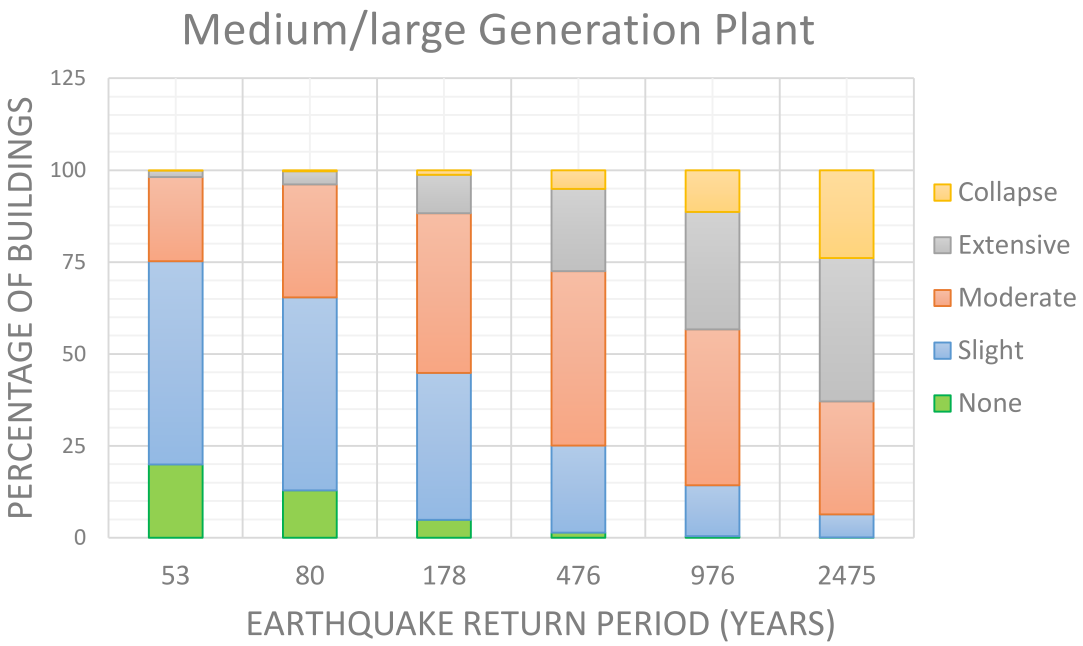


Figure 84: Fragility Functions for Anchored-Medium/Large Generation Plant (EPN-02)

Substations (EPN-03) are classified into low, medium and high voltage substations. The fragility curves for EPN-03 are presented for damage states i.e., slight, moderate, extensive and collapse limit states (Figures 85-87). These fragility curves are based on numerical method and proposed by FEMA-HAZUS technical manual in 2003. Results are presented in terms of damage matrix in Figure 88 and show that anchored low voltage substations exceeding 23% slight, 34% moderate, 31% extensive and 3% collapse limit states. Similarly, results (Figure 89) for anchored medium voltage substations show that 15% slight, 22% moderate, 51% extensive and 6% collapse limit states. Finally, for anchored high voltage substation show that (Figure 90) 1% slight, 2% moderate, 68% extensive and 28% collapse limit states exceeding at 10% probability of exceedance event. The detailed damage matrices for different probability of exceedance are shown in Tables 40-42 for the anchored low, medium and large substations.

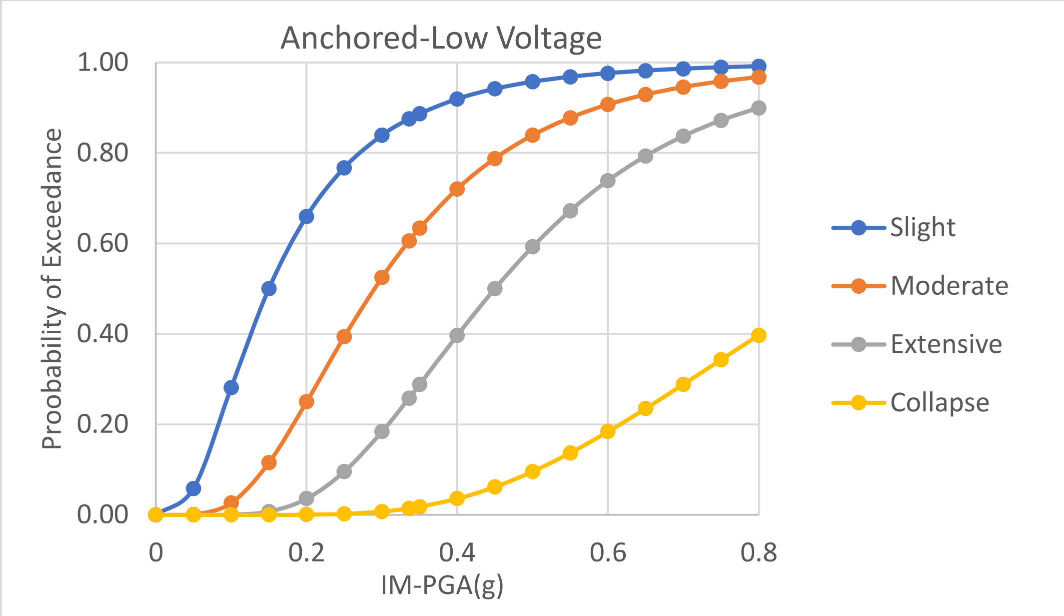


Figure 85: Fragility Functions for Anchored-Low Voltage Substation (EPN-03)

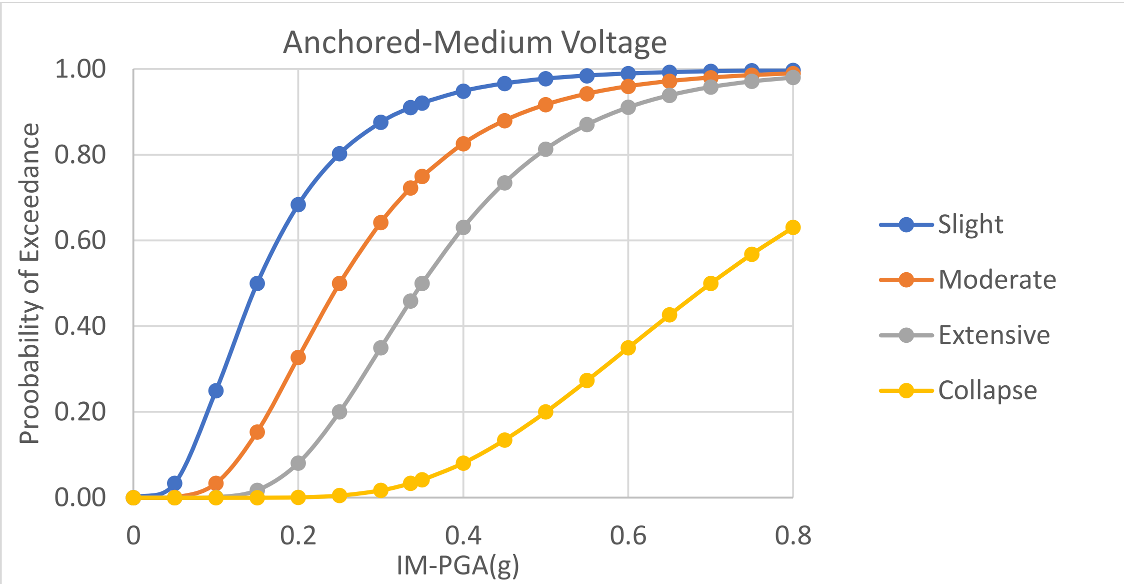


Figure 86: Fragility Functions for Anchored-Medium Voltage Substation (EPN-03)

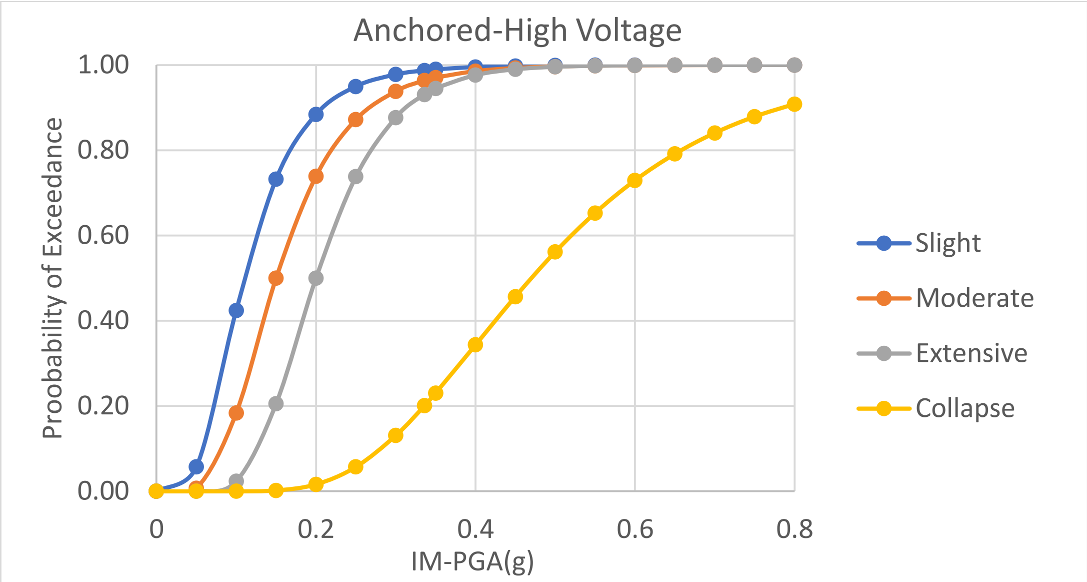


Figure 87: Fragility Functions for Anchored-High Voltage Substation (EPN-03)

Table 40: Damage Matrix for Anchored Low Voltage Substation (EPN-03)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 44 | 40 | 14 | 1 | 0 | 100 |
| **80** | 35 | 41 | 21 | 3 | 0 | 100 |
| **178** | 20 | 35 | 32 | 12 | 0 | 100 |
| **476** | 10 | 23 | 34 | 31 | 3 | 100 |
| **976** | 5 | 14 | 27 | 47 | 8 | 100 |
| **2475** | 2 | 6 | 15 | 56 | 21 | 100 |

Table 41: Damage Matrix for Anchored Medium Voltage Substation (EPN-03)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 43 | 36 | 18 | 3 | 0 | 100 |
| **80** | 32 | 36 | 24 | 7 | 0 | 100 |
| **178** | 16 | 28 | 30 | 25 | 1 | 100 |
| **476** | 6 | 15 | 22 | 51 | 6 | 100 |
| **976** | 3 | 7 | 12 | 61 | 16 | 100 |
| **2475** | 1 | 3 | 4 | 54 | 39 | 100 |

Table 42: Damage Matrix for Anchored High Voltage Substation (EPN-03)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 21 | 21 | 29 | 29 | 0 | 100 |
| **80** | 12 | 15 | 24 | 47 | 1 | 100 |
| **178** | 4 | 6 | 10 | 72 | 8 | 100 |
| **476** | 1 | 1 | 2 | 68 | 28 | 100 |
| **976** | 0 | 0 | 0 | 48 | 51 | 100 |
| **2475** | 0 | 0 | 0 | 24 | 76 | 100 |

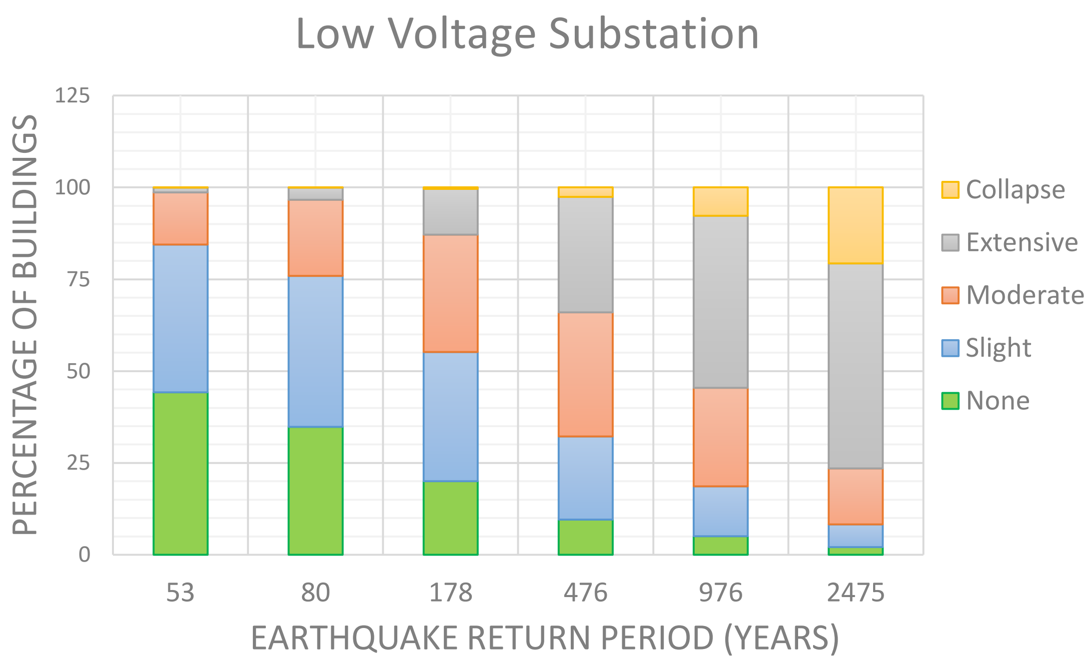


Figure 88: Damage Matrix for Anchored-Low Voltage Substation (EPN-03)

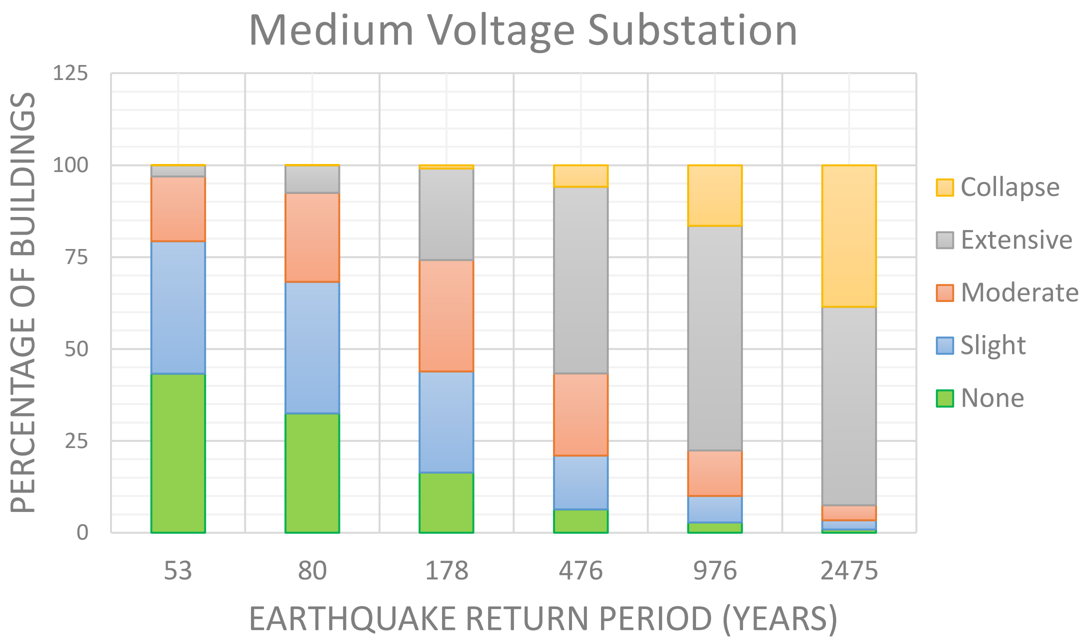


Figure 89: Damage Matrix for Anchored-Medium Voltage Substation (EPN-03)

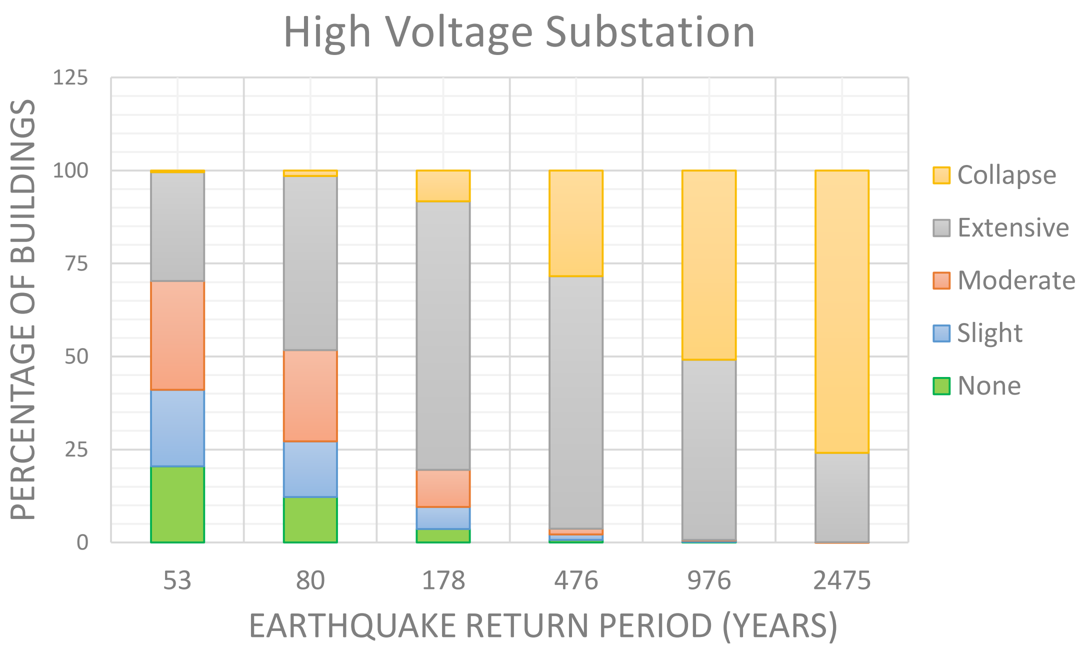


Figure 90: Damage Matrix for Anchored-High Voltage Substation (EPN-03)

In HAZUS methodology, waterfront structures are categorised on the basis of height (H) of structure and the site specific shear wave velocity (Vs). The height of waterfront structures is more than 10m and the average shear wave velocity is around 300m/sec (close to 260m/sec) has been considered in this report. Based on this the fragility functions (Figure 91) proposed by HAZUS methodology for H >10m and Vs=260m/sec are employed herein for four different damage states such as slight, moderate, extensive and collapse limit states. Results are presented in terms of damage matrix (Figure 92) and show that 61% slight, 34% moderate and 3% extensive limit states exceeding at 10% probability of exceedance event. The detailed damage matrix for different probability of exceedance is shown in Table 43.

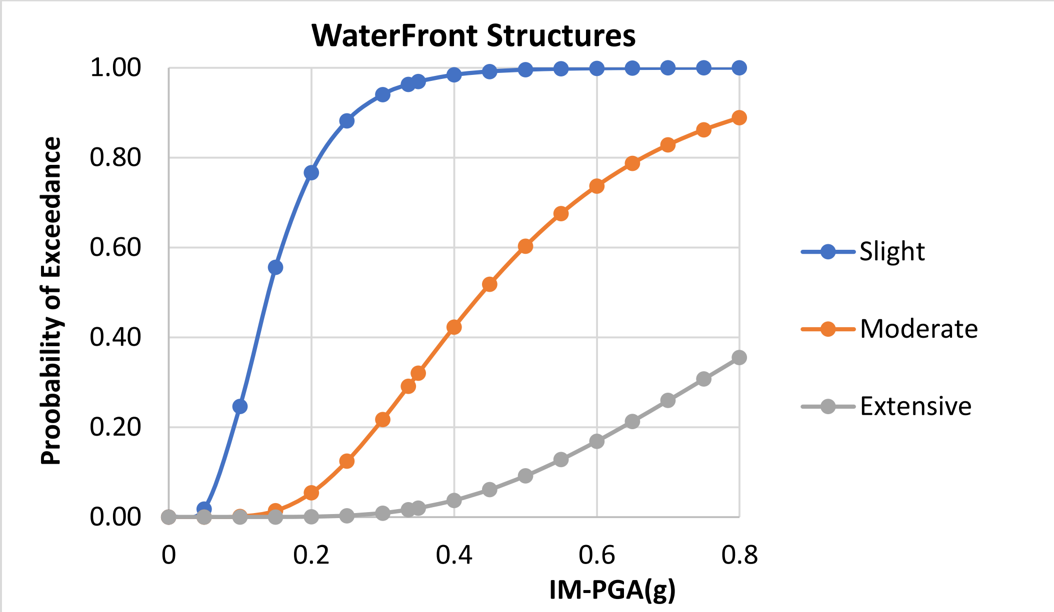


Figure 91: Fragility Functions for Waterfront Structures

Table 43: Damage Matrix for Waterfront Structures

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 36 | 61 | 2 | 0 | 0 | 100 |
| **80** | 24 | 71 | 5 | 0 | 0 | 100 |
| **178** | 9 | 75 | 15 | 0 | 0 | 100 |
| **476** | 2 | 61 | 34 | 3 | 0 | 100 |
| **976** | 1 | 43 | 49 | 7 | 0 | 100 |
| **2475** | 0 | 24 | 57 | 19 | 0 | 100 |

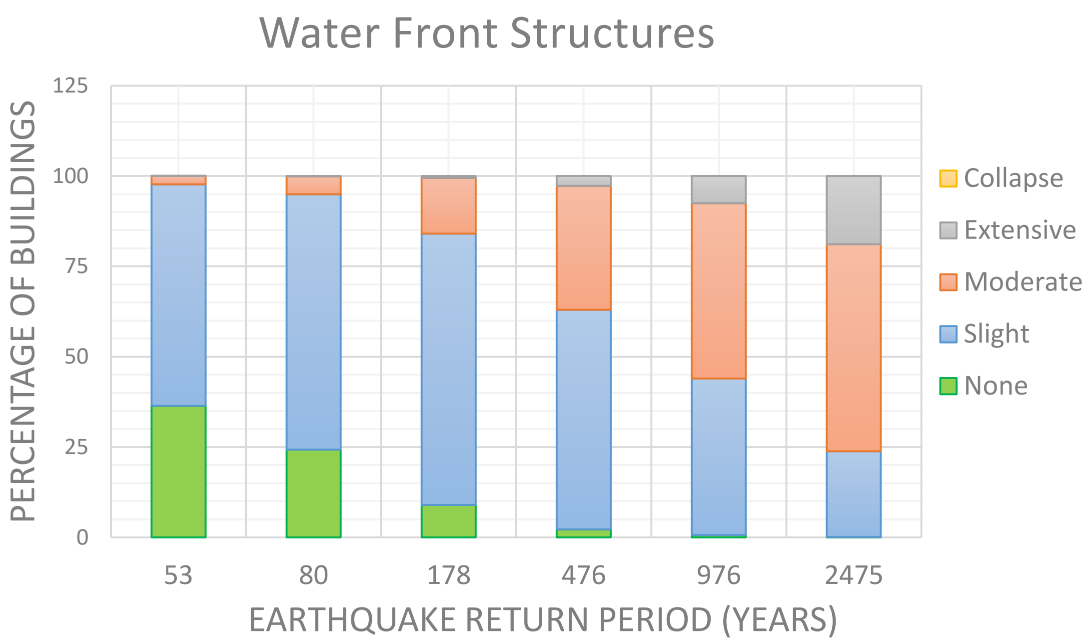


Figure 92: Damage Matrix for Waterfront Structures

Cranes and cargo handling equipment are classified into stationery and unanchored rail mounted equipment. The fragility curves for stationery and unanchored rail mounted equipment are presented for damage states i.e., slight, moderate and extensive limit states shown in Figures 93-94. Results are presented in terms of damage matrices (Figures 95-96) and show that stationery equipment exceeding 33% slight, 23% moderate and 8% extensive limit states. Rail mounted equipment exceeding 39% slight, 41% moderate and 14% extensive limit states. The detailed damage matrices for different probability of exceedance are shown in Tables 44-45.

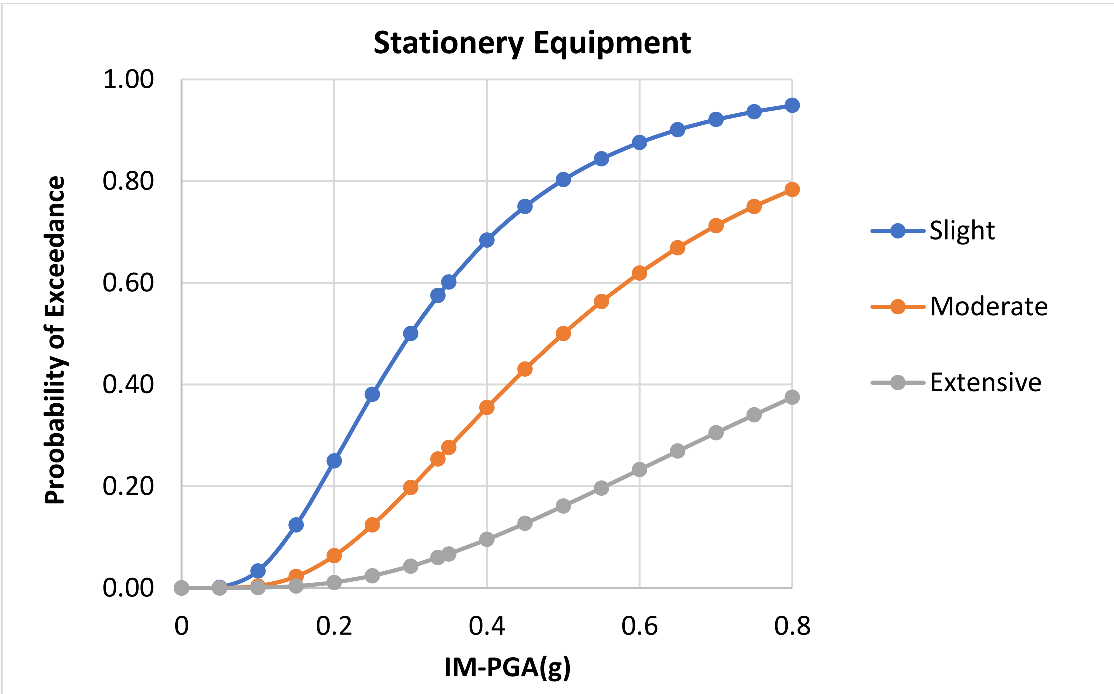

Figure 93: Fragility function for Stationery Equipment

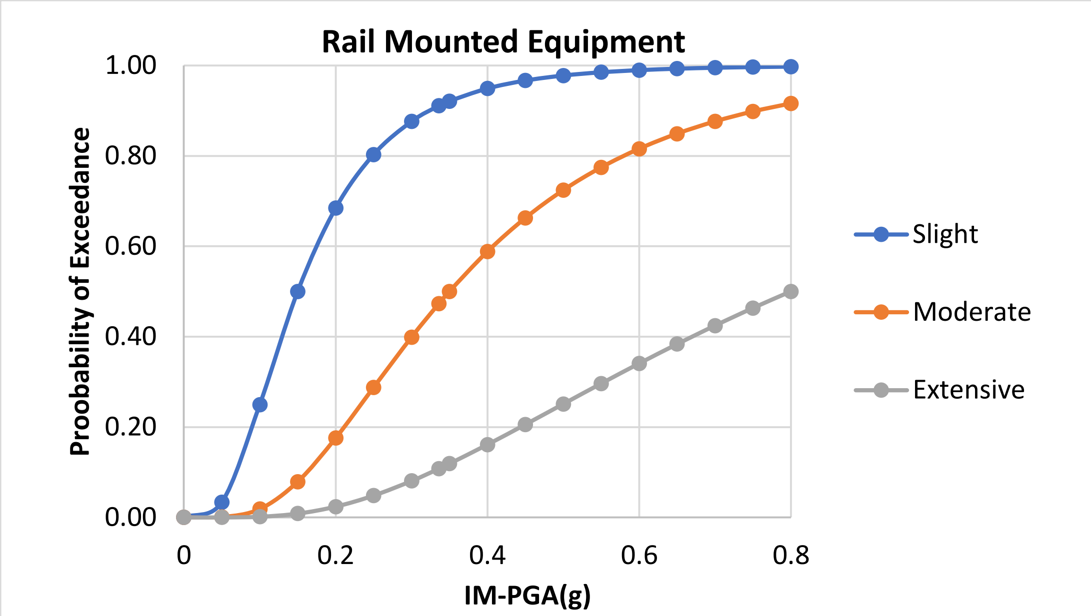


Figure 94: Fragility function for Rail Mounted Equipment

Table 44: Damage Matrix for Stationery Equipment

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| Years | % | % | % | % | % | % |
| 53 | 84 | 13 | 3 | 1 | 0 | 100 |
| 80 | 76 | 18 | 5 | 1 | 0 | 100 |
| 178 | 57 | 28 | 12 | 3 | 0 | 100 |
| 476 | 36 | 33 | 23 | 8 | 0 | 100 |
| 976 | 22 | 31 | 32 | 14 | 0 | 100 |
| 2475 | 11 | 25 | 39 | 25 | 0 | 100 |

Table 45: Damage Matrix for Rail Mounted Equipment

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| Years | % | % | % | % | % | % |
| 53 | 43 | 46 | 9 | 1 | 0 | 100 |
| 80 | 32 | 51 | 15 | 2 | 0 | 100 |
| 178 | 16 | 50 | 27 | 6 | 0 | 100 |
| 476 | 6 | 39 | 41 | 14 | 0 | 100 |
| 976 | 3 | 28 | 47 | 23 | 0 | 100 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **2475** | 1 | 16 | 47 | 36 | 0 | 100 |

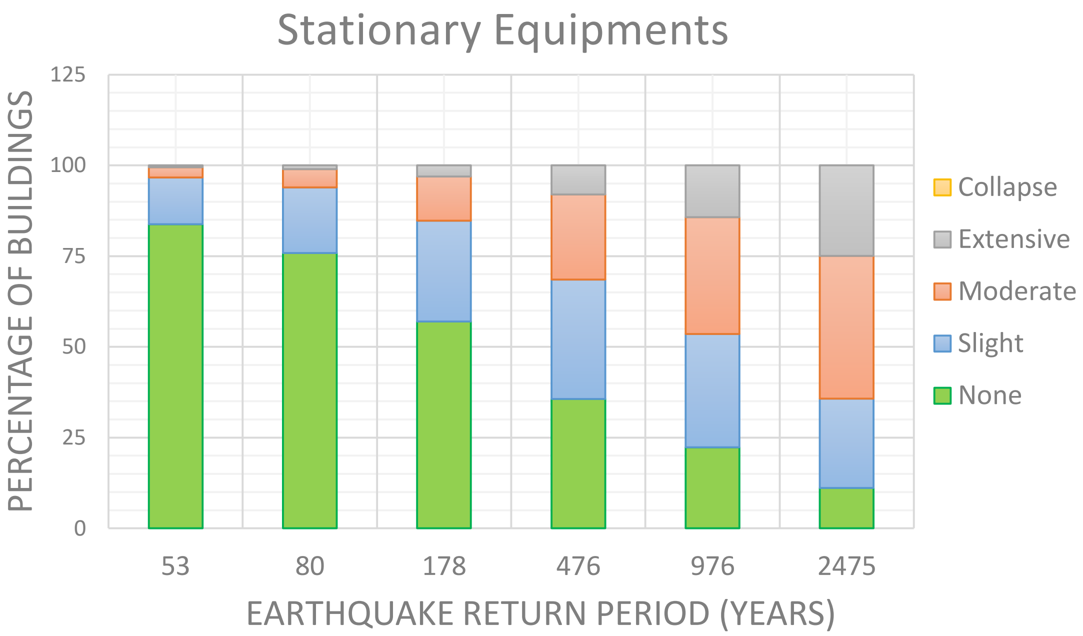


Figure 95: Damage Matrix for Stationary Equipment

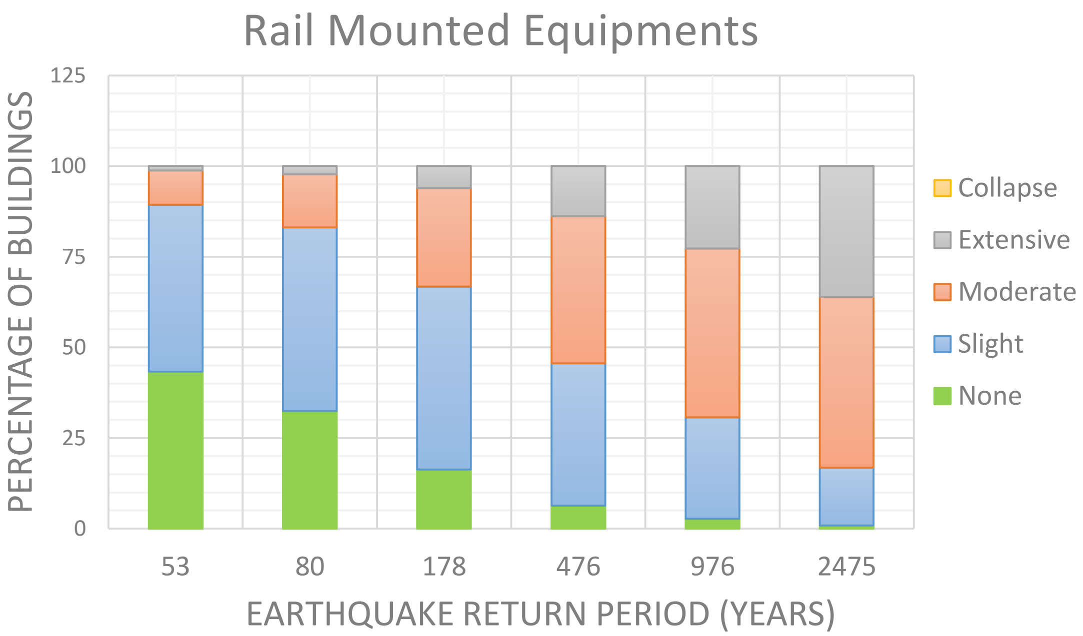


Figure 96: Damage Matrix for Rail Mounted Equipment

Fuel facilities are categorised into low seismic and high seismic building structures with anchored and unanchored components. The fragility curves (Figure 97) for unanchored high seismic buildings are presented for damage states of, slight, moderate, extensive and collapse limit states. Results show that (Figure 98) fuel facilities for unanchored high seismic buildings with backup power system exceeding 23% slight, 54% moderate, 14% extensive and 7% collapse limit states. The detailed damage matrix for different probability of exceedance is shown in Table 46.

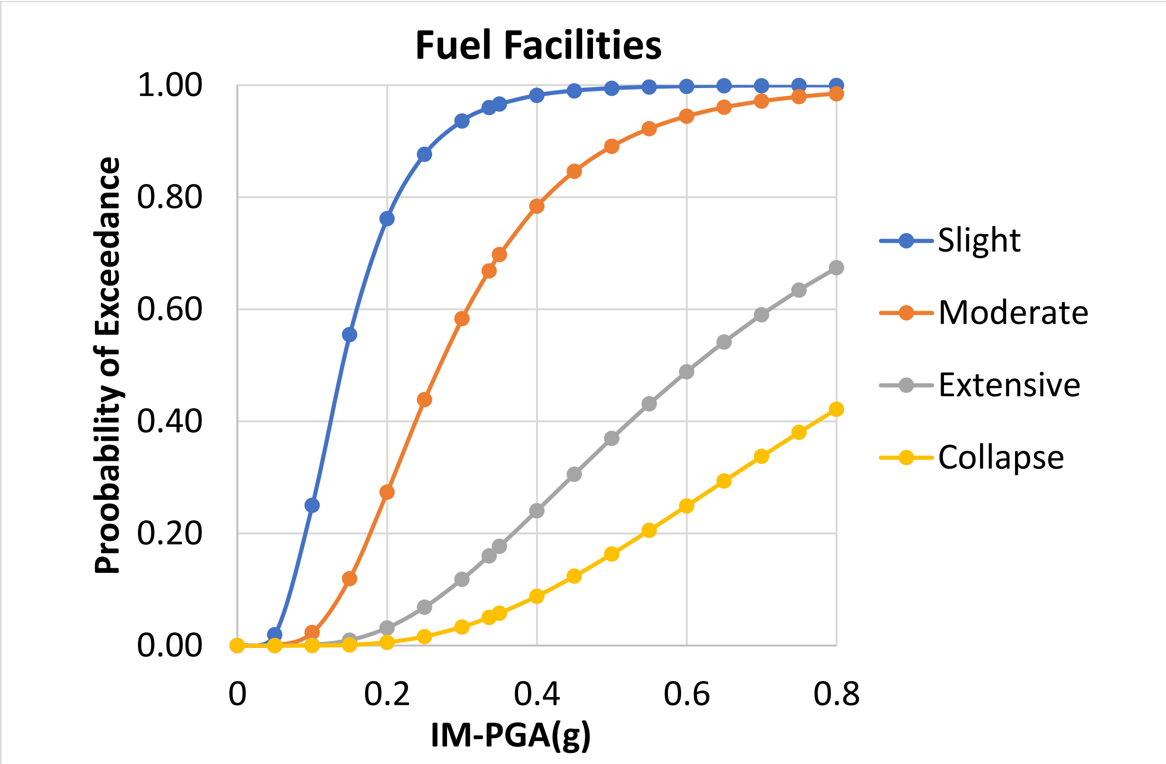


Figure 97: Fragility Functions for Fuel Facilities (High Seismic Building with Unanchored Components)

Table 46: Damage Matrix for Fuel Facilities (High Seismic Building with Unanchored Components)

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 37 | 47 | 15 | 1 | 0 | 100 |
| **80** | 25 | 49 | 23 | 2 | 1 | 100 |
| **178** | 9 | 41 | 41 | 6 | 2 | 100 |
| **476** | 2 | 23 | 54 | 14 | 7 | 100 |
| **976** | 1 | 12 | 53 | 19 | 14 | 100 |
| **2475** | 0 | 5 | 44 | 24 | 27 | 100 |

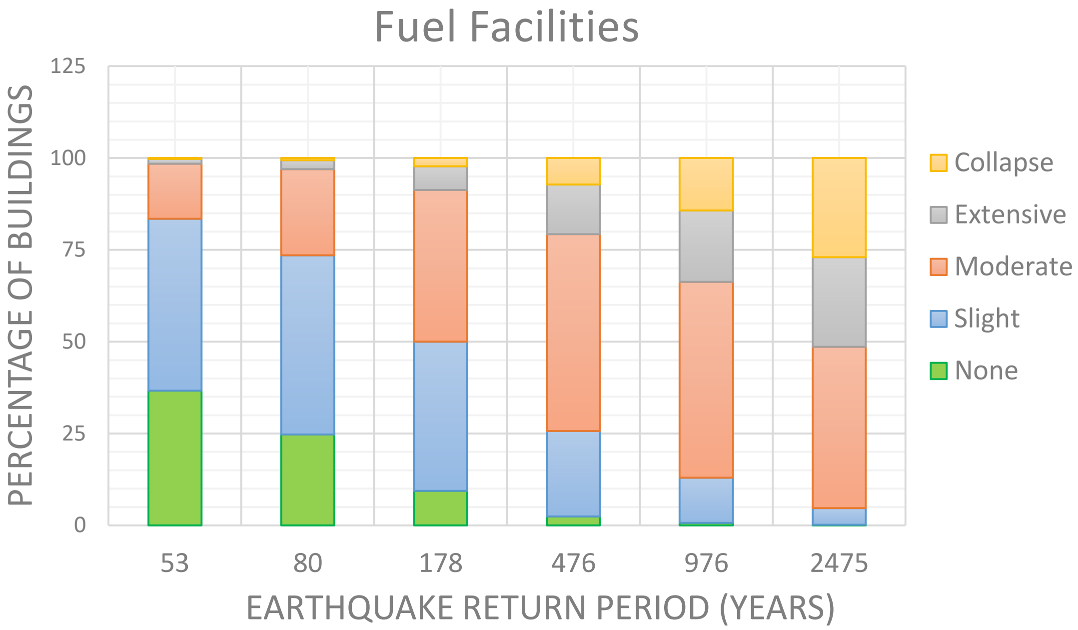


Figure 98: Damage Matrix for Fuel Facilities (High Seismic Building with Unanchored Components)

Refineries are categorized into small and medium/large oil refineries in this report. Further classification of these is based upon anchored and unanchored components. Four different damage states such as slight, moderate, extensive and collapse are considered herein and their corresponding fragility curves are shown in Figures 99-100. Results are presented in terms of damage matrices (Figures 101-102) and show that for anchored small oil refineries 42% slight, 7% moderate, 12% extensive and 7% collapse limit states exceeding at 10% probability of exceedance event. Similarly, for anchored medium/large oil refineries show that 34% slight, 12% moderate, 2% extensive and 0% collapse limit states exceeding at 10% probability of exceedance event. The detailed damage matrices for different probability of exceedance are shown in Tables 47-48.

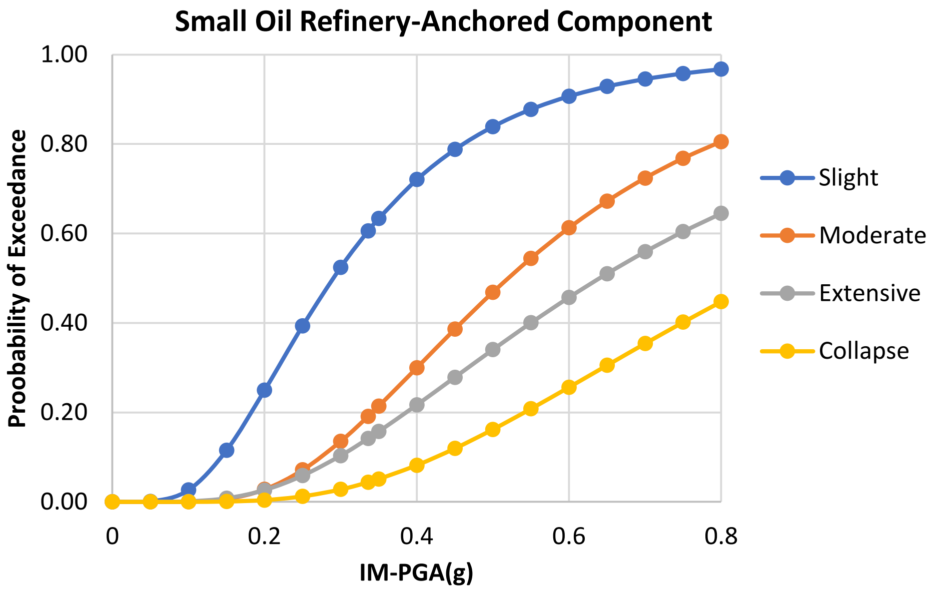


Figure 99: Fragility Functions for Small Oil Refineries with Anchored Components

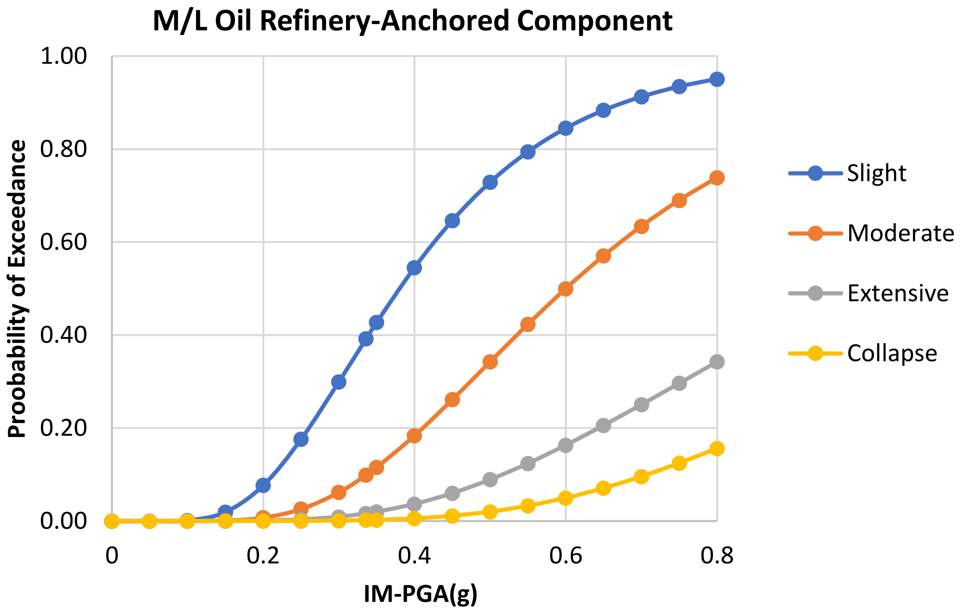


Figure 100: Fragility Functions for Medium/Large Oil Refineries with Anchored Components

Table 47: Damage Matrix for Small Oil Refineries with Anchored Components

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 84 | 14 | 0 | 1 | 0 | 100 |
| **80** | 76 | 21 | 0 | 2 | 0 | 100 |
| **178** | 55 | 35 | 2 | 6 | 2 | 100 |
| **476** | 32 | 42 | 7 | 12 | 7 | 100 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **976** | 19 | 39 | 12 | 17 | 14 | 100 |
| **2475** | 8 | 28 | 16 | 20 | 28 | 100 |

Table 48: Damage Matrix for Medium/Large Oil Refineries with Anchored Components

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 97 | 3 | 0 | 0 | 0 | 100 |
| **80** | 93 | 7 | 1 | 0 | 0 | 100 |
| **178** | 78 | 19 | 3 | 0 | 0 | 100 |
| **476** | 51 | 34 | 12 | 2 | 0 | 100 |
| **976** | 31 | 39 | 23 | 6 | 1 | 100 |
| **2475** | 14 | 33 | 35 | 12 | 6 | 100 |

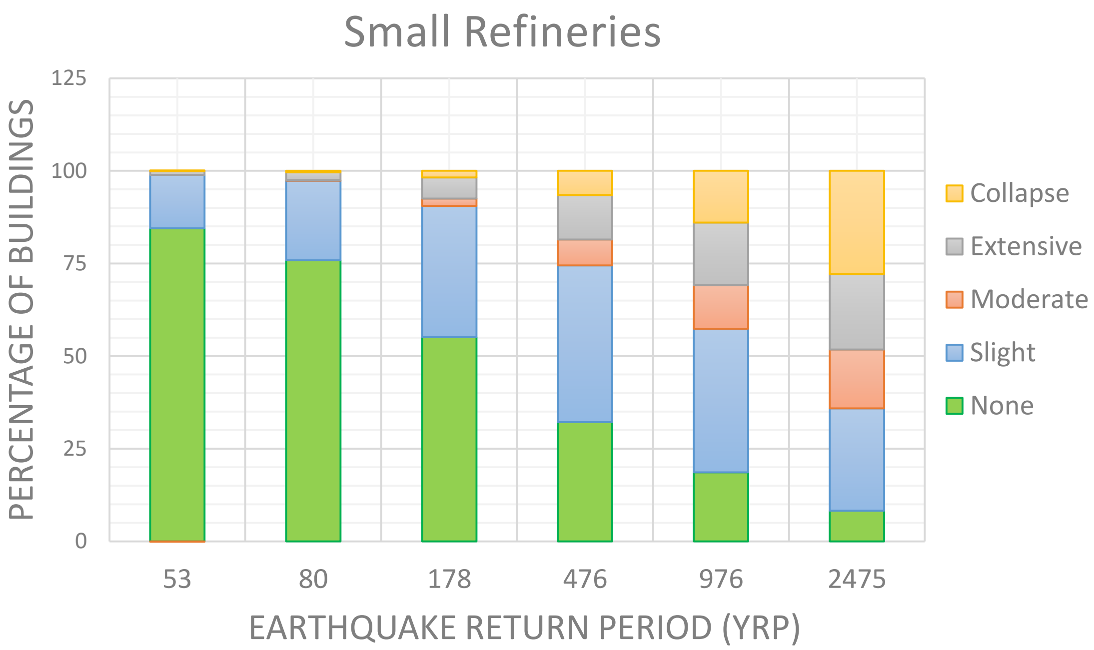


Figure 101: Fragility Functions for Small Oil Refineries with Anchored Components

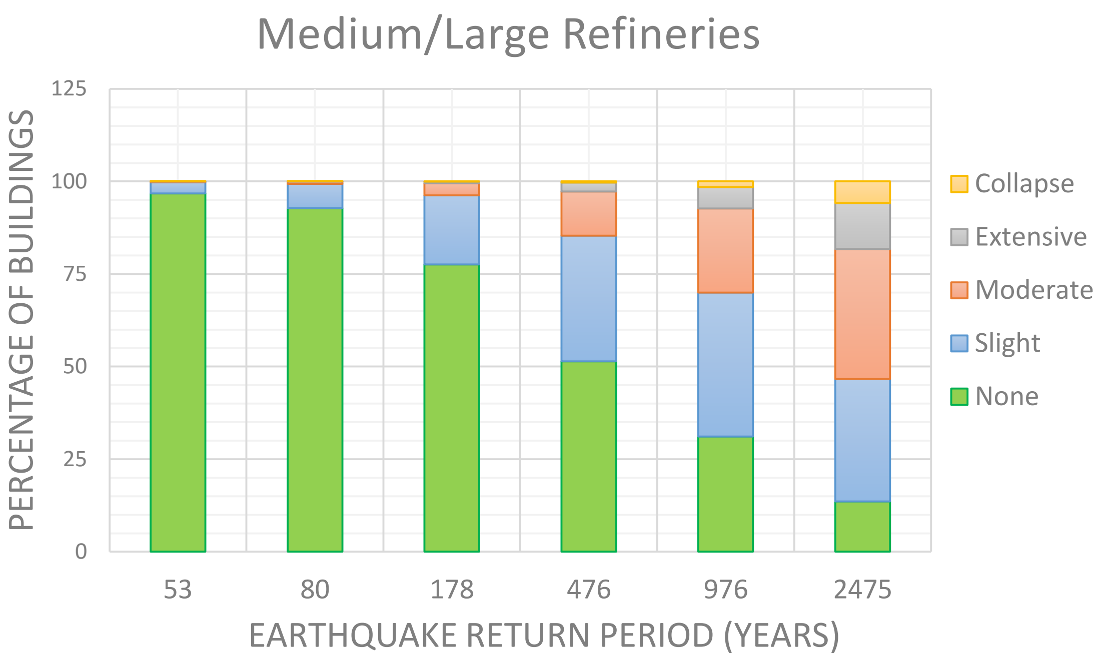


Figure 102: Fragility Functions for Medium/Large Oil Refineries with Anchored Components

Pumping plants are classified into low seismic reinforced concrete (RC) buildings and high seismic RC buildings. The fragility curves (Figure 103) for anchored pumping plants are presented for damage states for slight, moderate, extensive and collapse limit states. Results are presented in terms of damage matrix (Figure 104) and show that anchored low seismic RC buildings exceeding 33% slight, 42% moderate, 9% extensive and 4% collapse limit states. The detailed damage matrix for different probability of exceedance is shown in Table 49.

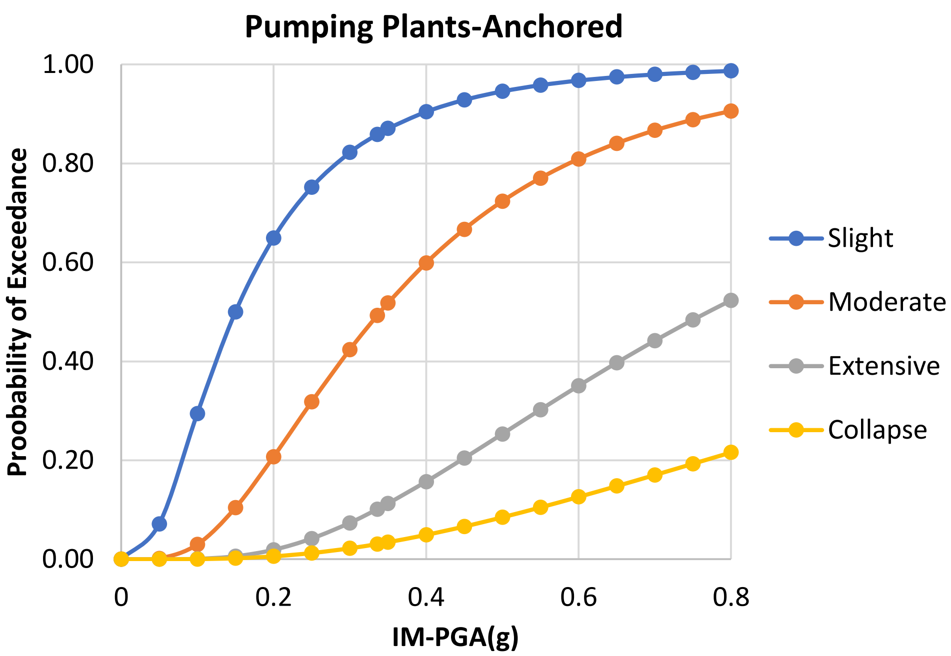


Figure 103: Fragility function for High Seismic Pumping Plants with Anchored Components

Table 49: Damage Matrix for High Seismic Pumping Plants with Anchored Components

| Return Period | None | Slight | Moderate | Extensive | Collapse | Total |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 45 | 42 | 13 | 1 | 0 | 100 |
| **80** | 36 | 44 | 18 | 1 | 1 | 100 |
| **178** | 22 | 42 | 31 | 4 | 2 | 100 |
| **476** | 11 | 33 | 42 | 9 | 4 | 100 |
| **976** | 6 | 24 | 47 | 15 | 7 | 100 |
| **2475** | 3 | 15 | 45 | 24 | 14 | 100 |

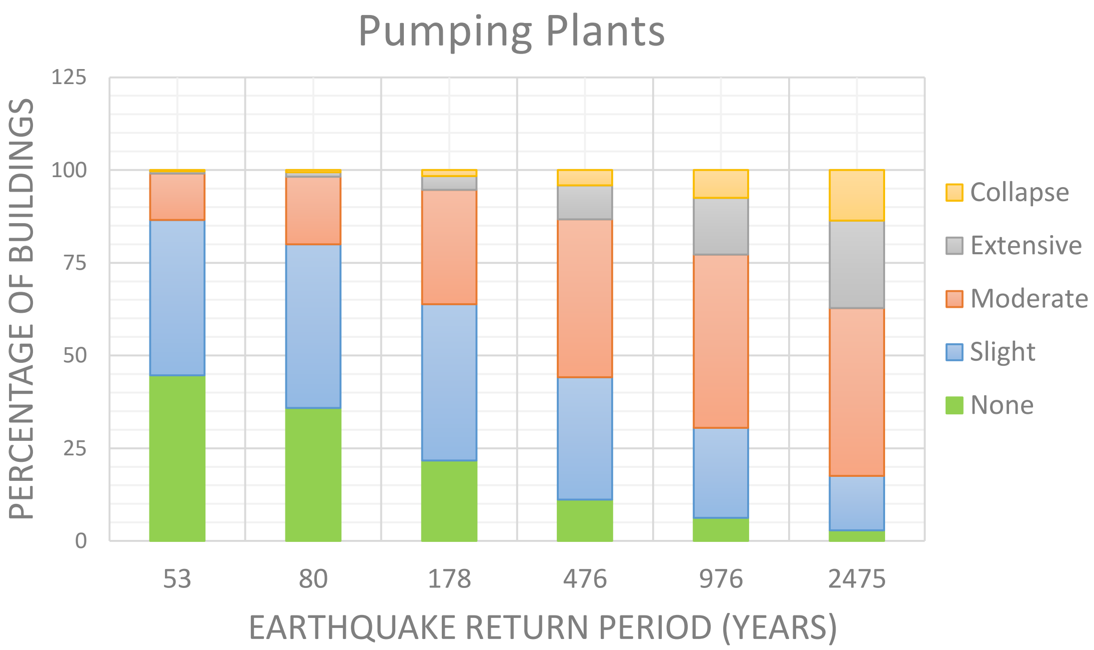


Figure 104: Damage Matrix for High Seismic Pumping Plants with Anchored Components

Tank farms are classified with anchored and unanchored components. The fragility curves for anchored tank farms are shown in Figure 105 for damage states slight, moderate, extensive and collapse limit states. Results are presented in terms of damage matrix (Figure 106) and show that anchored low seismic RC buildings exceeding 38% slight, 0% moderate, 25% extensive and 5% collapse states. The detailed damage matrix for different probability of exceedance is shown in Table 50.

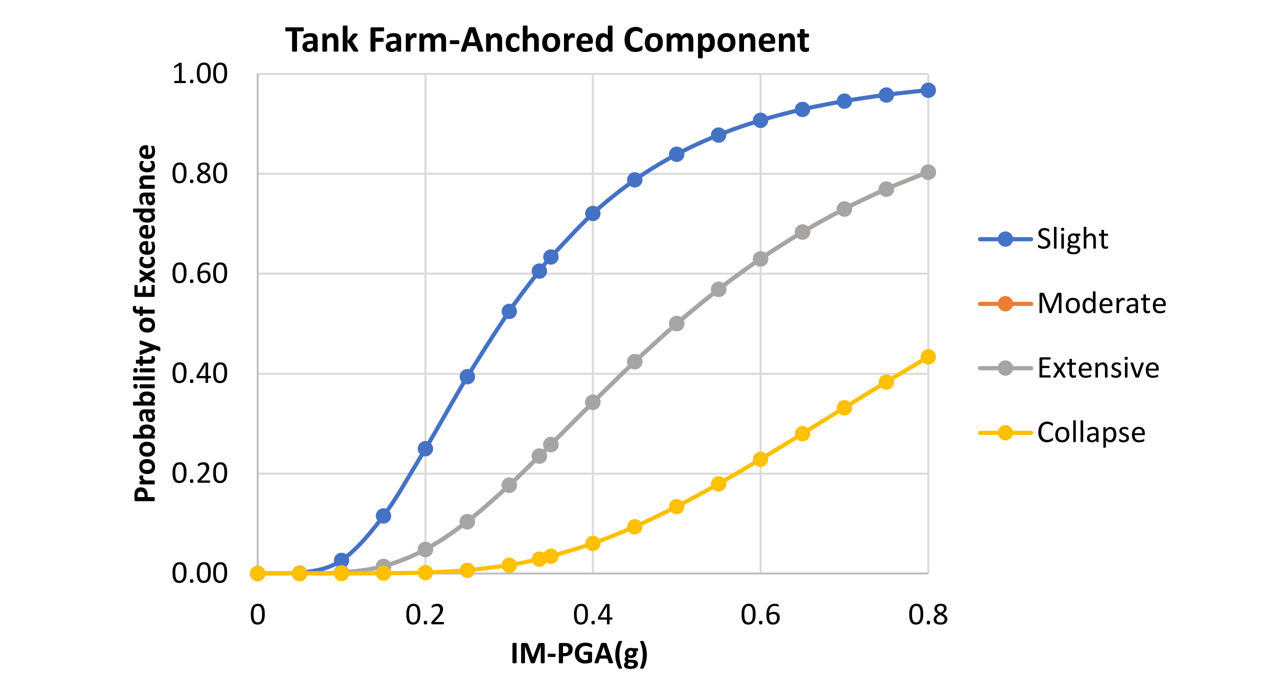


Figure 105: Fragility Functions for Anchored Tank Farms

Table 50: Damage Matrix for Anchored Tank Farms

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 84 | 13 | 0 | 2 | 0 | 100 |
| **80** | 76 | 20 | 0 | 4 | 0 | 100 |
| **178** | 55 | 32 | 0 | 12 | 1 | 100 |
| **476** | 32 | 38 | 0 | 25 | 5 | 100 |
| **976** | 19 | 35 | 0 | 35 | 11 | 100 |
| **2475** | 8 | 26 | 0 | 40 | 25 | 100 |

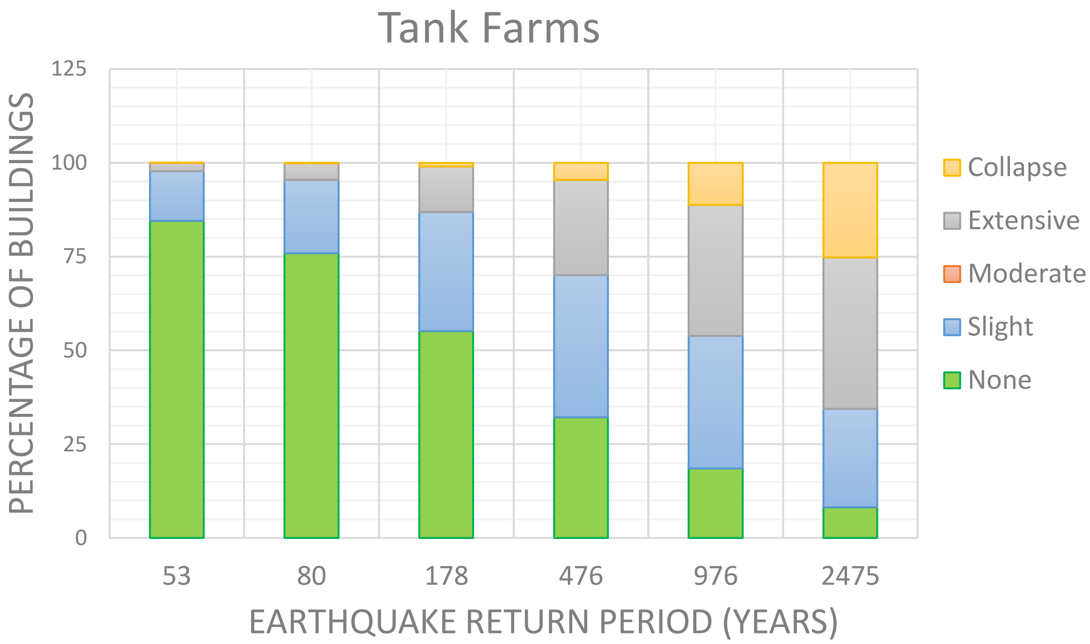


Figure 106: Damage Matrix for Anchored Tank Farms

The fragility functions (Figure 107) for communication facilities are plotted for four different limit states. These fragility curves are based on the probabilistic combination of subcomponent damage functions using boolean expressions. Results are presented in terms of damage matrix (Figure 108) and show that 29% slight, 38% moderate, 19% extensive and 3% collapse limit states exceeding at 10% probability of exceedance event. The detailed damage matrix for different probability of exceedance is shown in Table 51.

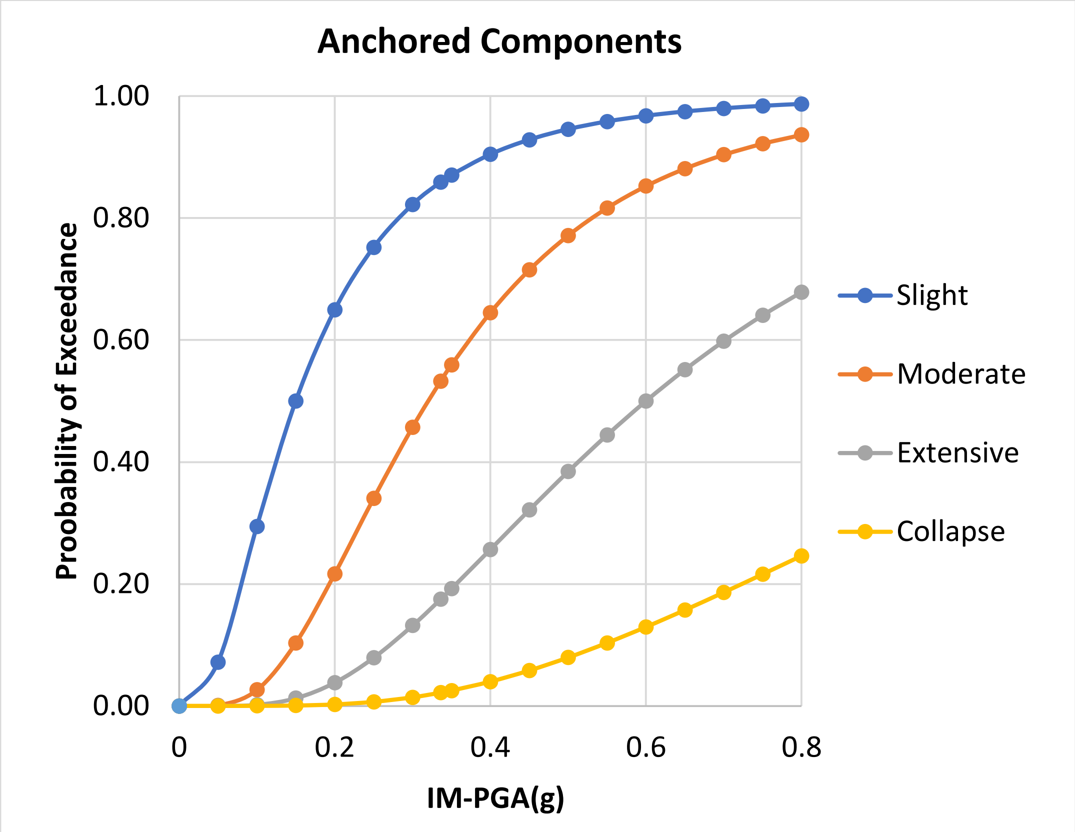


Figure 107: Fragility Functions for Communication Facilities with anchored components

Table 51: Damage Matrix for Communication Facilities with anchored components

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 45 | 42 | 12 | 2 | 0 | 100 |
| **80** | 36 | 43 | 17 | 3 | 0 | 100 |
| **178** | 22 | 39 | 29 | 9 | 1 | 100 |
| **476** | 11 | 29 | 38 | 19 | 3 | 100 |
| **976** | 6 | 19 | 39 | 28 | 7 | 100 |
| **2475** | 3 | 10 | 34 | 38 | 14 | 100 |

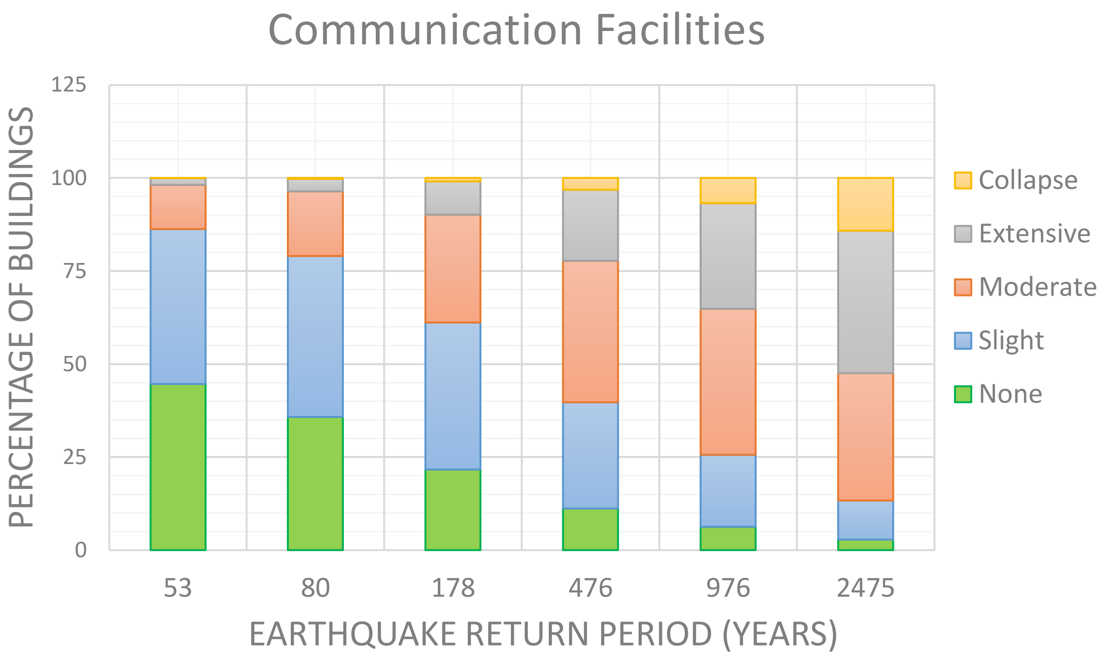


Figure 108: Damage Matrix for Communication Facilities with anchored components

Water treatment plants are classified into anchored and unanchored plants in this report. The fragility curves from SRM-LIFE (2007) are employed for the vulnerability assessment of water treatment plants. These were derived through fault-tree analysis, using the fault-tree and the fragility curves of sub-components proposed in HAZUS methodology (NIBS 2004). These employed curves are applicable to water treatment plants with anchored components and no backup power. Four different damage states such as slight, moderate, extensive and collapse are considered herein and their corresponding fragility curves are presented in the Figure 109. Results are presented in terms of damage matrix (Figure 110) and show that 19% slight, 55% moderate, 21% extensive and 6% collapse limit states exceeding at 10% probability of exceedance event for anchored water treatment plants. The detailed damage matrix for different probability of exceedance is shown in Table 52.

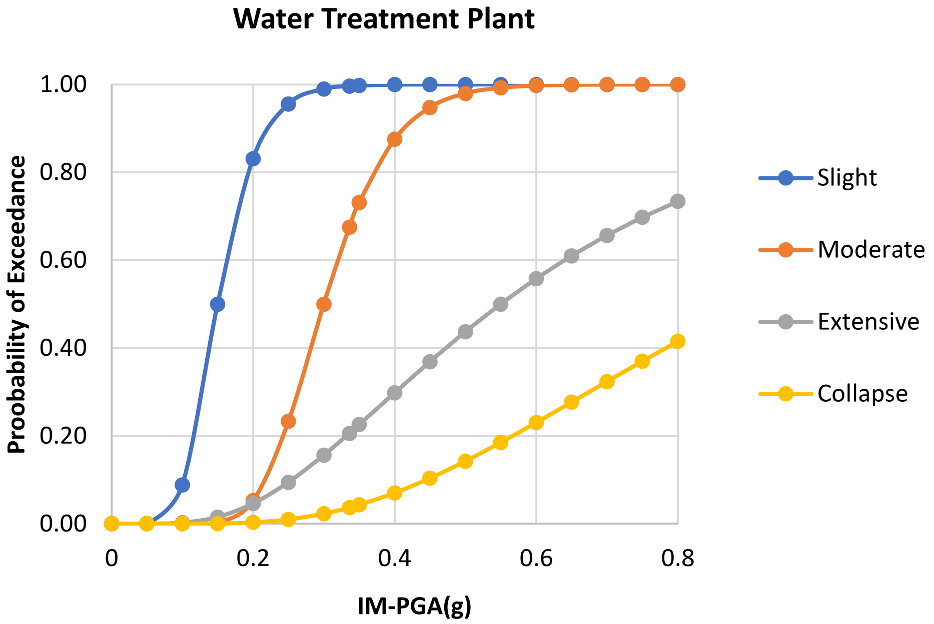


Figure 109: Fragility Functions for Anchored Water Treatment Plant

Table 52: Damage Matrix for Anchored Water Treatment Plant

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 37 | 61 | 1 | 1 | 0 | 100 |
| **80** | 18 | 77 | 0 | 4 | 0 | 100 |
| **178** | 3 | 64 | 22 | 10 | 1 | 100 |
| **476** | 0 | 19 | 55 | 21 | 6 | 100 |
| **976** | 0 | 3 | 56 | 28 | 12 | 100 |
| **2475** | 0 | 0 | 42 | 33 | 25 | 100 |

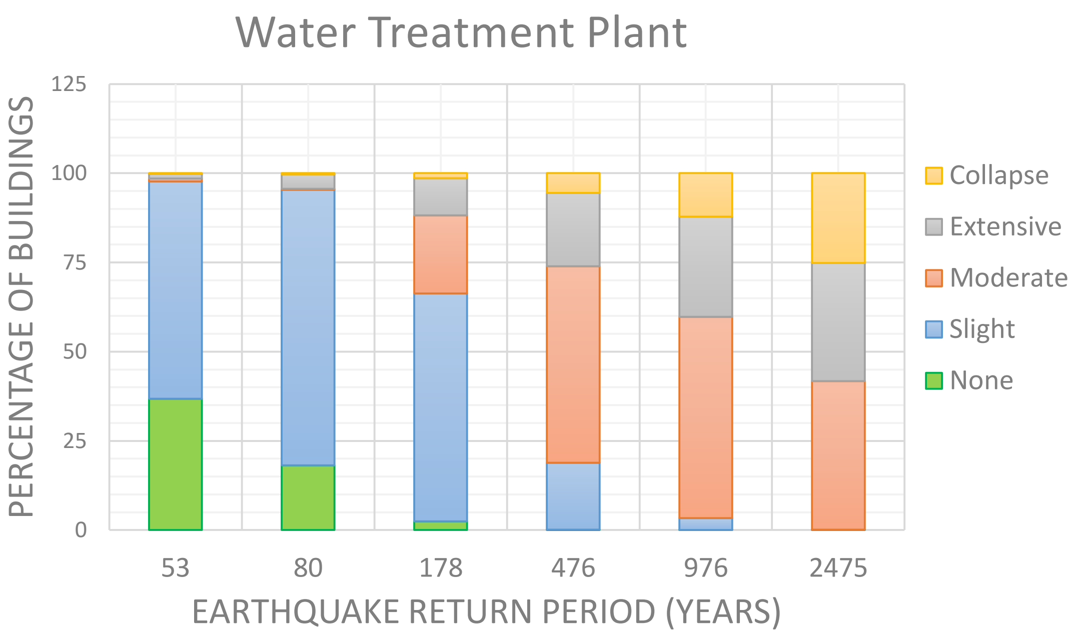


Figure 110: Damage Matrix for Anchored Water Treatment Plant

Waste-water treatment plants are classified into low seismic RC buildings and high seismic RC buildings. The fragility curves (Figures 111-112) for anchored waste-water treatment plants are presented for damage states slight, moderate, extensive and collapse. The fragility curves from SRM-LIFE (2007) are employed for the vulnerability assessment of waste-water treatment plants. Results are presented in terms of damage matrices (Figures 113-114) and show that anchored low seismic RC buildings exceeding 13% slight, 51% moderate, 7% extensive and 28% collapse limit states. Similarly, for anchored high seismic RC buildings 13% slight, 51% moderate, 33% extensive and 2% collapse limit states may exceed at 10% probability of exceedance event. The detailed damage matrices for different probability of exceedance are shown in Tables 53-54.

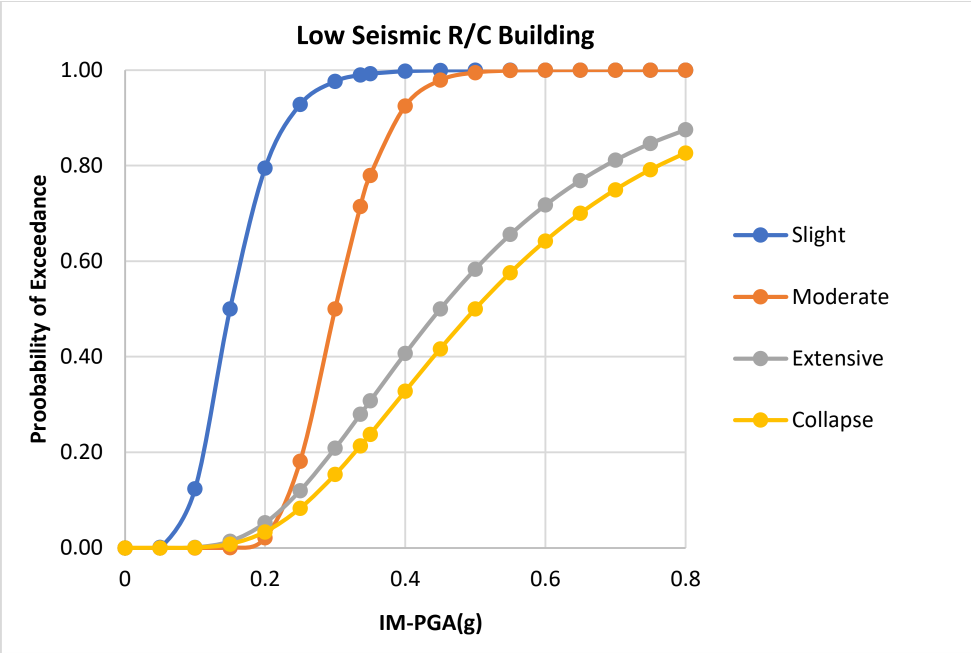


Figure 111: Fragility function for Low Seismic RC Building Waste Water Treatment Plant

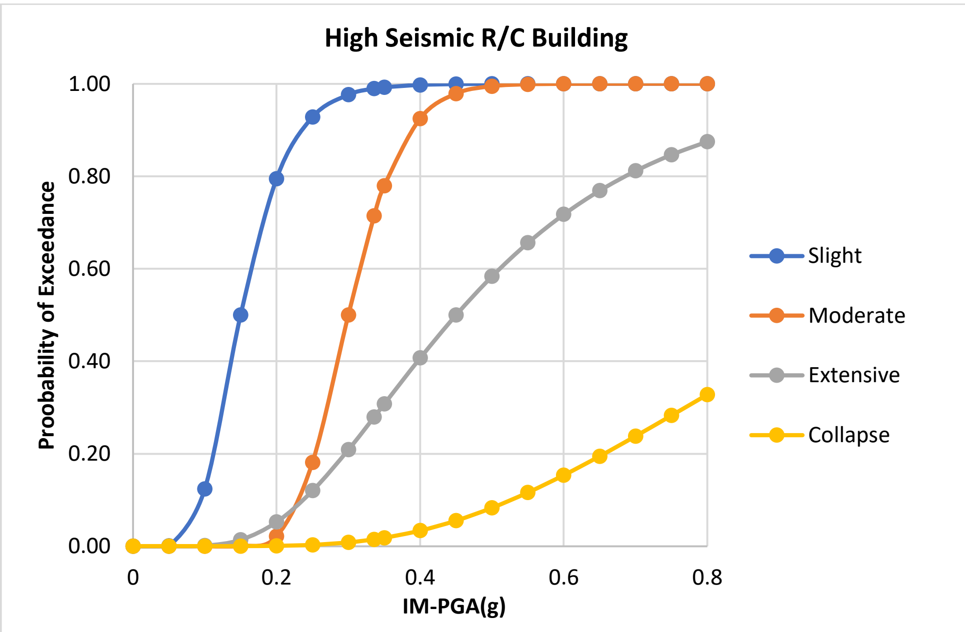


Figure 112: Fragility function for High Seismic RC Building Waste Water Treatment Plant

Table 53: Damage Matrix for Low Seismic RC Building Waste Water Treatment Plant

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 39 | 59 | 0 | 1 | 1 | 100 |
| **80** | 22 | 73 | 2 | 2 | 1 | 100 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **178** | 5 | 65 | 15 | 4 | 11 | 100 |
| **476** | 0 | 13 | 51 | 7 | 28 | 100 |
| **976** | 0 | 1 | 45 | 8 | 46 | 100 |
| **2475** | 0 | 0 | 26 | 7 | 67 | 100 |

Table 54: Damage Matrix for High Seismic RC Building Waste Water Treatment Plant

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 39 | 59 | 0 | 2 | 0 | 100 |
| **80** | 22 | 73 | 2 | 3 | 0 | 100 |
| **178** | 5 | 65 | 15 | 15 | 0 | 100 |
| **476** | 0 | 13 | 51 | 33 | 2 | 100 |
| **976** | 0 | 1 | 45 | 47 | 7 | 100 |
| **2475** | 0 | 0 | 26 | 57 | 17 | 100 |

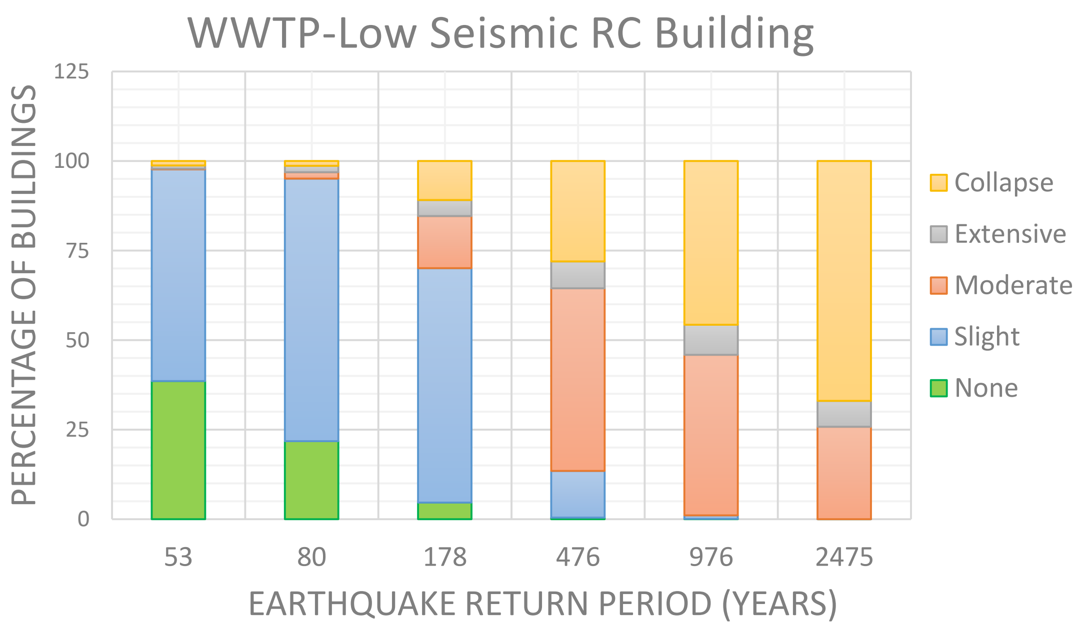


Figure 113: Damage Matrix for Low Seismic RC Building Waste Water Treatment Plant

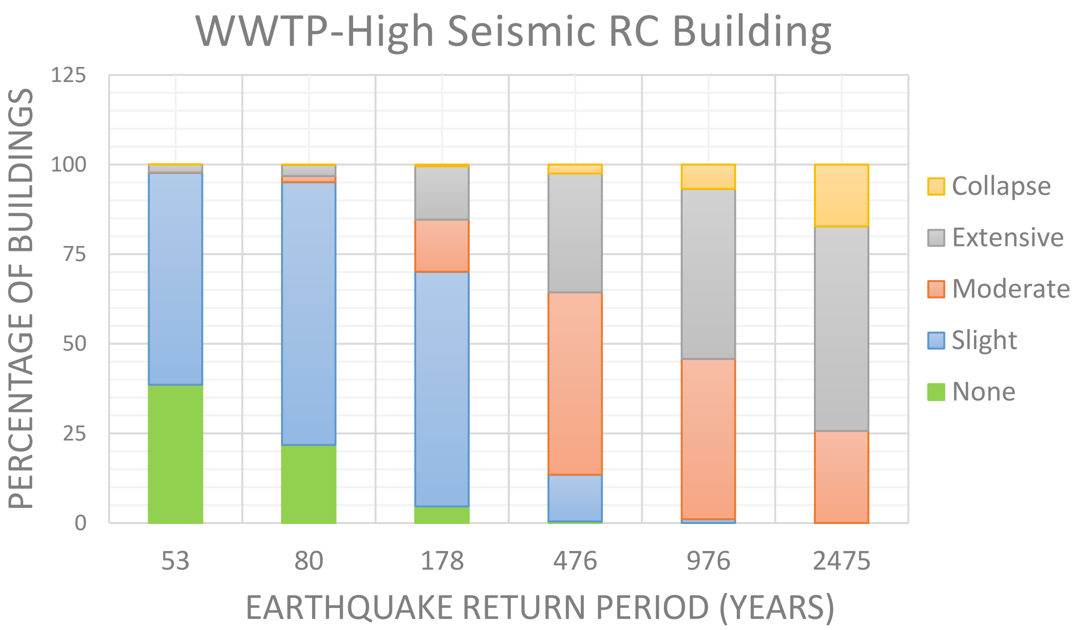


Figure 114: Fragility function for High Seismic RC Building Waste Water Treatment Plant

Pumping Stations are classified into low seismic RC buildings and high seismic RC buildings. The fragility curves (Figures 115-116) for anchored pumping stations are presented for damage states slight, moderate, extensive and collapse. The fragility curves from SRM-LIFE (2007) are employed for the vulnerability assessment of pumping stations. Results are presented in terms of damage matrices (Figure 117-118) and show that anchored low seismic RC buildings exceeding 4% slight, 33% moderate, 16% extensive and 46% collapse limit states. Similarly, for anchored high seismic RC buildings 26% slight, 71% moderate, 2% extensive and 1% collapse limit states may exceed at 10% probability of exceedance event. The detailed damage matrices for different probability of exceedance are shown in Tables 55-56.

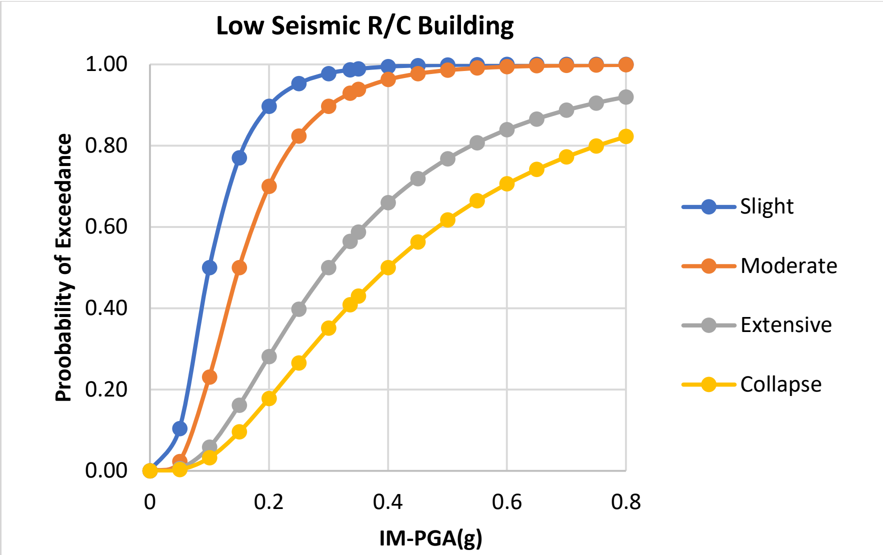


Figure 115: Fragility Functions for Low Seismic RC Building Pumping Stations

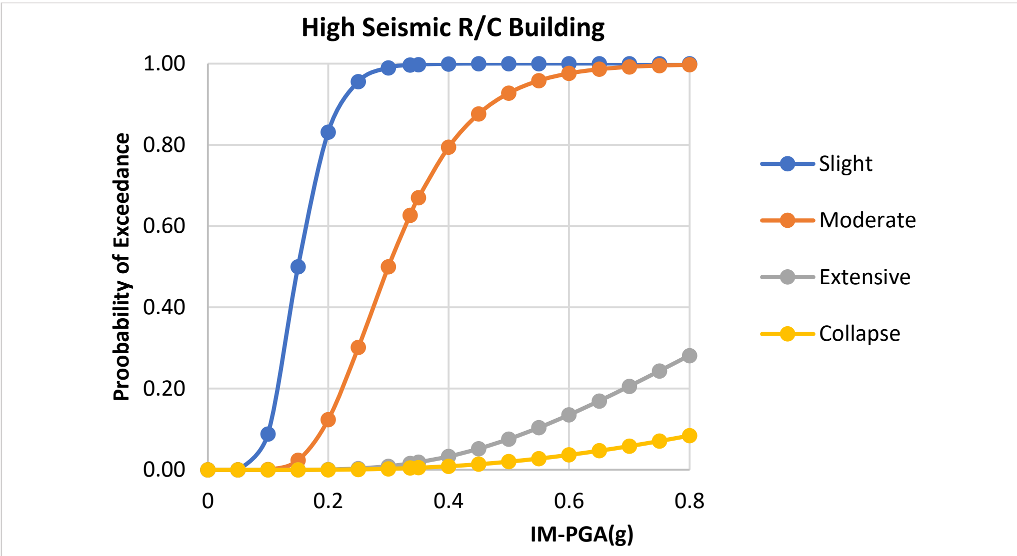


Figure 116: Fragility Functions for High Seismic RC Building Pumping Stations

Table 55: Damage Matrix for Low Seismic RC Building Pumping Stations

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 18 | 25 | 37 | 8 | 12 | 100 |
| **80** | 11 | 20 | 42 | 10 | 17 | 100 |
| **178** | 4 | 11 | 42 | 14 | 30 | 100 |
| **476** | 1 | 4 | 33 | 16 | 46 | 100 |
| **976** | 0 | 2 | 24 | 15 | 59 | 100 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **2475** | 0 | 0 | 14 | 13 | 72 | 100 |

Table 56: Damage Matrix for High Seismic RC Building Pumping Stations

| **Return Period** | **None** | **Slight** | **Moderate** | **Extensive** | **Collapse** | **Total** |
|---|---|---|---|---|---|---|
| **Years** | % | % | % | % | % | % |
| **53** | 37 | 59 | 5 | 0 | 0 | 100 |
| **80** | 18 | 70 | 11 | 0 | 0 | 100 |
| **178** | 3 | 59 | 38 | 0 | 0 | 100 |
| **476** | 0 | 26 | 71 | 2 | 1 | 100 |
| **976** | 0 | 10 | 84 | 5 | 2 | 100 |
| **2475** | 0 | 2 | 83 | 11 | 4 | 100 |

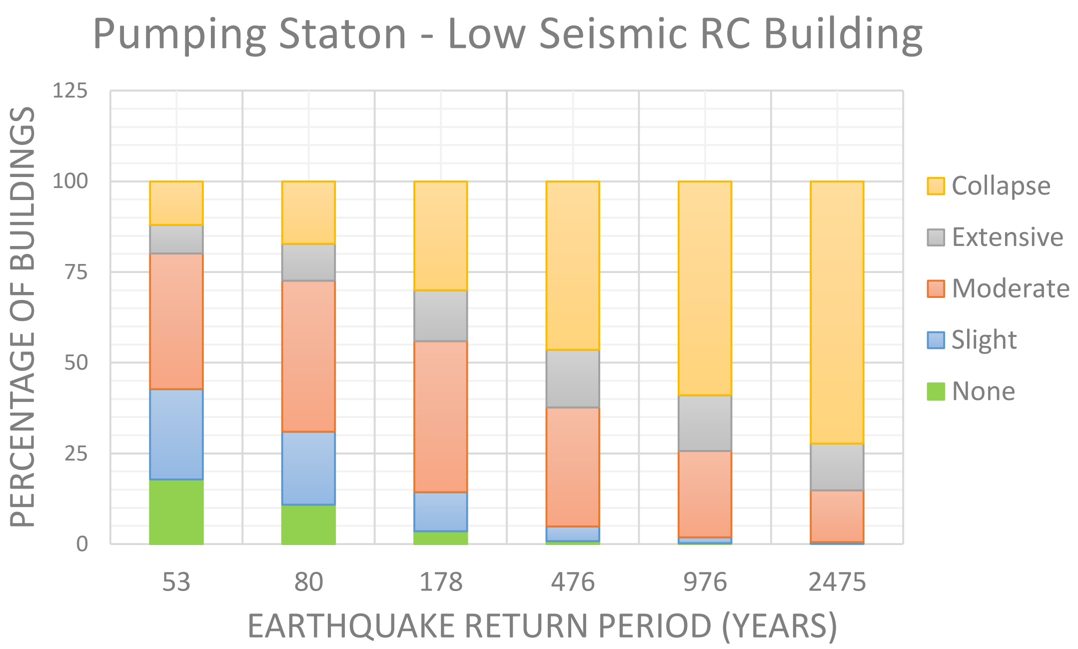


Figure 117: Damage Matrix for Low Seismic RC Building Pumping Stations

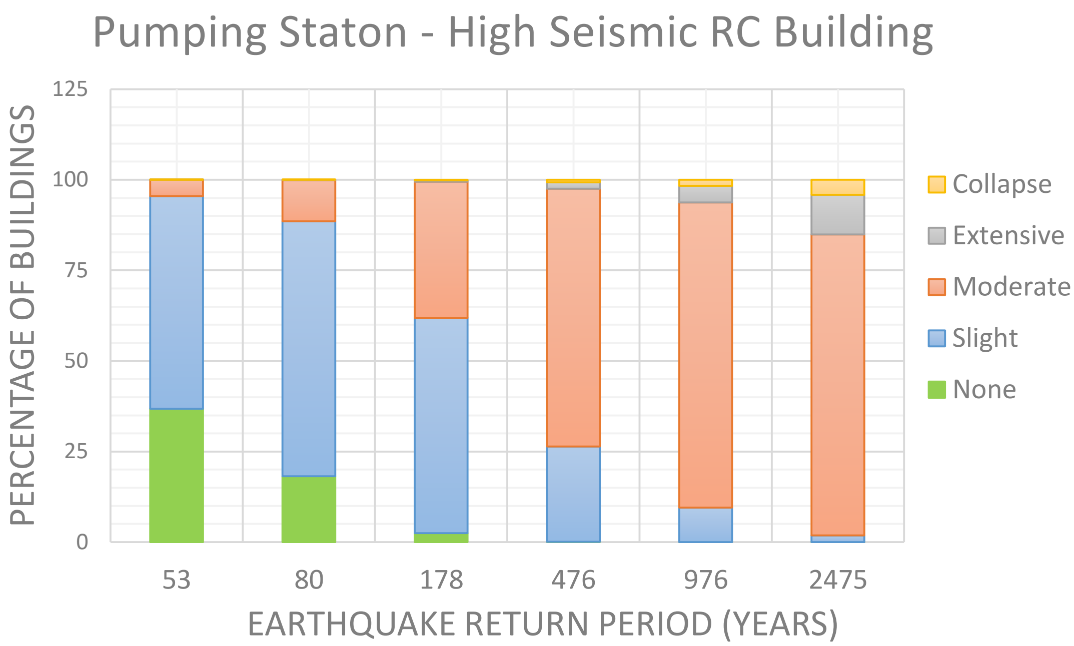


Figure 118: Damage Matrix for High Seismic RC Building Pumping Stations

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# Chapter 8 – Conclusions

This report present results of  direct physical damage assessment of built infrastructure in Karachi including buildings, bridges, electric power network system, harbour system, oil and gas system, telecommunication system, and water and waste water systems.

The work limited to the development of damage matrices considering probabilistic earthquakes to existing structures given knowledge of typologies, classification, and the ground motion intensity measure (i.e., peak ground acceleration-PGA). Damage states describing the level of damage to each of the existing structure classification are defined as minor, moderate, extensive and collapse. Fragility curves are developed for each classification based on empirical and analytical approaches. The work was mainly divided into four steps. In the first step, a detailed data collection rubric considering the scope of the project for considered inventory has been developed.  In the second step, GIS mapping has been done based on typology classification regarding variant existing structures. In the third step, intensity measure peak ground acceleration (PGA) has been extracted from the hazard analysis for different probability of exceedance having a specific return period. In the fourth and final step, the suitable fragility curves are identified from the literature and the corresponding damage matrices for different structures have been plotted.

Results show that 25% reinforced concrete buildings, 26% unreinforced concrete buildings, 44% bridges, 10% electric power network system, 5% oil and gas system, 3% telecommunication systems and 9% water and waste water systems are susceptible to collapse at 10% probability of exceedance earthquake in 50 years.

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