ASSESSING THE INTERDEPENDENCY BETWEEN CRITICAL INFRASTRUCTURES DURING SEISMIC INCIDENTS: A CASE STUDY FOR PADANG CITY

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UNIVERSITI SAINS MALAYSIA
2022

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By

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This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF ENGINEERING (HONS.)
(CIVIL ENGINEERING)

School of Civil Engineering
Universiti Sains Malaysia

August 2022

Appendix A8

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2021/2022

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: ASSESSING THE INTERDEPENDY BETWEEN CRITICAL INFRASTRUCTURS DURING SEISMIC INCIDENTS: A CASE STUDY FOR PADANG CITY

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ACKNOWLEDGEMENT

Praised to Allah The Almighty for making this final year research project entitled ”Assessing The Interdependency Between Critical Infrastructures During Seismic Incidents : A Case Stud For Padang City “ to be completed within the stipulated time.

First and foremost, I would like to express my upmost gratitude to my final year project supervisor, Assoc. Prof. Ir. Dr Fadzli Mohamed Nazri for his motivation, guidance and encouragement throughout the completion of this project. His advice and opinion have helped me a lot to finish this project successfully.

Next, I would like to express a thousand thanks to Mr. Ahmed Al Maissi, currently an active PhD student in Civil Engineering, for reviewing and giving a plethora of useful suggestions to improve my work.

My ultimate acknowledgement is dedicated to my parents; my father, Shubandrio bin Jarkasi and my mother, Napsiah binti Ismail for their endless support and prayer. I would also like to express my thanks to my dearest siblings for their moral support throughout my study and to my friends for providing positive peer pressure and motivating me to focus on hitting progress milestones. This entire study will be very difficult without their support on my back.

Finally, I hope that this dissertation will benefit and assist anyone who is interested in the field of structural especially, studying the critical infrastructures interdependence system during seismic incident. This research was supported by “Ministry of Higher Education Malaysia for Fundamental Research Grant Scheme with Project Code: FRGS/1/2020/TK02/USM/02/1.

ABSTRAK

Pada era moden kini, kebergantungan masyarakat kepada infrastruktur kritikal semakin meningkat. Gangguan terhadap infrastruktur disebabkan oleh fenomena gempa bumi akan mengakibatkan kerosakan dan kehilangan fungsi infrasturktur, dan hubungan saling kebergantungan infrastruktur antara satu sama lain, dapat merumitkan lagi isu ini disebabkan oleh kesan melata. Kajian penyelidikan ini dijalankan di bandar Padang, salah satu kawasan dimana bencana gempa bumi sering terjadi di Indonesia. Berdasarkan tinjauan literatur, kaedah penyelidik lepas yang sesuai akan digunakan untuk mengkaji saling kebergantungan antara infrastruktur kritikal dimana ianya belum pernah dilakukan di kawasan ini. Terdapat dua kaedah pengumpulan data iaitu tinjauan infrastruktur kritikal dan soal selidik dalam talian. Berdasarkan tinjauan kualitatif, kaedah taraf kefungsian digunakan untuk mendapatkan tahap kerosakan infastruktur. Hasilnya, tahap kerosakan menara dan pencawang telekomunikasi adalah "Tinggi" manakala bagi bekalan air dan bangunan adalah "Sederhana", dan untuk jalan raya adalah "Rendah". Berikutan itu, analisis risiko seismik telah dijalankan untuk menilai saling kebergantungan antara infrastruktur kritikal di mana keputusan yang dijangkakan adalah taraf kebergantungan antara infrastruktur kritikal. Keputusan menunjukkan taraf kebergantungan antara jalan dan hospital adalah "5-Penting", manakala antara jalan dan menara telekomunikasi adalah "3-Sederhana dan taraf kebergantungan "2-Kecil" diperoleh antara jalan dan balai bomba, balai polis, dan juga pencawang. Akhirnya, hasil daripada kajian ini boleh digunakan dalam reka bentuk, pemulihan dan perancangan pengurusan bencana untuk penilaian keselamatan infrastruktur kritikal. Dengan itu, daya tahan masyarakat dapat dipertingkatkan dan Matlamat Pembangunan Mampan (SDGs) 11: Bandar dan komuniti mampan terutamanya dalam mengurangkan bencana dan orang yang berada dalam situasi terdedah dapat dikecapi.

ABSTRACT

Our modern society is becoming increasingly reliant on the Critical Infrastructure (CIs) functionality. The disruption towards the infrastructure due to seismic incidents could result in significant damage and functionality loss, and together with the existing interdependency relationship with other infrastructures, complicate the issue further due to cascading effects. This research study was conducted in Padang city, one of the most disaster-prone area in Indonesia. Based on the literature review, a suitable method from past researcher is utilised for interdependency study between critical infrastructures which is yet to be done in the study area. There are two approaches used for data collection which is by surveying existing CIs using Google Earth and by an online questionnaire survey via Google Form. Based on the qualitative survey, a functionality rating method is done to obtain the level of damage occurred to the investigated CIs. From the result, damage level for telecommunication tower and substation are "High" while for water supply and buildings is "Moderate", and for roads is "Low". Following that, a seismic risk analysis was conducted to assess the interdependency between investigated critical infrastructures where dependency rating between critical infrastructures is assigned. The result shows that the dependency rating between road and hospital is "5-Essential", while between road and telecommunication tower is "3-Moderate. Lastly, the dependency rating of "2-Minor" is obtained between road and fire station, road and police station, and road and substation. Eventually, the results from this study could be used in design, restoration and disaster management planning for safety assessment of critical infrastructures, thus wider community resilience is improved which supports the Sustainable Development Goals (SDGs) 11: Sustainable cities and communities particularly in reducing disasters and people in vulnerable situation.

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CHAPTER 1

INTRODUCTION

1.1 Historical Background of Earthquake Incidents in Padang, Indonesia

Padang is the capital and largest city of West Sumatera, Indonesia with a population of approximately 900,000 people. The city is one of the disaster-prone areas in Indonesia due to its territory lies within one of the world's most active fault lines namely the "Ring of Fire" (Mulyani et al., 2015).

One of the major earthquake that effected Padang includes Mw 7.6 earthquake which occurred off the island of Sumatera, near the city of Padang on 30th September 2009. The epicentre of the earthquake was located about 57 kilometres west of the low-lying city of Padang and at a sea depth of 71kilometres (Wilkinson et al., 2009). According to the National Disaster Management Agency, the earthquake has resulted in 1117 deaths, 2902 injuries, and 186 people missing (BNPB, 2009). Building damage and human casualties are illustrated in Figure 1.1 for each of Padang's affected districts. Houses, schools, and hospitals were destroyed as pictured in Figures 1.2(a), 1.2(b), and 1.2(c), respectively.

Furthermore, the state and private hospitals, which should serve as a main hub for organising Padang's health disaster preparedness, have been seriously damaged. The area's electricity was also out, disrupting essential facilities like healthcare and communication. Transportation networks were also affected roadway blockage due to settlements and cracks (Refer Figure 1.2(d)). The losses of functionality for one infrastructure, together with the existing interdependencies relationship with other infrastructures, complicate the issue further due to the cascading effects (Laugé et al., 2013). As a result, society's welfare is severely harmed, making emergency response more difficult and increasing the overall effect of the hazards.

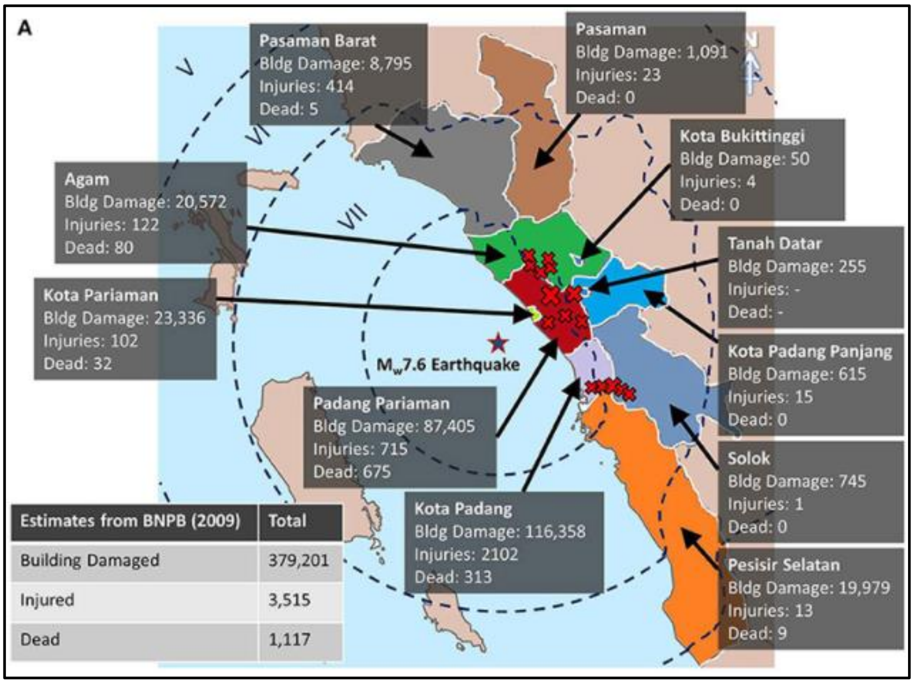

Figure 1.1: Distribution of losses in the district of Padang (Chian et al., 2019)

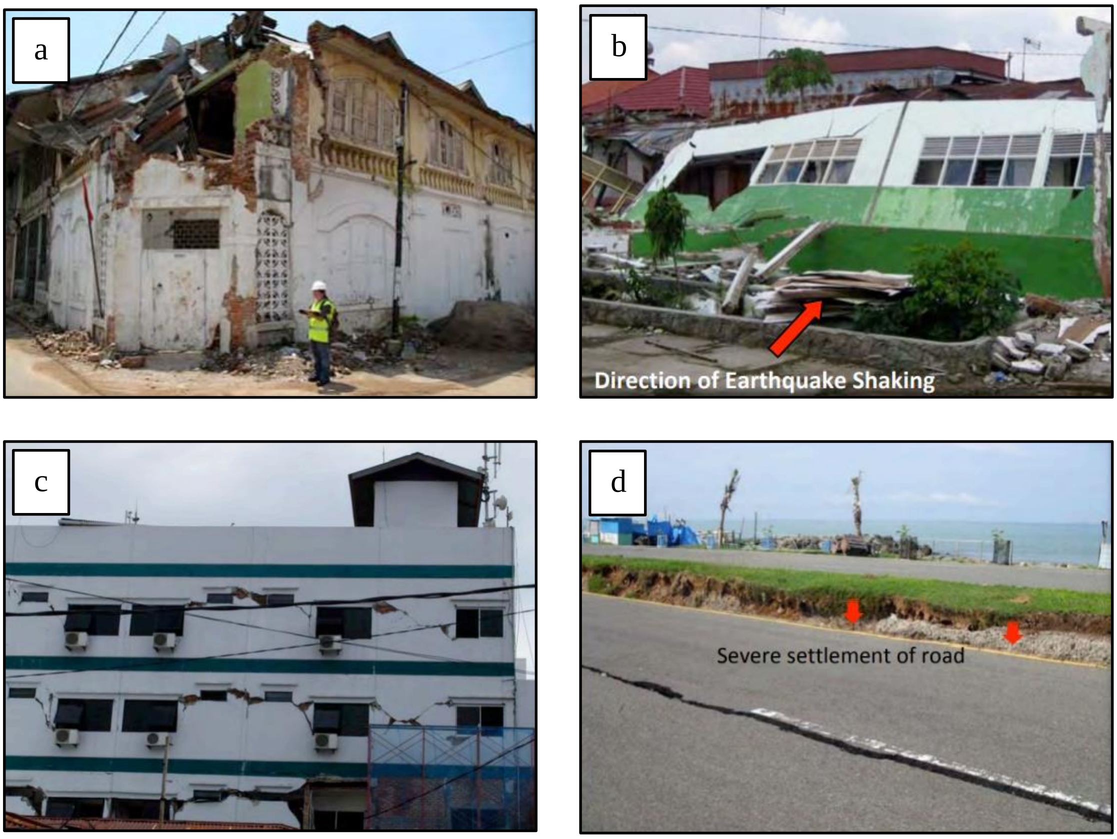

Figure 1.2: (a) Damaged house (b) Collapsed of school (c) Extensive cracks

(d) Settlement on the roadway (Wilkinson et al., 2009)

1.2 Critical Infrastructures and Their Interdependencies

Critical Infrastructures (CIs) comprise the essential services and facilities that communities depend on which includes utility services (i.e. water, wastewater, power, gas and telecommunications), transportation networks (i.e. roading, rail, ports and airports) and critical facilities i.e. hospitals, police, fire and ambulance stations, Emergency Operations Centres (Brunsdon, 2001). The recent natural disasters have significantly increased society's concern about CIs' vulnerabilities given that the welfare of society is dependent on CIs proper functioning (Laugé et al., 2013). Therefore, many countries focus greatly on pre-disaster emergency in which crisis management is developed in order to reduce the number of fatalities and injuries. Brunsdon (2001) highlighted an essential earthquake preparedness elements for critical infrastructure across the 4Rs of Emergency Management which are Reduction, Readiness, Response and Recovery. For instance, the critical facilities such as hospitals, civil defence and utility emergency operations centre must be situated in seismically robust buildings, with alternative locations to ensure these facilities are not affected from the events. Besides, Zhang et al. (2012) emphasize the importance of supportive medical forces as part of the rescue management plan to improve prognosis and reduce death and disability.

However, the complexity of CI systems and their interdependencies makes the crisis management more challenging because failures can spread from one to another, exacerbating and prolonging catastrophic effects. The term "Interdependency" refers to one infrastructure that has direct impact on the performance of another infrastructure system (Hughes et al., 2020). For example, Kobe Earthquake in 1995 have caused major building and highway collapsed and these impacts spread to the other infrastructure including electricity and telecom outage, gas and water line fracture, etc. and therefore disrupting society's welfare (Rahman, 2005).

In this research, a proposed approach to assess the interdependencies will be adopted where it links to a broader assessment of criticality and risk. As a result, risk mitigation strategies can be established and prioritised by identifying the critical infrastructure elements at high risk, based on the proposed risk assessment framework. Hence, by building the critical infrastructure management plans, the critical facilities especially hospitals and other emergency operations centre will not be severely affected and the allocation of supportive medical forces as rescue team can meet the demands in the most critical areas.

The Padang earthquake in 2009 had a devastating effect on many buildings and affected infrastructure and communities in the area. According to a field report by Earthquake Engineering Field Investigation Team (EEFIT), the critical infrastructure such as hospitals, lifelines, transportation networks and so on were all affected. Wilkinson et al. (2009) stated that immediately after the event, the main trunk for the central Padang region was severed resulting in total loss of 500 litre/second water supply. The distribution network was also affected as a result of pipe damage as well as local power loss, thus leaving the central region without water. Consequently, the hospitals experienced insufficient water for the patients and for critical hospital procedures. Meanwhile, the earthquake caused minor damage to Padang's transportation networks, with no vehicular bridges reported as unsafe for travel and only a few roads closed. However, in the Pariaman district, landslides and slope failure did cause interruption to roads and a pedestrian bridge, with a number of road networks becoming impassable (Wilkinson et al., 2009). As a result, it complicated rescue efforts and aided in delivery.

1.3 Problem Statement

As the frequency and severity of seismic events have grown in recent decades, so it has the likelihood that disruption in Critical Infrastructure (CIs) would result in a functionality losses of important services. The interdependency among critical infrastructures has exacerbated the risks and vulnerabilities due to the impacts can lead to cascading effects expanding across another critical infrastructure system. For instance, disruption of roadway during seismic incidents could affect other service or system such as transportation system, water supply system, telecommunication system, etc. Hence, crisis managers must comprehend the existing CIs interdependencies, analyse existing assessment tools, and identify current crisis management gaps to reduce the impacts resulted from the earthquake event.

The study about interdependency between Critical infrastructures is yet to be done within Padang city while only few studies focussing on Seismic Risk Analysis was done. There are several approaches and methods have been developed by past researchers but the method by Hughes et al. (2020) in particular, showed the most comprehensive aspects of seismic risk framework that highlighted both vulnerability assessment as well as interdependencies between CIs. However, the criticality of one infrastructure is determined based on the author’s judgment. Hence, the results' dependability is questionable since it is not based on experimental data but simply on expert judgement. Therefore, to address this gap in the literature, this research study assessed the interdependency between CIs by using the mentioned method but in different location which in Padang city. The judgement from the Padang community who have experienced the earthquake is collected to identify the criticality of infrastructure by conducting an online questionnaire survey.

1.4 Objectives

The objectives of this study are:

1. To evaluate the structure and infrastructures damage by conducting functionality rating method on the basis of qualitative survey.
2. To assign the interdependency rating between the investigated critical infrastructures.

1.5 Scope of Work

This study begins with desk study to survey the existing Critical Infrastructures (CIs) around the selected study area. Given this research study is a small scale project, hence the location of study area will be focussed on a small circular region in Padang city with a radius of 1 kilometres. Google Earth Pro is utilised to identify physical infrastructures for example hospital, fire station, substation, and other infrastructure that can be seen with eyes. Meanwhile, for buried infrastructure such as water pipe, sewerage, telecommunication cable, etc. are neglected since it is complicated to obtain corresponding information.

Besides, the screening work utilises online tool which is Google Form instead of traditional field survey due to the financial constraints and the location of study area is far away from researcher's place. The questionnaire survey intends to obtain judgement of Padang community in determining the criticality of investigated infrastructure, instead of utilising self-judgement by the researcher's experience as in the original approach. In the questionnaire, the infrastructures such as hospital, police station, fire station, substation and telecommunication tower are being rated by the respondents. As for road network, there is no consideration of traffic volume for determining its criticality, but it is based on the road hierarchy according to the Indonesian Public Work Department.

1.6 Dissertation Outline

The dissertation for this project consists of 5 chapters, namely Introduction, Literature Review, Methodology, Results and Discussion, and Conclusion. Chapter 1 of this dissertation provides an insight on the background of study, problem statements, objectives, scope of work as well as dissertation outline.

Chapter 2 is the literature review which discusses the related review or research articles done by previous researchers particularly on the approaches used in their respective Seismic Risk Analysis (SRA). Moreover, past seismic risk analysis related studies in the Padang city are compiled and reviewed to determine the research gap.

Chapter 3 is relating to the methodology of this study, which describes the overall flow method and approaches adopted to conduct this project. Firstly, the two stage of data collection which is existing critical infrastructures survey and online questionnaire survey is discussed accordingly. Next, the detailed steps of analysis stage for the functionality rating method and the physical interdependency assessment are presented.

Chapter 4 refers to the results and discussion of this study which covers the results obtained from the analyses. The results obtained are thoroughly discussed to identify important trends, patterns and reasoning behind this project.

Lastly, Chapter 5 concludes the overall achievement of this project regarding the initial targeted objectives. Suggestions and recommendations are provided as reference for those who wish to further improve this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, this research is broken down into several components while the findings and results generated by previous research related to the components are discussed. Firstly, Section 2.2 covers on the questionnaire survey and the method that is suitable to build this questionnaire. Next, an overview of the past researchers' approaches to model the Seismic Risk Assessment (SRA) framework reviewed in Section 2.3. Following that, Section 2.4 and 2.5 discussed about Criticality and Interdependencies studies towards Critical Infrastructures (CIs) respectively. Finally, Section 2.6 summarizes the SRA related studies done in the past few years that focus on this research subject which is assessing interdependencies between road network and Critical Infrastructures (CIs).

2.2 Questionnaire Design

A questionnaire is a research tool that consists of a series of questions that are used to gather data from respondents. These instruments use an interview-style structure and incorporate either written or oral questions. Questionnaires are popular research methodologies because they provide a quick, efficient, and low-cost way to collect huge amounts of data from big sample volumes (Young, 2015). Questionnaires can be administered online, over the phone, on paper, or in person. Researchers can acquire both qualitative and quantitative data by using open and closed research questions, resulting in more thorough results.

Firstly, quantitative survey is done to gather data that may be expressed numerically. It is frequently used by researchers to correlate data with particular demographics data like age, gender, and region, even though the survey population is relatively vast. For instance, Harnantyari et al. (2020) analyse the significance of the relationship between tsunami awareness and evacuation behaviour and the demographic characteristics of respondents, including gender, age and location. Paul et al. (2022) and Öztekin et al. (2016) conducted a similar quantitative survey to understand risk perceptions and preparedness about earthquakes. Dörnyei (2003) highlighted that there are three main types of closed questions used in quantitative survey which is Likert scales, semantic differential scales and numerical ratings scales. For instance, BPNP (2013) design the questionnaire mostly as Likert scale consist of a stimulus statement with each response option is given a numerical value (Strongly agree = 5, strongly disagree = 1), and binary question which has only two possible answer ("yes" or "no") .

Secondly, qualitative survey questions are designed to collect information that is difficult to quantify, such as attitudes, behaviours, and difficulties. They are frequently used to examine behavioural clues that could help guide the questions in an interview-style situation. Open-ended qualitative survey questions frequently concentrate on the "why" or "how" of a respondent's response and seek to elicit contextual information about specific sets of data. For example, Harnantyari et al. (2020) asked questions such as "How long does it take for you to arrive at the evacuation area?" and "What did you do when you knew about the tsunami attack?" to study the respondents' behaviour during tsunami event. Because qualitative survey questions are open-ended, it is possible to find solutions that might not have been offered in a conventional quantitative survey.

On top of that, the researcher may even choose to use both quantitative and qualitative methods in his or her research design, in a combined or mixed methods approach (Andrew and Halcomb 2009). For example, Alam (2016) used both quantitative (i.e. questionnaire survey) and qualitative (i.e. focus group discussions and informal interviews) data collection techniques to understand how local residents perceive and prepare for earthquake and tsunami in SE Bangladesh. Tagliacozzo (2018) adopted a mix of qualitative and quantitative methods (a survey and semi structured interviews) to gather insights from recovery agencies on the communications strategies and social media use after the Christchurch earthquake incidents.

2.2.1 Past questionnaire survey study

There are several past researchers conducted questionnaire survey in their study. Firstly, New et al. (2018) conducted questionnaire survey to calculate the seismic intensities of the affected areas in Myanmar. A modified questionnaire method using a fuzzy theory was used to estimate Medvedev–Sponheuer–Karnik (MSK) seismic intensity. This questionnaire was also used to confirm its validity by estimating the magnitude of the Kocaeli Earthquake on August 17, 1999. Ohta et al. (1979) devised the original approach for the Japan Meteorological Agency intensity scale, which was later extended by Murakami and Kagami (1991) to the Modified Mercalli intensity scale. This questionnaire-based method is widely utilised, particularly in rural areas where seismometers are poorly established (Fallahi et al, 2008; Murakami and Katta, 2001).

Besides, Ahmed & Zayed (2019) adopted questionnaire to assess the criticality of hospital building systems. A survey questionnaire was developed, and unstructured interviews were conducted to gather the opinions of experts in the field of hospital and building assets facility management. The survey comprises of the asset hierarchy proposed, the criticality assessment factors identified, as well as the relative weighting and rating of the different factors with regards to the varying hospital components.

Focussing the past studies in Padang, Putra et al (2017) conducted an interview-style structure where the resident received explanations for each item on the questionnaire from the interviewers, and answers were filled directly on the answer sheets. This survey produced a map of the shaking intensity and houses' vulnerability distribution in Padang. Apart from that, Fuady et al (2011) studied about Primary Health Centre disaster preparedness after the earthquake in Padang. Self-administered questionnaire, key informant interview, and direct observation were used to obtain the data on human resources, facilities preparedness, and the procedures.

Finally, National Agency for Disaster Management (BPNP) Indonesia conducted a pilot survey of knowledge, attitude and practice for disaster preparedness in Padang city. This survey is using interview-style questionnaire intended to assess people's knowledge, attitudes and capacities of communities residing at the coastal areas of Padang city for coping with the earthquake and tsunami disasters. The survey was designed for seven sections which are area/location, enumerator, list of household, information resources, knowledge and attitude to natural disaster, perception and knowledge on disaster mitigation, and economic and social status.

2.3 Seismic Risk Assessment (SRA) Framework

Seismic risk can be defined as the probability of losses occurring due to earthquakes within a given period of time including human lives, social and economic disruption as well as material damage (Wang, 2009). The seismic risk assessment can be expressed by three main qualitative expressions as illustrated in Figure 2.1, which are Hazard, Vulnerability and Exposure (Kamranzad et al., 2020; Hosseinpour et al., 2021).

RISK = HAZARD x EXPOSURE x VULNERABILITY

Figure 2.1: General SRA Framework

In brief, 'Hazard' is described as the potential of a natural hazard particularly earthquake to cause inflict damage and is characterized by its intensity or magnitude, location, frequency, and likelihood of occurrence. For example, Putra et al. (2012) assessed the hazard for Padang city based on the hazard curve at 10% probability of exceedance in 50 years, where the peak ground acceleration value is 0.7g. Similar study had also been done by Permana et al., (2018) hazard analysis in Northern Sumatra where the results show that the hazard for Padang city is 0.578g. Slightly difference of results were obtained due to different approaches adopted (i.e. numbers of data collected, formula, etc.) by each researcher. Nevertheless, according to National Disaster Management Agency, both findings classify earthquake threat in Padang city as moderate level since it is within 0.26g - 0.7g.

The term 'Exposure' indicates the number of people or assets which are exposed to hazard. Seismic exposure is examined in the context of human and physical exposures (Cutter et al. 2003; Birkmann 2013) in order to determine the population's most susceptible groups. (Morrow 1999; Cutter et al. 2003; Flanagan et al. 2011; Roncancio et al. 2020) discovered that age structure, gender, disability groups, family structure, and built environment are the most often cited features of human and physical exposures impacting social vulnerability. For example, Putra et al. (2014) assess the exposure toward non engineered houses based on the damage data of the 2009 Padang earthquake. Mulyani et al. (2015) studied the exposure towards different building categories commonly found in Padang. Rosyidi et al. (2011) has studied the exposure of road infrastructure and geo-failures during the earthquake event.

‘Vulnerability’ relates to the degree of loss to a specific element at risk (e.g., buildings, roadways, lifelines, etc.) in the case of an earthquake (Coburn and Spence 2002). Vulnerability functions is a key element in seismic risk assessment because they correlate a given level of seismic intensity to the likelihood of achieving or exceeding a particular level of damage (El-maissi et al., 2021). These can be used to estimate the degree of damage for a given asset type and the corresponding hazard intensity (i.e. peak ground acceleration). For instance, Hughes et al. (2020) determine the damage score based on the output of vulnerability functions which typically a damage percentage or probability of damage exceedance.

In previous studies, various methods and frameworks on seismic risk had been established, such as HAZards United States (HAZUS), the well-known methodology produced by Federal Emergency Management Agency (FEMA) in estimating seismic risk and potential loss based on extensive urban data of buildings, population, and economic activities (FEMA, 2021); Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters (RADIUS) which enables users to perform an aggregated loss estimation in terms of building and population vulnerabilities (Okazaki 2000); the Earthquake Disaster Risk Index (EDRI) model to measure the seismic risk by considering the seismic hazards and vulnerability (Davidson, 1997). Aside from the current models, several researchers have introduced approaches for measuring seismic risk from other perspectives, such as hazard factors, vulnerabilities (exposure, resilience, and coping ability) that might potentially contribute to seismic risk.

Kamranzad et al. (2020) incorporated the commonly practiced framework of Earthquake Risk Assessment (ERA) in his study to address the quantification of the present-day earthquake risk in Tehran in order to provide an insight into the status of relative risk between different districts and the possibility of relative comparison between them. On the other hand, Rini (2013) extended the existing ERA framework developed by Kythreoti (2002) and Khan (2011) by considering earthquake associated hazard particularly tsunami thus called Earthquake Tsunami Risk Assessment (ETRA) Framework. The extended framework is then adopted in multi-hazard risk assessment of buildings in Padang City, Indonesia. Moreover, Mili et al. (2017) has developed a holistic model assessing earthquake risk based on hazard, vulnerability and response capacity. The proposed model is adopted in two districts of Tehran, having different physical and socio-economic characteristics, to evaluate the safety level for earthquakes. Furthermore, Sauti et al. (2021b) proposed a holistic model composing three essential indicators which are exposure, resilience and capacity to conduct a GIS-based seismic risk assessment at a local district situated in Pahang, Malaysia.

As the focus of this research project is on physical infrastructure particularly on roadway and CIs, there are few related studies that have been conducted by past researchers related to this scope of study. Firstly, Hughes et al. (2020) proposed risk assessment framework component consisting of likelihood, vulnerability and consequences to assess interdependencies of transportation network in New Zealand. Sun et al. (2021) explored a new pathway towards seismic resilience of Road Networks (RNs) under earthquake hazards, by leveraging post-shock rapid responses as the key to minimize the functionality losses of RNs, especially in the immediate aftermath of earthquakes. Omar et al. (2021) analysed the physical seismic emergency response capacity in Dhaka, Bangladesh by developing five indicators and one of them is rescue and evacuation accessibility where the road network within the city is studied during seismic hazard.

2.4 Criticality/ Critical Infrastructures (CIs)

Critical assets are defined as those that ‘are especially significant to societal wellbeing and that therefore merit priority attention by utilities in emergency response and recovery’ (New Zealand Lifelines Council, 2017). On the other hand, critical infrastructures comprise the essential services and facilities on which communities depend (Brunsdon, 2001). These can be further subdivided into three categories: utility services (i.e., water, wastewater, power, gas, and telecommunications) ; transportation networks (i.e., roading, rail, ports, and airports) ; critical facilities (i.e., hospitals, police, fire and ambulance stations, emergency management Emergency Operations Centers). Given the focus of this study towards roadway, a transport route could be critical because it carries high volumes of traffic, or it could be the only access route to a hospital.

There are many experts expressed their interest in doing research on CIs that were subjected to seismic events for the past few years. For instance, Mualchin (2005) conducted seismic hazard analysis for CIs in California by implementing Deterministic Hazard Seismic Assessment (DSHA) method in order to assess effects from the largest single earthquake called Maximum Credible Earthquake (MCEs). Moreover, Mon et al. (2017) investigated the structural vulnerability of hospital buildings and facilities, to assess the performance of urban lifeline systems in Yangon, Myanmar. This is because medical facilities should be structurally resilient and also be functional for medical services by sustainable supply of urban lifeline systems (i.e., electric power, water , etc). Furthermore, a study by Baker (2007) about seismic vulnerability was conducted to assess interdependent CIs which are European gas and electricity transmission networks from a topological point of view, whereby the electricity network depends on the gas network through gas-fired power plants.

Focussing on the transportation network particularly roadway, a case study that has been conducted in Canadian University Campus by Ventura et al. (2008) where Seismic Risk Assessment (SRA) was used to evaluate damage of the CIs including buildings and lifeline systems such as water, roads, gas and electricity system. For instance, the electricity and road systems were assessed using the ATC-13 methodology and FEMA-224 and the results were mapped on a block by block basis using GIS software. Apart from that, Argyroudis et al. (2020) proposed a resilience assessment framework and then applied to critical highway assets such as bridges, tunnels, embankments, slopes or retaining walls, exposed to an earthquake events.

Moreover, Hughes et al. (2020) proposed a core module constitutes critical and interdependency assessment approach. Table 2.1 shows a regularly used criticality rating that provides enough resolution for the assessment. It also includes a proposed criticality rating with some sample descriptions for a national level evaluation (adapted from Hughes, 2016). These criticality descriptions might differ depending on whether the setting is local, regional, or national.

Table 2.1: Proposed criticality ratings, with descriptors for a national assessment (adapted from Hughes, 2016)

Colour	Category	Example description (national-level context)
1	Minimal	A local infrastructure element whose failure would have a minimal local economic or social impact.
2	Minor	A local infrastructure element whose failure would have a moderate to serious local economic or social impact, or it is a locally important lifeline, ensuring access or continuity of supply of essential services during an unforeseen event.
3	Moderate	An important infrastructure element whose failure would have a significant economic or social impact to a region, or it is a significant lifeline, ensuring access or continuity of supply of essential services during an unforeseen event.
4	Major	A major infrastructure element whose failure would have a significant economic or social impact to more than one region, or it is a regionally significant lifeline, ensuring access or continuity of supply of essential services during an unforeseen event.
5	Vital	A vital infrastructure element whose failure would have a nationally significant economic or social impact, or it is a nationally significant lifeline, ensuring access or continuity of supply of essential services during an unforeseen event.

On top of that, the proposed interdependency assessment approach by Hughes et al. (2020) suggests two forms of criticality:

i. Base criticality: This is an input that refers to the number of persons, users, or properties served by an infrastructure component.

ii. Modified criticality: This is an output that indicates the impact of interdependence on the base criticality of an upstream infrastructure or corridor.

2.5 Interdependencies study

The term “Interdependency” refers to a mutual link between two systems which is, a bidirectional relationship between two infrastructures through which the state of each one infrastructure influences or is correlated to the status of the other (Rinaldi et al., 2001). For instance, the reliance on power supply to operate traffic lights that control the operation of a road. The intricate linkages between multiple infrastructure systems are characterised by connection directionality and branching topologies, which frequently create a complicated web as illustrated in Figure 2.5.

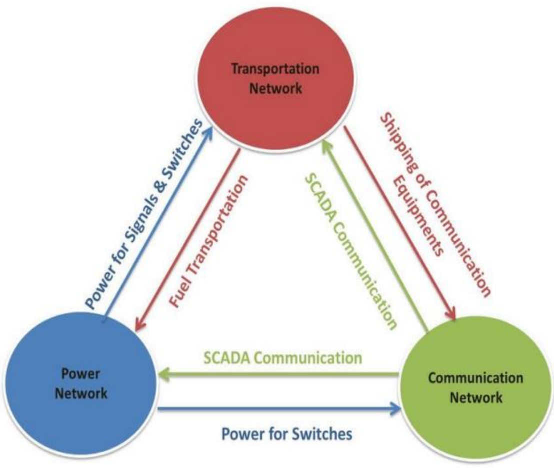

Figure 2.2: Example of the interdependencies within the transportation, power and communications network infrastructure (Hughes et al., 2020)

Critical infrastructures interact at different levels, and a failure in one type of infrastructure may impact the functionality of others. It is thus becoming increasingly important to take these interdependencies into account when assessing the vulnerability of critical infrastructure. If the vulnerabilities in infrastructures are exploited, they could be disrupted or disabled, possibly causing severe consequences such as a loss of life, economic losses, and even damages to national security. In critical infrastructure protection, interdependency within a critical infrastructure is of major concern to government as safety and security measures in order to reduce the risks of failure. In response, an increasing amount of studies are being conducted to understand the nature of critical infrastructure interdependency.

Syed et al. (2018) proposed an integrated simulation framework that models dependencies of electricity system on the road network. The framework uses a damage map of electricity network components and integrates them with road access time to these damaged components for estimating the electricity outage time of a region. The outcome of this study can be used for recovery planning, identification of vulnerabilities, and adding redundancies in an infrastructure network.

Ventura et al. (2008) produced interdependencies mapping between critical infrastructures through intergrated hazard analysis located in canadian university campus. The complex system of interdependencies among critical infrastructure has heightened the risks and vulnerabilities for Canada, and for other countries. Hence, the ultimate goal of this research is to develop a methodology that helps strengthening the resiliency of critical infrastructure. The interdependency among CIs particularly (roads-buildings) and (water system-buildings) were assessed and the results are presented in a map.

Kilaniti and Sextos (2019) established a holistic framework for the multi-criterion assessment and management of the seismic risk and resilience of roadway networks. Different sources of uncertainty that contribute to the overall network seismic risk, namely, hazard and vulnerability, coupled with consequences analysis are accounted for and integral aspects of resilience such as network functionality and post-earthquake time-dimension are integrated into the overall process. The proposed framework is implemented into a GIS-based software and constitutes a useful decision-making tool for the stakeholders, to quantify and improve the resilience of their roadway network.

Hughes et al. (2020) proposed an approach for assessing interdependencies that aligns with the literature review and addressed the gaps within the existing tools and platforms. It is found that each of the models had a different purpose, associated strengths, and weaknesses, and none of the tools adequately addressed all the key interdependency typologies identified, nor did they evaluate interdependencies incorporating criteria such as strength. According to the Institution of Civil Engineers (ICE, 2013) there are four distinct typologies which are physical, digital, geographic, and organisational. Meanwhile, the strength can be categorised based on level of impact to a dependent infrastructure caused by the failure of an upstream dependency (AECOM, 2017; New Zealand Lifelines Council, 2017).

Table 2.2: Strength rating adopted by Hughes et al. (2020)

Strength rating	Strength descriptor
Low	Minimal requirement to maintain functionality/full level of service during business as usual and post-event.
Moderate	Minimal requirement to maintain functionality/full level of service during business as usual BUT important in maintaining at least a partial level of service post-event.
High	Required for 100% of level of service during business as usual and post-event.

2.6 Summary

2.6.1 Seismic risk Assessment Case Study

Seismic risk assessment (SRA) is the evaluation of current seismic risk i.e. looking at the existing building stock and exposure under a given hazard and evaluating potential losses. Hence it is composed of three main parts: (1) Seismic Hazard Assessment ; (2) Seismic Vulnerability Assessment ; (3) Exposure Assessment. As the frequency and severity of seismic events have grown in recent decades, many researcher addressed this issue in their study as listed in Table 2.3.

Table 2.3: SRA case study conducted around the globe

Author	Research Description
(Sauti et al., 2021)	SRA based on exposure, resilience, and capacity indicators to seismic hazard at a local district situated in Pahang, Malaysia.
(Sun et al., 2021)	Explored a new pathway towards seismic resilience of Road Networks (RNs) under earthquake hazards in Luchon, France.
(Omar et al., 2021)	Analysed the physical seismic emergency response capacity in Dhaka, Bangladesh and shows areas that lack emergency seismic response capacity that need mitigation measures.
(Pavel et al., 2021)	SRA of lifelines system (water, sewage, gas and electricity) in Bucharest, the capital city of Romania is performed.
(Altindal et al., 2021)	SRA for an old urban centre in Beyoglu, Istanbul by using site-specific probabilistic hazard and vulnerability data.
(Kamranzad et al., 2020)	Earthquake Risk Assessment (ERA) for Tehran is performed in order to provide an insight into the status of relative risk between different districts in Tehran based on hazard, vulnerability and exposure

(Hughes et al., 2020)	SRA framework component consisting of likelihood, vulnerability and consequences to assess interdependencies of transportation network in New Zealand.
(Oreta, 2017)	SRA framework includes a checklist that assesses qualitatively the school building's assets, seismic hazards and vulnerabilities to the various hazards
(Mili et al., 2017)	ERA for assessing earthquake risk and determining priorities for risk reduction and management in urban zone of Tehran based on hazard, vulnerability and response capacity.
(Goda et al., 2016)	SRA for Malawi, Indonesia based on a generic concept of risk and is comprised of three main elements, i.e., exposure, hazard, and vulnerability.
(Lin et al., 2012)	NEES Integrated Seismic Risk Assessment Framework (NISRAF) framework for assessment of the impact of earthquakes on civil infrastructure systems, particularly buildings and bridges in California.

After all, there are many studies have been carried out related to seismic risk assessment and various approaches and framework have been developed. However, the method by (Hughes et al., 2020) in New Zealand showed the simplest approaches and most comprehensive aspects of seismic risk framework that highlighted both vulnerability assessment as well as interdependencies between CIs, which aligned with scope of this research study. Therefore, this research project will assess the vulnerability of critical infrastructures in the city of Padang based on the developed approach which details of this method are explained in the following chapter.

2.6.2 Seismic Risk Assessment study in Padang City

The selected study area for this research study is located in Padang city, Indonesia. Therefore, past studies on SRA are needed to be reviewed in order to identify the research gap for this study area. Table 2.4 shows several studies had been done by past researcher focussing on Padang city.

Table 2.4: SRA conducted in Padang city

Author	**Research Description**
(Mulyani et al., 2015)	Earth Tsunami Risk Assessment (ETRA) for different building categories in Padang city, Indonesia.
(Putra et al., 2014)	Assess the exposure toward non engineered houses based on the damage data of the 2009 Padang earthquake.
(Kusumastuti et al., 2014)	Developed and implemented a framework to assess the resilience in Cilacap region and Padang city, Indonesia.
(Husrin et al., 2013)	Conducted a study focussing on Critical infrastructures in the City of Padang by Tsunami Vulnerability assessment.
(Rosyidi et al., 2011)	Investigated the exposure of road infrastructure and geofailures, (i.e., settlement of roads and bridges and slope failure) during the earthquake event in Padang.

Based on the review through previous related studies done in Padang city, there is only few studies focussing on seismic risk assessment. In fact, study about interdependency between Critical infrastructures is yet to be done within this area. Therefore, to address this gap in the literature, this research study assessed the interdependency of critical infrastructures between transportation network (roadway) and critical facilities (hospitals, police, fire and ambulance stations, etc.). The purpose is to provide a quantitative tool for the government to decide if, and how much, remedial work is required in a particular district (Coskun et al., 2020). The results are presented through GIS mapping method, hence allow further assessment to be done in the future based on the outcome of this project.

2.6.3 Interdependency case study

In response to the significant damage and loss of functionality of infrastructure during seismic event, there are many efforts are currently being devoted to developing models and methods capable of analyzing the interdependency of critical infrastructure systems. Therefore, the new method by past researcher shall be reviewed in order to identify the most suitable method to be adopted with the selected study area Table 2.5.

Table 2.5: Interdependency study by past researchers

Author	**Research Description**
(Hassan & Mahmoud, 2020)	Proposes new framework accounting the independence between all relevant infrastructure for estimating full functionality and recovery of healthcare systems in a community following earthquake occurrence.
(Hughes et al., 2020)	Proposes a new framework component consisting of likelihood, vulnerability and consequences to assess interdependencies of transportation network in New Zealand.
(Cardoni et al., 2020)	Study the effects of a seismic event on a large-scale virtual city, implicitly modeling the interdependency between the buildings and the electric distribution network.
(Omidvar et al., 2014)	Demonstrate the power and water infrastructure interdependency by using the extended Petri net and Markov chain with a case study of one of the municipal districts of metropolitan Tehran, the capital of Iran.
(Huang et al., 2014)	Proposes a new method addressing interdependency and the feedback effects between different types of critical infrastructures by using a hybrid model.

Based on literature of interdependency studies, the method by (Hughes et al., 2020) showed the simplest approaches and most comprehensive aspects of the seismic risk framework that highlighted both vulnerability assessment as well as interdependencies between CIs, which aligned with the scope of this research study. In comparison of other methods, Hughes et al. (2020) focus the interdependency between transportation networks and other critical infrastructures. Meanwhile, the remaining studies focus up to two critical infrastructures only in assessing the interdependence behaviour such as relevant infrastructure in healthcare system (Hassan and Mahmoud 2020), between buildings and electric distribution network (Cardoni et al. 2020), and between power and water infrastructure (Omidvar et al., 2014).

In all of the studies, they highlighted that the investigation of the interdependencies among different critical infrastructures is fundamental to prevent possible cascading effects and frequent functionality loss. The cascading effect implies that the interdependency between the infrastructures can cause failure to spread from one to another, thus exacerbating and prolonging catastrophic effects. For example, outages in power systems caused the failures of traffic signals, water supply pumping stations and automated teller machines, as well as the closure of businesses (Ouyang, 2014).

Hence, the urge to provide a practical and transparent method is increasing in recent decades for infrastructure providers to understand and manage their critical infrastructure networks better with regard to the hazards they face and the failures that may occur, not only from their respective service but from other dependent infrastructures too. Subsequently, it helps the disaster management team in decision making for instance it could be used in design, restoration and disaster management planning for safety assessment of critical infrastructures.