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Earthquake Disaster Mitigation Strategy: Lessons Learned from Indonesia

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Abstract

Purpose: Determining the mitigation strategy for earthquake-induced disaster. The primary objective of this review is to distill valuable lessons than can help minimize the tragic consequences of earthquake-induced disasters.
Methodology: This study comprises a meta-ethnography analysis drawing from various scientific manuscripts, online news sources, and Youtube channels. The manuscript scrutinizes five profoundly impactful earthquakes in Indonesia, specifically: Aceh earthquake, Padang earthquake, Yogyakarta earthquake, Palu earthquake, and Banten Earthquake
Results: The proposed strategies outlined in this manuscript encompass the establishment of early warning systems for disaster preparedness, the implementation of urban planning for disaster-resilience, the identification of seismic hazard zone in densely populated areas, the enhancement of disaster education, and the promoting of earthquake-resistance construction practices.
Applications/Originality/Value: The strategy for mitigating earthquake-induced disaster should follow the characteristics of disaster in the specific area. Understanding previous history of earthquake is prominent to determining the earthquake-induced disaster mitigation strategy.

Introduction Section

Uncovering earthquake prediction models remains a challenge (Mogi, 1967). This is why the occurrence of earthquakes has led to significant disasters. Earthquake-induced disasters have caused significant devastation on a global scale. In some cases, these seismic events have been followed by additional catastrophes, such as tsunamis, landslides , and liquefaction (Gusmian, 2019). The Aleutian tsunami of 1946, triggered by a 7.4 magnitude earthquake, stands as one of the deadliest tsunamis in the U.S (Okal, 2011). The Valdivia earthquake, registering at a magnitude 9.5 (Cisternas et al., 2005) struck on 22 May, 1960, at 19.11 UT in South Chile (Johnston et al., 2008) devastating earthquake generated a tsunami that claimed the lives of two to five thousand people and resulted in an economic loss of approximately US$ 500 to 800 million (Daniell et al., 2017). In 1964, a 9.2 magnitude Alaska earthquake struck Alaska, inducing landslides and triggering a tsunami (Parsons et al., 2014). The affected areas included Alaska, the west coast of the United States, Hawaii, and Japan, resulting in the loss of 136 lives (Daniell et al., 2017). The magnitude of 9.0 Tohoku earthquake in 2011 remains one of the most significant earthquake worldwide, with a death toll exceeding 15 thousand people (Farrell et al., 2015).

Understanding the cause of earthquake is essential for determining effective mitigation strategies to reduce the impact of such disasters. There are three primary causes of earthquakes: tectonic earthquakes resulting from the movement of earth's lithospheric, volcanic earthquake triggered by volcanic eruption, and earthquakes caused by the collapse of rock formations. Notably, tectonic activity, in certain instances, precede volcanic activity or volcanic eruptions potentially inducing tectonic events (Eggert & Walter, 2009). Moreover, aftershock typically follow main earthquakes, a phenomenon commonly associated with tectonic earthquake and (Mogi, 1967) and the accurate prediction of such events remains a challenging task.

Indonesia, located within the Pacific Ring of Fire, is a convergence point of four major tectonic plates (Siagian et al., 2014). This country is home to 127 active volcanoes, it's the eruptions of which can trigger earthquakes. Indonesia has witnessed several significant seismic event such as Aceh earthquake, Padang earthquake, Yogyakarta earthquake, Palu earthquake, and Banten earthquake which have resulted in physical destruction, loss of human life, and environmental degradation. Earthquake have caused destruction to buildings, roads, bridges, and other vital infrastructure (Gusmian, 2019).

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The significant impact of the earthquakes in Indonesia can be attributed to three major factors: high population density, geographical position, and the lack of infrastructure quality. Therefore, it is crucial to determine strategies for mitigation to reduce human fatalities, physical and environmental damage, as well as economic losses.

Indonesia has taken proactive steps in earthquake mitigation, such as promoting the construction of earthquake-resistant building within the community and enhancing community awareness and education about the importance of earthquake mitigation. Moreover, Indonesia has established the Earthquake Warning Alert System (EWAS) as an early warning mechanism for earthquakes. Additionally, the BMKG has integrated Internet of Things (IoT) technology for facilitate the online sharing of earthquake-related information. Despite these efforts, some of these systems have faced operational challenges.

Based on the aforementioned explanation, it is imperative to develop a strategy to mitigate the impact of earthquake related-disasters in Indonesia. This paper undertakes a comprehensive review of various literature sources relating to the occurrence of earthquakes in Indonesia, which have resulted in significant damage both the human and natural environment, thereby impacting social and economic development.

Research method

This study applies a meta-ethnography approach, involving the researcher's interpretative synthesis of qualitative research and other secondary sources (Noblit, 2018). This methods allows for the synthesis and analysis of information from previous phenomena studied (Bryman, 2012).

This study adopts a methodology in line with the approach outlined by Noblit and Hare (1988), as framework that has been previously utilized by researchers such as Siau and Long (2005), von Seggern (2021), among others. The meta-ethnography process involves seven key steps: initiating the study, defining the initial scope of relevance, reviewing the relevant literature, determining the connections between studies, translating these findings into a cohesive framework, synthesizing these translations, and ultimately articulating the resulting synthesis.

This study is an investigation of earthquake-induced disaster, focusing on a comprehensive review of literature sources. The literature has been sourced from from various sources of search engine, including Google, Scholar Google, Youtube. The keywords selected for literature search are specifically tied to five major earthquake-induced disasters in Indonesia. These include the Aceh earthquake in 2004, the Padang earthquake in 2006, the Yogyakarta earthquake in 2007, the Palu earthquake in 2018, and the Banten earthquake in 2019. The designated keywords are as follows: "gempa Padang 2009", "mitigasi gempa Padang", 'kronologi gempa Padang"," gempa Padang September 2009", " kelemahan kelebihan gempa padang","gempa Krakatau" , "Penyebab gempa Krakatau", "Dampak gempa Krakatau", "Titik koordinat gempa krakatau". "Gempa Aceh 2004", "Dampak gempa Aceh 2004", "penyebab gempa Aceh 2004", "Indian ocean tsunami 2004", "Gempa bumi Sumatra - Andaman", "jurnal Gempa Jogja 2006", "gempa Jogja 2023", "gempa Jogja 2006", "Kerugian akibat gempa Jogja", "dampak gempa di Jogja", "Gempa bumi Palu 2018", "lokasi pusat gempa bumi Palu", "upaya mitigasi gempa bumi Palu", "likuifaksi gempa bumi Palu", "mitigation strategy for earthquake ". Through an extensive literature search, a total of 26 scientific journals, 30 online news, and 5 Youtube channels have been reviewed. The detail number of literature sources reviewed in this research is presented in Table 1.

Table 1. Number of literatures reviewed

Sources	Number
Jurnal	6 (Banten), 5 (Padang), 4 (Aceh), 6 (Yogyakarta), 5 (Palu)
Online News	2 (Banten), 3 (Padang), 9 (Aceh), 9 (Yogyakarta), 7 (Palu)
Youtube	1 (Banten), 1 (Padang), 3 (Yogyakarta)

Through the literature review process focused on earthquake-induced disaster in Indonesia, we have essential information relating to the earthquake's location, its underlying causes, the resulting impact on both individuals and society, as well as the measures undertaken for mitigation and the challenges faced during their implementation. Subsequently, we have formulated recommendations for a comprehensive mitigation strategy. These recommendations draw from the insights of previous case studies within Indonesia and are enriched by insights gained from earthquake-induced disasters worldwide.

Results

Earthquakes in Indonesia

Padang Earthquake

The Padang earthquake occurred on September, 30, 2009 at 17:16:10 WIB (BPBD Kota Padang, 2019). There are four arguments regarding the location and magnitude of Padang earthquake (Setyonegoro, 2013). Table 1 shows the institutions that monitor the locations and magnitudes of earthquakes. These four institutions include the Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), a national institution in Indonesia; the United States Geological Survey (USGS), a U.S.-based national institution; the Deutsches GeoForschungsZentrum (GFZ), a German Research Centre for Geosciences; and the Japan Meteorological Agency (JMA).

Table 2. The location of Padang earthquake

Institutions	Location	Distance from the epicentral (km)	Earthquake magnitude (Ritcher)
BMKG	0.84° S – 99.65° E	71	7.6
USGS	0.79° S – 99.96° E	80	7.6
GFZ	0.80° S – 99.87° E	84	7.8
JMA	0.79° S – 99.99° E	-	7.7

Another argument shows that the epicenter was located 60 km to the west-north-west of Padang, with a focal depth of 81 km (Bothara et al., 2010). This earthquake's epicentre did not align with the subduction zone of the Indo-Australian Plate beneath the Eurasian plate (Grundy, 2010). This earthquake did not trigger a tsunami. West Sumatera positioned within the subduction zone between Eurasian Plate and Indian Ocean Plate, along with the presence of the Sumatera Fault Zone and the Mentawai Fault Zone, characterizes the western region of Sumatra as an area situated on the periphery of active tectonic plates (Setyonegoro, 2013). In 1779 and 1833, this regions also experienced severe earthquakes with magnitudes of 8.7 Ritcher scale and 8.8 Ritcher scale accompanied by tsunamis reaching heights of 5-10 meters (Bothara et al., 2010).

The impact of the Padang earthquake extended far beyond the local residents of Padang Pariaman, reaching as far as the offshore Mentawai Islands to the west and the inland regions of Sumatera, (Pekanbaru) to the east. The seismic event resulted in a range of social and environmental consequences. The toll of casualties from this earthquake was significant, with a minimum of 1.117 fatalities, 1.214 people injured, 181.665 buildings destroyed, and an estimated 451.000 individual displaced within the Padang-Pariaman area (Setyonegoro, 2013). The high casualty rate can be attributed to the densely populated coastal regions of Padang. Urban growth in Padang has driven the expansion of communities in to low-lying coastal zones, which were formerly marshlands. The soil composition in this area is soft and fragile, comprised of sand, silt, and mud. The large population residing in this coastal regions with vulnerable soil condition significantly contributed to the extensive structural damage (Bothara et al., 2010).

This earthquake also had a significant impact on building damage; even newer structures made of concrete or steel experienced substantial destruction. The seismic event also triggered landslides, burying several villages and causing the loss of over 600 lives. The earthquake also led to phenomena such as liquefaction and lateral spreading (Bothara et al., 2010). Liquefaction occurred in areas several kilometers from the coast following the earthquake (Tohari et al., 2011). In Padang, liquefaction occurred in various locations, including roads, riverbanks, sports fields, and playgrounds (Hakam, 2012).

Banten Earthquake

The Banten Earthquake occurred on January 23, 2018, with a magnitude of 6.1 on the Richter scale. The epicenter of this earthquake was located at 7.23° S; 105.90° E (BMKG), 43 kilometers from the Lebak Regency, Banten. The earthquake was not followed by a tsunami. It was felt across almost the entire Banten region and the West Java Province (Julius et al., 2021). This seismic activity was caused by the activity in the Sunda Strait-Banten segment, which is one of the subduction zones in the southern part of Java Island (Febriani et al., 2021).

In the Banten region, this earthquake event resulted in damage to a total of 1,231 buildings, comprising 1,125 lightly damaged and 106 severely damaged structures. The damage occurred in 16 districts located in the southern coastal areas of Banten. The damage was due to the inability of the buildings to withstand the earthquake's shaking and poor building quality (Hiola et al., 2018). When considering the three affected provinces (West Java, Banten, and DKI Jakarta), the number of damaged buildings reached 8,467 units spread across 73 districts. The most significant damage to houses occurred in the Lebak Regency and Sukabumi Regency (Setiadi et al., 2020).

Aceh earthquake

The Aceh earthquake occurred on December 26, 2004, off the west coast of Sumatra with a magnitude of 9.3 on the Richter scale, accompanied by a tsunami. This tectonic earthquake in Aceh was caused by the Indo-Australian plate moving northward and subducting beneath the Eurasian continental plate. The epicenter of the earthquake was situated approximately 155 km off the northwestern coast of Sumatra, Indonesia, and about 255 km southeast of Banda Aceh, at a depth of 30 km. The earthquake in Aceh is the second-largest earthquake in the world after the 9.5 Richter scale earthquake in Chile (Ghobarah et al., 2006).

The Aceh earthquake resulted in a loss of life totaling no less than 300,000 people. This event led to extensive damage, both physical and non-physical. The physical aspect encompassed the destruction of infrastructure, including residential and office buildings, as well as economic centers. The non-physical aspect involved issues related to health, psychology, and education (Tejakusuma, 2005). The physical damage to buildings occurred due to several factors, including inadequate construction quality, unreinforced masonry, and weak foundations (Ghobarah et al., 2006).

The earthquake causes the uplift and subsidence of the island surfaces. This event affects the dynamics of coral reef ecosystems, resulting in widespread coral death and the relocation of coral species from one place to another (Hagan et al., 2007).

Palu earthquake

Palu is the capital city of South Sulawesi which is situated at 0°,36”-0°,56”S and 119°,45” – 121°,1”E. Geographically, Palu contains of mountains, valleys, rivers, gulfs, and sea sides.

Friday 28 September 2018 at 17.02 WIB, 7.4 Ritcher magnitude earthquake shaked Palu and Donggala, South Sulawesi. The epicenter of the seismic was 0.18°S and 119.85°E 26 km from South Donggala in the depth of 10 km. The earthquake shakes many cities including Donggala, Palu, Gorontalo, Poso, Majene, Soroako, Kendari, Kolaka, Konawe Utara, Bone, Sengkang, Makassar, Gowa, Toraja, North and East Kalimantan (BMKG, 2018). Soon after, the early warning for tsunami alarmed by BMKG. But, at 17.37 WIB the alarmed was stopped. Unfortunately, later on, tsunami swap Palu bay. The height of tsunami from 2.2 – 11.1 meter.

The Palu earthquake was caused by tectonic activity, strike-slip fault movement of Palu-Koro Fault System (Bradley et al., 2019), which is located between the Australian Plate and the Eurasian Plate. This earthquake triggered the marine sediment landslide in the depth of 200-300 of Palu bay. Unfortunately, this landslide caused tsunami in Palu Bay. Moreover, the landslide-induced earthquake causes liquefaction of granular materials, which is a process that decreases shear strength and eases downhill movement, even on gradual inclines (Watkinson & Hall, 2019). The most significant flow slides was occurred in Petobo, Jono Oge, and Lolu village community which is clustered within alluvial sediment of the Palu River Valley (Mason et al., 2021).

Earthquake in Palu killed more than 4000 inhabitants, more than 4000 people injuries, 667 missing people, destroyed 68 thousand of building, and loss of economic approximately UD$ 11 million (Mason et al., 2021). Landslide in the Palu valley was responsible to the most fatalities (Bradley et al., 2019).

Yogyakarta earthquake

The Yogyakarta Earthquake occurred on May 27, 2006, at 05:55 AM local time, with a magnitude of 5.9 on the Richter scale. This tectonic earthquake shook the Yogyakarta region and parts of Central Java. The epicenter of the earthquake was located beneath the sea at a depth of 130 meters, 37 kilometers south of Yogyakarta, resulting from the collision of the Indo-Australian and Eurasian tectonic plates (Masykur, 2006). The areas most affected by the earthquake were Bantuk, Yogyakarta, and Klaten in Central Java. The high level of damage was primarily attributed to the high population density in the affected areas (Elnashai et al., 2007).

The earthquake resulted in significant human casualties, with 6,000 reported fatalities, 50,000 injuries, 600,000 people displaced, and over 127,000 houses damaged Other sources mention that the earthquake caused more than 5,700 fatalities, over 37,000 injuries, and the total destruction of more than 156,000 houses and other buildings (Elnashai et al., 2007).

Furthermore, the earthquake had a significant impact on the damage to educational buildings. In Yogyakarta, 2,155 educational facilities suffered severe damage or total collapse. In Bantul Regency, 949 or 90% of educational buildings were damaged. In Central Java, 752 educational buildings were damaged or destroyed. Klaten Regency had the highest level of damage in Central Java, with 64 buildings destroyed and 257 buildings severely damaged, which accounted for 38% of all buildings in the area. Public infrastructure, such as government offices and bridges, also experienced damage (Elnashai et al., 2007).

The earthquake had various emotional, physical, and cognitive impacts. In terms of emotional effects, individuals displayed behaviors such as shock, anger, sadness, numbness, profound grief, oversensitivity, dissociation, and a sense of helplessness in the face of the disaster. Physical impacts included injuries and wounds caused by the earthquake, broken bones, bruises from falling debris, physical exhaustion, difficulty sleeping, headaches, and a weakened immune system, making victims more susceptible to illness. In terms of cognitive impacts, survivors experienced difficulties in concentration, decision-making, memory function disruptions, and often lost their rationality in their actions(Masykur, 2006).

Proposed mitigation strategy for earthquake disaster

The earthquake that occurred in Aceh (2004), Yogyakarta (2006), Padang (2009), Palu (2018), and Banten (2019) stand out as the most devastating seismic events in Indonesia history. Drawing from the lessons learned from these catastrophic incidents, we have put forth a set recommendation for mitigating the earthquake-induced disasters.

Early warning system for disasters

The early warning system plays a vital role in minimizing disaster-retaled fatalities, particularly when it comes to earthquakes. However, accurately predicting earthquake events remains a formidable challenge. As a result, early warnings are currently feasible mainly for swarm earthquake that exhibit regular regular pattern. But, the early warning system for earthquakes can significantly contribute to reducing the casualties resulting from subsequent disaster triggered by earthquakes, such as tsunamis, landslides, and liquefaction.

Research conducted after the Palu earthquake, shows the critical role of maintaining tsunami alerts, as discontinuing such warnings can exacerbate disaster impacts. Studies also reveal that the majority of fatalities in the Palu Eartquakes were a consequence of earthquake-induced landslides (Bradley et al., 2019). During the Aceh, Padang, and Yogyakarta earthquakes, early warning systems were not yet in place, leading to highesr casualties. Especially in Aceh, where the tsunami warning system was underdeveloped at that time, resulting in a greater loss of life due to tsunamis.

Urban planning for disaster-resilience

Understanding the disaster history of a region is of paramount importance. For example, in Sumatran Fault area, which encompasses Aceh and Padang, Hurukawa et al. (2014) documented six earthquakes with magnitudes exceeding 7.0 between 1921 to 2012. Pasari et al. (2021) study identified the potential for earthquakes with magnitudes exceeding 6.5 in Java's urban centers, including Jakarta, Surabaya, Bandung, Semarang, Serang dan Yogayakarta. Albini et al. (2014) highlighted the lack of historical seismic activity records in Indonesia. It suggests the need to conduct in-depth studies of the country's historical disaster alongside geological research related to earthquakes. Such efforts from the foundation for developing disaster-resilient areas capable of mitigating earthquake-induced damage, with the Palu earthquake as a crucial case study.

Identify seismic hazard zones in high-density population areas

The fatalities were more common in areas with high population density, Such as Aceh, Padang, Yogyakarta, Palu, and Banten, resulting in a greater number casualties. Yogyakarta as a poignant example in this regard, where a magnitude 6.4 Ritcher earthquake resulted in 5.7 thousand fatalities due to its dense population, surpasing the death toll of the earthquakes in Padang and Palu.

Disaster education

Disaster mitigation through education is essential for communities residing in the seismic hazard zones, including areas like Aceh, Padang, Yogyakarya, Palu, and Banten. Many of these communities have called these regions home for generations, with seismic risks handed down through ancestral knowledge. The most impactful mitigation strategy involves educating the community about earthquake-induced disasters, fostering a heightened awareness. Disaster preparedness is a key solution to minimize the impact on earthquake-victims. Education efforts should target individuals of all age groups, from the young to the elderly. In the case of Indonesia, where earthquakes are a significant concern, education stands as a cornerstone of disaster risk reduction.

Constructing earthquake-resistant buildings

Relocation people from high-density areas is an impossible mission. Therefore, the alternative strategy to reduce earthquake-induced disasters is the construction of earthquake-resistant buildings. Moreover, it is imperative to implemented regulations for construction standards aimed at minimizing the hazards.

Conclusion

Indonesia is a country prone to various natural disasters, with earthquakes posing one of the most formidable challenge. Their unpredictable nature has unfortunately resulted in the highest fatalityrates among all disasters. Examining the historical earthquake record provides valuable lessons for better anticipating and mitigating these devastating events. From this analysis, we have formulated five key recommendations: establishing early warning system for disaster preparedness, implementing urban planning for disaster-resilience, identifying seismic hazard zone in high-density population regions, enhancing disaster education, and promoting the construction of earthquake-resistance buildings.

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