Supplementary Information - Online resource 1

Title: Paired-event analysis of risk dynamics for nine paired earthquake events

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Table S1. Indicators and sub-indicators used in this study, including definition of sub-indicators and description of (examples of) the parameters used

Indicator	Definition	(Examples of) description of parameters
Impact		
Number of fatalities	Number of fatalities due to the direct impacts of an earthquake event	Number of fatalities, e.g. reported in open-access databases and scientific articles
Number of injuries	Number of injured people due to the direct impacts of an earthquke event	Number of injured people, e.g. reported in open-access databases and scientific articles
Direct economic impact	Direct economic impacts are due to the direct physical effect of an earthquake on economic resources, e.g. homes	Earthquake damage to buildings expressed in Euros, e.g. recorded by insurance companies
Hazard		
Intensity of Earthquakes	Earthquake intensity is a measure of the level of shaking caused by an earthquake at a particular location.	Modified Mercalli Intensity (MII) Scale, which ranges from I (barely perceptible shaking) to XII (total destruction). The unit of measurement for earthquake intensity is a categorical scale (e.g. MMI VI).
Magnitude of Earthquakes	The magnitude of an earthquake is a measure of the amount of energy released during the earthquake	Measured on the Scale of Richter, the unit of measurement for earthquake magnitude is a logarithmic scale, with each unit increase representing a tenfold increase in the amplitude of the seismic waves. For example, an earthquake with a magnitude of 6.0 is ten times more powerful than an earthquake with a magnitude of 5.0.
Duration of Ground Shaking	Duration of the earthquake startinng at the trigger point	Number in seconds or minutes
Surface Proximity	The focal depth of an earthquake is the depth within the Earth's crust where the earthquake originates (i.e. the surface proximity of the hypocentre)	Measured in kilometres below the Earth's surface
Exposure		
Exposed People	Number of people located in affected areas	Number of inhabitants in earthquake affected areas, e.g. from population statistics
Exposed Area	Size of affected areas (e.g. urban area)	Total area in km^2 e.g. official statistics
Exposed Assets	Number of assets located in affeted areas	Number of buildings in affected area, e.g. estimated from satellite imagery and reported in scientific articles
Vulnerability		

Lack of awareness and precaution	Lack of understanding of the risk (e.g. sources, hazards, potential consequences, etc.) Depends e.g. on experience, risk communication campaigns	Ineffective risk communication, lack of earthquake experience, and lack of awareness campaigns
Lack of preparedness	Lack of knowledge and capacities developed by communities and individuals to effectively anticipate and respond to an event	Lack of early warning systems and lack of response plans
Insufficient official emergency/crisis management	Organisational emergency or crisis management during an event was insufficient to optimally mitigate impacts	Lack of emergency plans, non-effective governance, and ineffective disaster risk management
Insufficient coping capacit	Coping capacity, which is the ability of communities using available skills and resources, to manage an event was insufficient due to a lack of funding (insurance, risk transfer), resources or skills	Insufficient public earthquake compensation or aid to individuals and businesses form government
Management Shortcomings		
Stuctural disaster risk management shortcomings	Problems with infrastructure management; failed or did not work optimally during event because of sub-optimal design	Inadequate building codes, poor enforcement regulations, and insufficient retrofitting
Non-stuctural disaster risk management shortcomings	Non-structural risk management measures, e.g. land-use/spatial planning that avoids increase of exposure in hazard-prone areas and private property level risk mitigation measures were not optimally implemented	Lack of hazard and risk maps

Detailed review-style reports on each paired event

Contents

This section comprises the detailed review-style reports on the 9 paired earthquake events. An overview of the ID, location, and year of the events can be found below. The reports can be found on the subsequent pages.

ID	Area	Years of events
1	New Zealand, Oceania	2010 & 2011
2	China, Eastern Asia	2010 & 2013
3	Ecuador, South America	2016 & 2019
4	Japan, Eastern Asia	2004 & 2011
5	Peru, South America	2007 & 2011
6	Indonesia, South Asia	2004 & 2005
7	Haiti, Caribbean	2010 & 2021
8	Chile, South America	2007 & 2015
9	Italy, Southern Europe	2009 & 2016

Paired event ID 1 – New Zealand

Paired earthquake event: 4th September 2010 and 22th February 2011 Earthquakes in Canterbury region, New Zealand

Short description of both events with a focus on impacts

The 2010-2011 Canterbury Earthquake Sequence (CES), which included the Mw 7.1 Darfield earthquake and Mw 6.2, 6.0, 5.9, and 5.8 aftershocks, occurred on a series of previously unknown, largely blind, active faults in New Zealand's eastern South Island (Quigley et al. 2016). Quigley et al. (2016) also state that the CES is one of the best-documented historical earthquake series on Earth. The CES's proximity to, and beneath, a major urban centre allowed for the rapid and detailed collection of vast amounts of field, geospatial, geotechnical, hydrologic, biologic, and seismologic data, as well as the documentation of incremental and cumulative environmental responses to seismic forcing over the course of a long earthquake sequence (Quigley et al. 2016). This case-study review analyses the Mw 7.1 Darfield earthquake and its Mw 6.2 aftershock earthquake.

The September 2010 earthquake in Canterbury, New Zealand, also known as the Darfield earthquake, was a severe quake that caused significant damage to houses and infrastructure around the area, especially, Christchurch, the main city in the Canterbury area. It was New Zealand's most destructive earthquake since the Hawke's Bay Earthquake in 1931. The earthquake caused substantial financial losses, with the overall cost of damage projected to be approximately $2.19-5 billion USD (Daniell et al. 2012; Dhakal 2010; Parker and Steenkamp 2012). As the incident occurred at night (at 4:35AM) and almost everyone was at home in their typically earthquake-safe dwellings, no fatalities were reported, although two people were injured (CRED 2023; Parker and Steenkamp 2012) and ~300,000 people affected (CRED 2023). If the earthquake had happened earlier on Friday night or during business hours on a working day, the city's structural devastation would very probably have resulted in many more casualties (McLean et al. 2012).

As previously mentioned, the earthquake was followed by a series of aftershocks, the most damaging of which struck Christchurch on February 22, 2011. This tragic event caused considerable damage and loss of life, with 181 fatalities (CRED 2023), 2000 injured (Wareham and Bourke 2013), and ~300,000 people affected (CRED 2023). The damage to the city's infrastructure was also severe, with many buildings and roads irreparably devastated. Property damage cost more than $30 billion NZD, plus an estimated $10 billion NZD for upgrading to higher standards during reconstruction, inflation, and economic interruption. Thus, the damage was predicted to cost roughly $40 billion NZD (approximately 21.4 billion USD), making it one of the most expensive disasters in New Zealand's history (New Zealand Treasury 2011). Nevertheless, virtually all damaged residences remained usable (despite many being extremely unpleasant, chilly, and frequently damp). However, most of the city’s Central Business District (CBD) buildings were destroyed beyond repair. The CBD was blocked for nearly a year, causing significant disruption to companies. Sewerage and water supply facilities were extensively damaged, owing mostly to liquefaction.

Christchurch had not yet fully recovered from earthquake that occurred on September 4, 2010, when the earthquake hit on February 22, 2011. Most people were shocked by the consecutive and far more intense earthquake (according to its MMI); it was a setback for people who were only beginning to restore their lives following the previous incidents (McLean et al. 2012).The CES earthquakes had an (indirect economic) impact on employment in the region, particularly in Christchurch City. People either lost their employment or had to adjust their working conditions (such as travelling to various locations to work, etc.) as a result of the serious business disruption (Potter et al. 2015). Following the two earthquakes, there was a significant drop in employment, which went from 67% in September 2010 to 63% in September 2011 (CERA 2013).

Descriptions of processes between events with a focus on risk management

The Darfield earthquake mostly damaged rural and sparsely inhabited regions, but the 2011 earthquake severely damaged Christchurch's metropolitan districts, including the CBD and residential neighbourhoods (EQC 2011). Many of the buildings in Christchurch's CBD were older structures that were not meant to survive powerful earthquakes, but buildings in rural regions were often newer and more earthquake resistant (EQC 2011). According to Hare and Galloway (2011), the findings from the building evaluation processes following the Darfield earthquake suggested a few problems: (1) Limited estimates of the pre- and post-earthquake building capacity: Detailed calculations of the pre- and post-earthquake building capacity were not frequently done. Ordinarily, comparisons to the design lateral load at the time of construction were made, and comprehensive calculations were only undertaken when the structure required considerable repairs, strengthening, or if it was thought to be earthquake-prone; (2) Extent of hidden damage: Detailed evaluations found several instances of structural flaws or hidden damage that were missed by level 2 inspections. Different review criteria resulted in variable degrees of discovery, and certain engineers' lack of participation in the sharing process made it more likely that potentially major problems would go undetected; (3) Lack of forced reviews: The procedure made clear the necessity of compulsory evaluations outside the realm of fast assessments, especially for structures without immediately apparent damage. The green plaque that was applied to certain properties during the emergency may have deceived the owners. It was suggested that all structures that are not excluded from the laws governing earthquake-prone buildings undergo thorough examinations; (4) The pragmatic approach suggested was to provide evaluations for all buildings not exempt from the Earthquake Prone Building legislation, excluding only residential structures unless they have two or more stories and contain three or more household units. However, it may be possible to develop more detailed filtering criteria to determine which buildings require evaluation.

The Canterbury earthquake sequence in New Zealand uncovered a number of issues with infrastructure management and suboptimal design. One of the major difficulties was the insufficiency of building codes, which did not account for the region's distinct seismic risk. The construction codes were mostly based on the notion that the area had a low seismic risk, which the earthquake proved to be erroneous (Cubrinovski et al. 2011a). Inadequate retrofitting was also an issue, since many structures that were retrofitted did not satisfy the needed seismic resistant criteria. This was attributed to a lack of awareness of existing building seismic performance and the effectiveness of retrofitting procedures (Turner et al. 2012). Features such as partitions, ceilings, and facades also performed poorly during the earthquake. These parts were not built or placed appropriately to resist seismic forces, resulting in extensive damage and a considerable risk to inhabitants (Dhakal 2010).

Several issues with non-structural risk management procedures were obvious prior to both the 2010 and 2011 Canterbury earthquake sequence in New Zealand. One of the major problems was a lack of thorough land-use and spatial planning, which could have minimized exposure in hazard-prone locations. Existing planning standards did not take seismic hazards into account effectively, resulting in the building of susceptible infrastructure in locations prone to liquefaction and ground shaking (Cubrinovski et al. 2011b). Saunders and Becker (2015) also state that, in terms of land-use planning, the Christchurch CBD's devastation was one of the most significant repercussions. The CBD was severely destroyed and would need to be rebuilt from scratch.

Event comparison with respect to hazard

The 7.1 magnitude Darfield earthquake in 2010 (43.55°S 172.18°E) (GNS Science 2010; Quigley et al. 2016) lasted roughly 40 seconds (Wood et al. 2012), featuring an epicentre 44 kilometres west of Christchurch's central business area, and had a hypocentral depth of 10.7 kilometres (Gledhill et al. 2011), whereas the consecutive 6.2 magnitude aftershock on in 2011 lasted approximately 10 seconds (GNS Science 2011) and was located 10 kilometres southeast of the Christchurch CBD (43.583°S 172.680°) (Gledhill et al. 2011), with a shallow depth of 5 km (GNS Science 2011). Although the 2011 earthquake had a smaller magnitude, its epicentre was substantially closer to Christchurch's city centre, resulting in more damage and loss of life (GNS Science 2011). The MMI values for the Darfield earthquake differed across different locations. The intensities in the epicentral area (Christchurch) were in the V to VII range, corresponding to moderate to violent shaking. The intensity of the second earthquake in 2011 was higher due to the epicentre's closeness to Christchurch. The intensity levels in the city ranged from VIII to IX, corresponding to severe to violent shaking.

Event comparison with respect to exposure

At the time of the Darfield earthquake, Christchurch City, which is located 40 km east of Darfield, had a population of about 370,000 people (Potter et al. 2015) and approximately 80% of the population was affected by the quake (CRED 2023). In terms of assets, both earthquakes caused significant damage. The Darfield earthquake inflicted substantial damage to Christchurch; in addition to many claims for damage to land and furnishings, EQC received claims for damage to about 140,000 houses (EQC 2011). This is a relatively considerable amount as the total number of residential buildings was 165,210 at that time (Statistics New Zealand 2006). In addition, severe liquefaction caused significant damage to the sewage infrastructure. Household toilets were rendered inoperable in locations where sewage reticulation had been severely damaged, and their usage was discouraged across the city due to damage to mains and pumping stations. The water delivery system was also impacted, and many residences, particularly in liquefied regions, were without water. In total approximately 300,000 people were affected by the Darfield earthquake, this number did not change for the Christchurch earthquake (CRED 2023).

The 2011 earthquake left extensive damage, especially in the city centre and eastern suburbs. According to Wareham and Bourke (2013), a total of 5,000 dwellings were planned for demolition, and another 5,000 had their long-term sustainability in doubt. About 110,000 buildings in the commercial centre required full demolition because they were extensively damaged. Moreover, despite the lack of structural damage, mechanical plant breakdowns did occur, and it took almost 2 years to fully fix them (Wareham and Bourke 2013).

Event comparison with respect to vulnerability

The findings of the study conducted by McClure et al. (2011) showed low anticipation of a significant earthquake in the Christchurch area before to the Darfield earthquake. The study found that there was a lack of historical awareness in the region; Christchurch’s citizens were not aware of previous earthquakes in the region. McClure et al. (2011) also state that there was an increase in earthquake likelihood judgments after the Darfield earthquake due to personal experience. Following the first earthquake, there was a major rise in vulnerability awareness in New Zealand. For instance, the police's priority tasks was gaining situational awareness and identifying life risks (McLean et al. 2012), which was successful as agency personnel acutely recognised emergency requirements during the 2011 earthquake.

In terms of resilience, the people of New Zealand are currently among the best prepared earthquake communities in the world. However, despite significant time, effort, and financial investment in public hazard education, levels of preparation for the Darfield event remained low, even when individuals did recognise their risk (Paton et al. 2015). Thus, there was an overall low perception of earthquake risk in Christchurch prior to the Darfield earthquake, which led to complacency and a lack of preparedness to recognize the potential risk (McClure et al. 2011). After the 2010 earthquake, the public and private sectors collaborated to create comprehensive disaster management and preparedness strategies. Overall people were more prepared as three territorial authorities (TAs)—the CCC (in the Art Gallery), Rangiora in the Waimakariri District, and Rolleston in the Selwyn District—declared local emergencies and set up Emergency Operations Centres (EOCs). Additionally, the Environment Canterbury (ECan) Group Emergency Coordination Centre (ECC) was established (McLean et al. 2012). As it developed, the incident on September 4 turned out to be a successful drill for the earthquake that occurred on February 22, 2011 (McLean et al. 2012).

According to McLean et al. (2012), within approximately 48 hours, New Zealand USAR Task Forces were fully deployed to Christchurch. Approximately 130 people gathered at the USAR facility close to the Woolston fire station. To help local teams, career and volunteer firemen from all around the nation were dispatched. During the emergency, more than 40 fire trucks were in Canterbury, and several smaller brigades responded to incidents more quickly than they would have in a typical year—in only two weeks. Also, streets were cleaned and buildings were examined despite the fact that there were neither direct fatalities nor a great number of injuries. (McLean et al. 2012).

Wounds, skin and respiratory diseases from sleeping outside ruined dwellings, and psychological stress were among the injuries caused by the 2021 earthquake. The ongoing COVID-19 epidemic aggravated the situation, making clinic and response team staffing problematic. The insurance sector contributed approximately 81% and 80% to the 2010 and 2011 earthquake events, respectively (King et al. 2014).

Sub-conclusion

The Canterbury Earthquake Sequence (CES) in New Zealand presented intriguing comparisons between different earthquakes, highlighting unique characteristics and outcomes. Despite the lower magnitude, the subsequent earthquake in 2011 had a more significant impact in terms of damage and loss of life compared to the initial Darfield earthquake in 2010. The higher number of casualties and injuries in the 2011 earthquake demonstrated how magnitude alone does not always determine the level of destruction.

The CES also revealed disparities in building codes and retrofitting practises. The damage inflicted by the earthquakes underscored the shortcomings of older structures that were not designed to withstand powerful seismic events. Non-structural elements, such as partitions and facades, exhibited varying degrees of resilience, further emphasising the need for comprehensive building regulations and retrofitting standards.

The earthquakes also had a profound impact on public perception and preparedness. The initial Darfield earthquake revealed a low perception of earthquake risk, leading to limited preparedness efforts. However, the subsequent events triggered heightened awareness and collaborative efforts to develop comprehensive disaster management strategies, emphasising the value of proactive measures in mitigating future seismic events.

Paired event ID 2 - China

Paired earthquake event: 14th April 2010 and 20th April 2013 Earthquakes in Qinghai Sheng and Sichuan Sheng provinces, China, respectively.

Short description of both events with a focus on impacts

The earthquakes on April 14, 2010, and April 20, 2013, in southwestern China, are two examples of significant seismic events that had substantial damage and loss of life. The 2010 Yushu earthquake was the strongest quake to occur on the fault's northwest portion in the previous 100 years (Zhang et al. 2010). As confirmed by the Ministry of Civil Affairs, Ministry of Public Security, and the Yushu Prefecture Government, the Yushu earthquake in Yushu District, Qinghai Sheng province (2010), killed 2,968 people, injured 12,135 people and listed 270 missing (CRED 2023; Liu et al. 2011; Chen et al. 2011; Zhang et al. 2010). The high-altitude, hypoxia-prone Tibetan plateau, which is primarily inhabited by ethnic minorities, was shaken by this powerful earthquake for the first time since the People's Republic of China was established. As a result, there was a significant negative impact on the region's economic and social development. Approximately RMB 44 billion Yuan (Approximately 6.6 billion USD) in direct economic losses were brought on by the earthquake (comprising RMB 350 million Yuan for the Sichuan Province and RMB 43.65 billion Yuan for the Qinghai Province) (Liu et al. 2011). According to Liu et al. (2011), the infrastructure category suffered the greatest loss, which included harm to roads, bridges, and other transportation assets as well as municipal water, hydropower, and communication systems, among other things. Damages to residential and non-residential structures in metropolitan areas accounted for the second-highest loss. Rural home losses make up a very minor portion of the losses.

On April 20, 2013, an earthquake struck Lushan County of Sichuan Sheng provinces, Ya'an District, China. The Lushan earthquake caused several landslides across a huge region, resulting in casualties, injuries, and damage to infrastructures including roads, drains, homes, and buildings (Xu et al. 2015). It killed 198 individuals and wounded thousands more; a total of 14.785 people (CRED 2023). Also, 25 people went missing (Chang et al. 2016). The direct economic loss was over 50 billion yuan (RMB) (approximately 7 billion US dollars) (Fang et al. 2013, 2015). After this incident, several analysts predicted that it would not have a substantial effect on China's economy's fundamentals (Tao 2014).

Descriptions of processes between events with a focus on risk management

In 2010, the building regulations were deemed to be inadequate in the affected area since most of the structures that fell after the Yushu earthquake were made of mud bricks (Liu et al. 2011). The region's distant location and insufficient resources make it difficult to implement construction rules and monitor building seismic performance (Wang and Mori 2012). Before the 2013 earthquake event, all hospitals and schools were built to higher standards and fortified to better withstand earthquakes, which helped them endure the Lushan earthquake (Yang et al. 2014).

There were various issues with non-structural risk management procedures prior to and during the seismic occurrences in China in 2010 and 2013. During the 2010 Yushu earthquake, one of the most serious problems was a lack of effective land-use and spatial planning, which resulted in increasing exposure in hazard-prone locations. This was owing to China's fast urbanisation and population expansion, which pushed the government to develop new regions without taking into account the possible hazards connected with earthquakes (Wang and Mori 2012).

Event comparison with respect to hazard

Two parts of the Ganzi-Xianshuihe fault zone were reactivated by the Yushu earthquake, which occurred on its northwesterly continuation. From south of Jielong in the west to south of Gyêgu (Yushu) in the east, there was a total of around 70 km of rupturing caused by the Yushu earthquake. The surface rupture zone's detailed mapping reveals that it is divided into two strike-slip segments, the western and eastern segments, by the Longbao Lake step-over (pull apart) basin (Li et al. 2012). The earthquake had a magnitude of 6.9 on the Richter scale and an epicentral intensity on the MMI scale of IX (Liu et al. 2011; Zhang et al. 2010), causing major ground shaking and damage to adjacent structures and infrastructure. The epicentre was in the Yushu Tibetan Autonomous Prefecture's Jiegu town (33.2°N, 103.4°E), with a focal depth of 14 kilometres (Sun et al. 2012, Zhang et al. 2010). The Yushu region is

3,600 metres above sea level and primarily comprises of hilly terrain. The earthquake in this region resulted in the formation of several liquefaction zones. The Yushu earthquake caused the soil layers coated by snow and ice to liquefy, and the liquefied sand burst through the snow and ice cover, causing sand to boil, ground fissures, and damage to the roadbed. This was the most severe liquefaction phenomena in decades (Yuan et al. 2022).

The Lushan earthquake (30.3° N, longitude 103.0° E) had a magnitude of 7.0 on the Richter scale (Tang et al. 2015) and occurred at a depth of 13 km (Fang et al. 2013), however the nearby region suffered less violent ground shaking as a result. Nevertheless, the quake was still powerful enough to badly damage infrastructure and structures, particularly in more densely populated areas around the epicentre. The maximum intensity on the MMI scale was also IX (Zhang et al. 2021). During the Lushan earthquake, liquefaction only occurred near river terraces and alluvial plains along the Shuangshi-Dachuan fault, a branch of the Longmenshan fault (Shi et al. 2014).

Event comparison with respect to exposure

During the Yushu earthquake, the exposed region was 42,687 square-kilometre, a population of 246,842 was exposed (Sun et al. 2012), and some 15,000 houses collapsed (Reliefweb 2010a). The size of the severely affected zone was around 4,000 square kilometres, while the extreme impacted region was mostly centred in Jiegu town, with a total area of 900 square kilometres (Sun et al. 2012). The exposed area of the Luchan earthquake was 35,862 km^2 (Yang et al. 2015) and a total of 2,198,785 people (CRED 2023) were affected as a result. Moreover, approximately 193,000 houses collapsed (Chang et al. 2016; Huang et al. 2015).

Event comparison with respect to vulnerability

Wu et al. (2022) conclude that during the 2013 Lushan earthquake, inhabitants' understanding of disaster risk prevention behaviours was generally inadequate. According to the findings, most locals did not demonstrate significant pre-disaster avoidance behaviours before the event, indicating a lack of knowledge and awareness.

According to Yang et al. (2014), by 2013, more than 12 million people in Sichuan Province had taken part in an earthquake drill to enhance understanding of how to respond to a large disaster. They also state that survivors of the Lushan Earthquake quickly recovered from their initial shock and began search and rescue operations due to improved preparation and based on previous disaster relief experience, as well as a national plan. Local rescue teams and medical authorities quickly organised and began to provide assistance. The Chinese people were reasonably well-prepared for the earthquake as there was an efficient and effective emergency rescue system set up (Yang et al. 2014)

The Chinese government built a national response system for large disasters, and it was incredibly effective in responding to the Yushu earthquake. This system's overall architecture was successful in accomplishing its objectives of effective and quick disaster relief. Due to the effectiveness of this method, the Yushu Earthquake disaster region was able to swiftly transition from the emergency response stage to the recovery and reconstruction stage (Liu et al. 2011). Moreover, as soon as the first earthquake struck, the Red Cross Society of China (RCSC) sent aid supplies, rescue teams, medical teams, ambulances, one emergency response team (ERT), and one sanitation ERT (ReliefWeb 2010a). Additional rescue personnel were sent by the Chinese government to the affected area. According to the province administration of Qinghai, 100,000 blankets as well as 5,000 tents were delivered to aid survivors in surviving the harsh winds and subfreezing temperatures (ReliefWeb 2010b).

Moreover, Lu and Xu (2014) state that relief supplies were also distributed directly after the Lushan earthquake; the Ministry of Civil Affairs has provided tents, cotton blankets, and temporary beds to the affected communities. These supplies were essential in giving the impacted populace temporary shelter and basic requirements. Lu and Xu (2014) also state that the Lushan earthquake had a rapid deployment of rescue teams from all around the nation—including the military, hospitals, NGOs, and unpaid volunteers—flew to the epicentre in Ya'an City, Sichuan Province's Lushan County. There was also a national medical emergency response team sent to Ya'an city, which included more than 180 physicians, 2,000 police officers, and firemen. To further help with the emergency response and rescue attempts, more than 6,000 military and armed police officers were sent (Lu and Xu 2014).

After the first earthquake, over $2.5 million has been donated to the Hong Kong Red Cross (HKRC) (ReliefWeb 2010a). Over 5000 other foundations, charities, and Red Cross organisations serving the general population were officially registered to help; the total quantity of goods and cash donations made across the country for the Yushu Earthquake disaster assistance came to 7.129 billion Yuan (approximately 1.1 billion USD) (Liu et al. 2011). After the consecutive earthquake, over $16.8 million in donations were given to HKRC to help relief, recovery, readiness, and risk reduction projects in Ya'an Prefecture (ReliefWeb 2010c 2018).

Sub-conclusion

The earthquakes that struck Qinghai Sheng and Sichuan Sheng provinces in China on April 14, 2010, and April 20, 2013, respectively, provide an interesting comparison in terms of their impacts and outcomes. Despite the earthquake in 2010 having a lower magnitude, it resulted in significantly higher casualties, injuries, and damage compared to the earthquake in 2013. This highlights that the magnitude of an earthquake alone does not necessarily determine the extent of its impact.

The Yushu earthquake of 2010 had a profound effect on the region, causing extensive damage to infrastructure and resulting in a large number of casualties. The earthquake revealed deficiencies in building regulations and construction practices, as many structures made of mud bricks collapsed. The Lushan earthquake of 2013 had a higher magnitude, and had lower fatalities but more direct economic impacts

The exposure to the earthquakes also differed in terms of population and infrastructure. The Yushu earthquake affected a larger population, resulting in a significant number of collapsed houses and leaving many people homeless. In contrast, the Lushan earthquake, while affecting a smaller population, still caused substantial damage to infrastructure and resulted in a considerable number of collapsed houses.

In terms of risk management, both events highlighted the importance of proactive measures. The Yushu earthquake exposed weaknesses in land-use planning and spatial management, indicating a lack of consideration for potential earthquake hazards during urban development. However, by the time of the Lushan earthquake, improvements had been made in disaster preparedness, including earthquake drills and the establishment of an effective emergency response system.

Paired Event ID 3- Ecuador

Paired earthquake event: 16th April 2016 and 22nd February 2019 Earthquakes in the coasts of Ecuador

Short description of both events with a focus on impacts

On April 16, 2016, an earthquake struck Ecuador's coast, close to the city Perdenales and killed approximately 670 people (CRED 2023; USGS 2016a) and injured over 27,000 (USGS 2016a). Also, as a result of the quake 9 people went missing (USGS 2016a) and the area's buildings, homes (approximately 35,000), and infrastructure got severely destroyed , leaving an estimated 250,000 people in need of humanitarian assistance (Kaminski et al. 2019). According to Toulkeridis et al. (2017), the approximate cost of the damages to the aforementioned infrastructure is 3.3 billion USD, equivalent to 3% of Ecuador's GDP in 2016.

On February 22, 2019, an earthquake struck Ecuador's eastern area, close to the Peruvian border; 115 km southeast of the town of Palora, in the Morona Santiago province, Ecuador. This connective earthquake killed six people and injured 9 others (CRED 2023), as well as extensively damaging the area's structures and infrastructure. The earthquake also caused landslides, which worsened damage and hindered rescue efforts. Beyond Ecuador, neighbouring countries including Peru and Colombia experienced some shaking as a result of the earthquake.

Descriptions of processes between events with a focus on risk management

The Ecuadorian Building Code (NEC-2014) was in agreement with the international state of practical knowledge in seismic design, according to Kagermanov et al. (2017), but its application and enforcement by local authorities required further refinement. Moreover, structures that were compliant with the version of the Ecuadorian Building Code at the time, and where ground accelerations were not excessively high, satisfied collapse prevention, with a few exceptions where common mistakes of irregularity and lack of ductility resulted in partial collapse, according to Kagermanov et al. (2017).

Event comparison with respect to hazard

The earthquakes that struck Ecuador's eastern coast on April 16, 2016 (0.38°N 79.92°W) and February 22, 2019 (2.19°S 77.05°W) were both large seismic occurrences; the magnitude of the 2016 earthquake was 7.8 (USGS 2016a), whereas the magnitude of the 2019 earthquake was 7.5 (USGS 2019a). The first seismic event had a focal depth of 21 km and an epicentre 29 km SSE of Muisne, Province of Esmeraldas (Toulkeridis et al. 2018; Gallegos and Saragoni 2017). Along the seaside, the modified Mercalli intensities (MMIs) peaked at a value of VIII (Smith and Mooney 2021). The time of the earthquake was between 60 and 120 seconds (Gallegos and Saragoni 2017). During the earthquake in 2016, many sand boils were created on the alluvial plain near the entrance of the Rio Briceo valley (Ecuador) (Salocchi et al. 2020).

The second earthquake in 2019 was 145 km deep (USGS 2019a) and arose from normal faulting that took place 132 km beneath western Ecuador as a result of the Nazca plate being subducted, at an intermediate depth. The Modified Mercalli intensity was VII (USGS 2019a). The earthquake lasted approximately 12-17 seconds (USGS 2019a)

Event comparison with respect to exposure

The two earthquakes had some similarities and differences in terms of exposure. Both earthquakes struck in areas with a high population density and extensive urbanisation. The 2016 earthquake primarily devastated the cities of Manta, Portoviejo, and Pedernales, and left tens of thousands in refugee camps, and directly affected over two million people (CRED 2023; Toulkeridis et al. 2018). The earthquake destroyed almost 7000 structures and badly damaged another 1000 (Guerrero-Miranda and Luque González 2021).

The area exposed to the 2016 quake was 9,600 km^2 (ReliefWeb 2016a). The 2019 earthquake affected an estimated 389,364 people (CRED 2023). 224 buildings were damaged and 10 were fully destroyed (Nievas et al 2020).

Event comparison with respect to vulnerability

According to the six months report of the emergency appeal (ReliefWeb 2016b), the Ecuadorian Red Cross (ERC) made public awareness campaigns, which began during the emergency phase of the 2016 earthquake. Volunteers from the Ecuadorian Red Cross (ERC) have been trained to assist with these initiatives. Also after the 2016 quake, targeted communities received orientation/awareness-raising seminars on safer shelter. A shelter aid programme for 500 households began in January 2017. Furthermore, the shelter cluster has collaborated to determine the supplies necessary (ReliefWeb 2016c). After the 2016 Earthquake, the Ecuadorian Red Cross (ERC) also assessed vulnerability and capability in the ten cantons of Pedernales, Jama, Sucre, and San Vicente in Manab province, as well as Muisne in Esmeraldas province. Based on the VCA results, efforts were being made to build community capacities through coordination with local governments, simulation, and the formulation and transmission of informational messages. During the early stages of reconstruction, the ERC began the process of developing training plans and protocols for the emergency medical unit (ReliefWeb 2016b).

In terms of preparedness, the ERC legal team continued leading a technical working group established during the emergency phase as part of the interagency coordination platform to work towards the enhancement of the country's legal framework for integrated disaster risk management, with the assistance of the IFRC disaster law programme (ReliefWeb 2016b).

According to the six months report of the emergency appeal (ReliefWeb 2016b), On April 16, 2016, Ecuador declared a state of emergency and issued a red warning in six provinces: Manab, Esmeraldas, Santo Domingo, Los Roses, Santa Elena, and Guayas. Pedernales (Manab province) had been named a disaster zone. Two days after the quake, the International Federation of Red Cross and Red Crescent Societies (IFRC) contributed 405,778 Swiss francs from its Disaster Relief Emergency Fund (DREF) to give humanitarian help to 40,000 individuals. The Ecuadorian government enlarged the State of Exception, allowing any international organisations that were not registered with the State to provide humanitarian relief within the country. On April 22 2016, an emergency appeal for 18,350,836 Swiss francs was issued to help 100,000 people for a period of 12 months. Approximately six months later, the International Fund for Relief and Development (IFRC) had issued a revised Emergency Appeal for roughly 15 million Swiss francs to support 85,234 individuals and to extend operations until August 2017. The operation had supported over 21,000 earthquake-affected families during the recovery phase (in those six months), partly due to the fact that during the emergency and early recovery phases, the National Society mobilised 765 Ecuadorian Red Cross volunteers and an additional 1,500 students from the Ecuadorian Red Cross Technical Institute (ISTCRE), frequently several times. Community health; water, sanitation, and hygiene promotion; housing, livelihoods, food security, and nutrition; disaster risk reduction; and national society capacity building were all areas of focus (ReliefWeb 2016b). The Central Emergency Response Fund (CERF) allocated over 7 million dollars after the 2016 earthquake (ReliefWeb 2016b,c) and over 1.5 million dollars after the 2019 earthquake (UN OCHA 2020).

Sub-conclusion

The earthquake that occurred on April 16, 2016, had a higher magnitude compared to the earthquake on February 22, 2019. However, despite the lower magnitude, the earthquake in 2019 still had significant impacts. Both earthquakes caused substantial damage and loss of life, but the 2016 earthquake had a greater overall impact. It resulted in a higher number of casualties and injuries compared to the 2019 earthquake. In terms of exposure, both earthquakes struck areas with high population density and extensive urbanisation. However, the 2016 earthquake directly affected a larger number of people and caused more widespread destruction of buildings and infrastructure.

The response and risk management measures implemented after the 2016 earthquake were more extensive compared to the 2019 earthquake. In 2016 there were concerted efforts to assess vulnerability, build community response capacities, and provide humanitarian assistance after the 2016 event. In contrast, the 2019 earthquake revealed gaps in comprehensive risk management planning. Despite its lower magnitude, the 2019 earthquake still caused significant damage to structures and infrastructure. The impacts were intensified by factors such as landslides, which worsened the destruction and hindered rescue efforts. Both earthquakes highlighted the need for improved enforcement of building codes and retrofitting vulnerable structures. However, the 2019 earthquake emphasised the ongoing challenges associated with limited financial resources and technical competence for extensive retrofitting measures.

Paired Event ID 4 - Japan

Paired earthquake event: 23rd October 2004 and 11th March 2011 Earthquakes in Japan

Short description of both events with a focus on impacts

The October 23, 2004 earthquake (hereinafter: Niigata Chuetsu earthquake) located along the coastal areas of southwestern Niigata Prefecture and stands out in a very active period of seismicity in Japan. Since the Kobe earthquake in 1995, the Niigata Chuetsu earthquake caused the most damage in Japan; killed 40 individuals (CRED 2023) and injured over 3,183 others (CRED 2023). Moreover, the direct cost of the disaster was estimated by Japanese officials to be $40 billion USD (Kayen 2008). The earthquake also produced hundreds of landslides and considerable damage to infrastructure such as roads and bridges. It hampered traffic and resulted in significant power outages in the impacted area. Also, more than 100,000 people were placed in temporary shelters as a result of the earthquake, and up to 10,000 were displaced from their upland houses for an extended period of time (Kayen 2008).

On March 11, 2011, an earthquake occurred off the pacific coast of Tohoku, Japan. The Tohoku earthquake generated a tsunami, which resulted in 15,641 deaths and 5,007 people that went missing (Mori et al. 2011). Also, 5940 people were injured (Dunbar et al. 2011) and approximately 131 thousand people got displaced (USGS 2011). The 2011 earthquake's economic effect was predicted to be over $235 billion, making it one of the most expensive disasters in history (Neumayer et al. 2014).

Descriptions of processes between events with a focus on risk management

The 2011 Tohoku earthquake was one of the most powerful ever recorded, resulting in a disastrous tsunami. The primary issues with infrastructure management during this event were connected to underestimating the probable tsunami threat and inadequate coastal defence design. Despite Japan's strong seismic design guidelines and enforcement laws, the event inflicted considerable damage to structures and infrastructure that were not meant to resist such a large-scale disaster (Fraser et al. 2012).

According to Goda and Song (2016), there was a hazard map prior to the 2011 earthquake event. Nevertheless, their study also states that the actual earthquake and tsunami exceeded historical events/scenarios considered in the hazard map that was developed in 2005 (Goda and Song 2016).

According to Satake et al. (2018), the 2011 earthquake and tsunami actually happened before preventative measures were implemented based on the most recent hazard estimates. The disaster underscored the significance of recognising disaster risk, increasing disaster risk governance, investing in disaster risk reduction for resilience, and improving disaster preparedness for effective response and "Building Back Better" in recovery, rehabilitation, and rebuilding. The Sendai Framework for Disaster Risk Reduction 2015-2030 established these action priorities (Satake et al. 2018). Thus, there are numerous lessons to be gained about Japan's disaster management practices from the 2011 Great East Japan Earthquake and Tsunami tragedy. As a result, they have undergone significant reform to advocate for programmes that would increase national resilience with the goal of fostering safe and secure communities (Koshimura and Shuto 2015).

Event comparison with respect to hazard

The magnitude 6.8 earthquake that struck Niigata, Japan, on October 23, 2004 (NASA Earth Observatory 2004), lasted around 3-6 seconds and was produced by movement of the Earth's crust along a fault line in the area (Honda et al. 2005). The Niigata Chuetsu quake had an estimated focal depth of 10 km (Kayen et al. 2008) and an intensity of IX on the MMI scale, according to Sato et al. (2006).

The 2011 Tohoku earthquake (38.3°N, 142.4°E) near Niigata, Japan, lasted about six minutes (Oskin 2022) and had a magnitude of 9.0 and was one of the greatest earthquakes ever recorded (Kaku et al. 2015). The subduction of the Pacific Plate beneath the North American Plate generated this earthquake, which triggered a catastrophic tsunami. The surface proximity was 29 km (Dunbar et al. 2011). The tsunami triggered by the 2011 earthquake had a huge impact on the region, inflicting major damage to coastal settlements and ultimately to the Fukushima Daiichi nuclear accident. The MMI was VIII (USGS 2011).

Event comparison with respect to exposure

Around 100 kilometres of the southwest Niigata prefecture's coastline regions were impacted by the Niigata-Chuetsu earthquake (Kayen et al. 2008). Approximately 59,000 people were affected by this earthquake (CRED 2023). According to Scawthorn and Rathje (2006), approximately 120,000 houses were destroyed by the quake (Japan Reconstruction Agency 2026).

The rupture region of the Tohoku earthquake is estimated to measure 450 km by 200 km (Mori et al. 2011). The 2011 quake damaged or destroyed at least 332,395 structures, 2,126 roads, 56 bridges, and 26 railroads (USGS 2011). The estimated amount of people exposed is 405,719 (NCEI 2023).

Event comparison with respect to vulnerability

There was a lack of individual risk-awareness during the 2004 Niigata Chuetsu earthquake, though authorities did have the understanding of risk (Gismondi 2012).

According to Greer (2012), Japan is the world leader in practically all elements of earthquake preparedness when using a single-hazard strategy. From 1980-2012, Japan has spent a large portion of its GDP ($400 million per year) on mitigating measures (Greer 2012). Despite this effort, individual readiness and knowledge remained low during the 2004 Niigata Chuetsu earthquake, particularly in rural areas where technical developments and policy implementation are typically delayed. The policy structure at the time in Japan did not enable enough preparation for a seismic event in rural regions (Gismondi 2012). The study conducted by Gismondi (2012) revealed an interview with local government officers stating that “Although we knew about the high seismic risk of the region, we did not organise emergency procedures in case of earthquakes. Residents were not aware where to evacuate, therefore when the first shake occurred panic spread in Kawaguchi with a good portion of the town residents trying to reach the local government buildings seeking support”. In addition, the absence of adequate early warning systems and evacuation strategies led to the large number of fatalities during the tragedy (Fraser et al. 2012).

After the 2004 earthquake, local governments made reconstruction plans that include infrastructure design, transportation, land-use management, urban design, relocation, economic and industrial outlooks, and the central government has modified coastal protection policies to reduce risks and improve disaster resilience (Koshimura and Shuto 2015). However, according to Greer (2012), the 2011 Japan Earthquake should serve as a representation that structural mitigation is not always sufficient. Japan, which may practise the greatest mitigation in the world, was unprepared for the events of March 15, 2011. The prevailing viewpoint is that Japan was not prepared for the worst-case scenario; instead, the government concentrated on the most likely scenario. The Japanese had not anticipated an earthquake of this magnitude. The greatest magnitude of the next earthquake was anticipated to be Richter scale magnitude 8.0-8.3 in the affected area's contingency plan (Greer 2012).

According to Satake et al. (2018), a warning system did not exist in 2004. According to Fujinawa and Noda (2013), since October 2007, Japan has had a well-developed public earthquake early warning (EEW) system. Several million people near the epicentre of the 2011 Tohoku earthquake and tsunami received the EEW about 15 to 20 seconds before the most severe shaking began, and many more people in surrounding districts had more lead time before less severe shaking began. 90% of these persons were able to take precautionary measures to preserve their own and family members' lives, or to take additional steps based on prior preparation (Fujinawa and Noda 2013). Furthermore, tsunami warnings were provided 20 minutes before the first destructive waves (Yamada 2011). This remarkable warning system bears witness to two things: money and strong administration. Appropriate funding proposals have resulted in Japan becoming the world's most technologically resilient country, with near immediate detection and seismic warning systems (Crowley and Elliott 2011).

Four years after the 2004 earthquake, a 25 trillion yen national budget was set aside for five years of restoration work (Koshimura and Shuto 2015).

After the 2011 Tohuku event, Japan urged that foreign humanitarian organisations refrain from intervening directly in impacted areas (DEC 2011). Despite accepting offers of aid, Japan's capacity to manage, and hence its resilience, appeared to be withstanding the deadliest disaster to hit the country (Crowley and Elliott 2011).

The tsunami generated by the 2011 earthquake also damaged the Fukushima Daiichi nuclear power facility, resulting in a nuclear disaster that forced a long-term evacuation of local residents. The government constructed 54,000 dwelling units for temporary use. These were intended to be used until secure permanent housing could be constructed. The government also rented out private homes and apartments and released vacant spaces from the public housing that was already in place for those who were impacted. Families who were able to return home but lacked the funds to make repairs were given subsidies of US$ 6,000 by the government (GSC 2013).

Sub-conclusions

The comparison between the Niigata Chuetsu earthquake in 2004 and the Tohoku earthquake in 2011 reveals significant differences in magnitude, impact, and consequences. While both events had their own level of devastation, the Tohoku earthquake stands out as one of the most powerful earthquakes ever recorded, resulting in a catastrophic tsunami and widespread destruction. It caused immense loss of life, injuries, and displacements, along with a substantial economic impact. The Tohoku earthquake affected a larger region and exposed a larger number of people to its effects. The preparedness levels and response strategies also differed, with the 2011 earthquake leading to reforms and improvements in disaster risk reduction and preparedness. The comparison highlights the importance of understanding the potential risks associated with earthquakes and tsunamis, as well as the need for effective risk management strategies and disaster preparedness. The Niigata Chuetsu earthquake serves as a reminder that even smaller-magnitude earthquakes can still cause significant damage and disruption, underscoring the importance of proactive measures to enhance resilience and infrastructure preparedness.

The contrasting outcomes of these two earthquakes emphasise the significance of accurate hazard assessments, timely warnings, and effective evacuation plans. The Tohoku earthquake revealed the need for improvements in coastal defence design and the recognition of worst-case scenarios, as the actual event surpassed historical expectations. These events have prompted Japan to further enhance its disaster risk reduction strategies and invest in building resilient communities. The lessons learned from these earthquakes have led to reforms in policies, infrastructure design, and early warning systems, aiming to better protect lives, reduce economic losses, and facilitate a more efficient response and recovery.

Paired Event ID 5 - Peru

Paired earthquake event: 15th August 2007 and 28th October 2011 Earthquakes in Ica region, Peru

Short description of both events with a focus on impacts

On August 15, 2007 an earthquake occurred 145 km south of Lima (Peru's Capital City), off the coast of southern Peru (Tang and Johnsson 2010). The Pacific Ocean's epicentre was 60 kilometres west of the provinces of Chincha and Pisco. The Pisco-Chincha earthquake was a thrust event that started near the Nazca-South American plate boundary, just to the north of where the Nazca ridge is subducting beneath the Peruvian forearc (Pulido et al. 2013). The earthquake had a tremendous social and economic impact, resulting in 593 fatalities (CRED 2023) and 1,844 injuries (Elnashai et al. 2008). About $300 million USD was the anticipated economic loss, which included damage to vital infrastructure (Tang and Johnsson 2010). According to Peru's Ministry of Economy and Finance (MEF), the estimation of the total public infrastructure reconstruction cost is 220.68 million USD (i.e. indirect economic impact) (Degg and Chester 2005).

The 2011 earthquake resulted in one person getting killed and 103-106 getting injured (CRED 2023; NGDC/WDS 2023).

Descriptions of processes between events with a focus on risk management

According to Taucer et al. (2009), there was inadequate retrofitting of older structures, which led to infrastructure management issues during the 2007 seismic event. Many older structures in Peru have not been updated to meet modern seismic design requirements, leaving them more vulnerable to earthquake damage. This is especially alarming considering the country's large proportion of older structures. The vast majority of structural malfunctions occurred in masonry constructions made of clay and brick. Nevertheless, a number of reinforced concrete structures also sustained significant harm or collapsed, frequently as a result of soft storey effects and a lack of vertical continuity. Even in contemporary building, the absence of ductile details was obvious and recurrent (Elnashai et al. 2008).

The Japan Society of Civil Engineers (JSCE) and Japan Association of Earthquake Engineering (JAEE) decided to support the deployment of a combined team with the Institute of Industrial Science at the University of Tokyo due to the event's size and the extensive damage. The mission's goals were to examine building and housing damage while taking structural and geotechnical factors into account, and to use the information learned to develop plans for disaster mitigation and rehabilitation (Degg and Chester 2005).

The Geological, Mining, and Metallurgical Institute of Peru (INGEMMET) began creating geological hazard maps for the country in the 1990s, focusing on regions prone to landslides, floods, and seismic activity (Ochoa and Santisteban 2009). Moreover, the National Centre for the Estimation, Prevention, and Reduction of Disaster Risk (CENEPRED) was founded in 2003 and has since been in charge of developing and updating hazard maps for different hazards such as earthquakes, tsunamis, and volcanic eruptions (Peruvian Government 2025).

According to Dominguez et al. (2017), in 2009, the regional government of Ica and the regional civil presented the 'Regional Plan for the Prevention and Attendance to Disasters - Ica Region 2009-2019' (Plan Regional de Prevención y Atención de Desastres - Región Ica 2009-2019). Also, the regional plan developed by the civil protection system in the department of Ica focused primarily on "prevention and response to emergencies or disasters to protect the people and patrimony of the department".

Event comparison with respect to hazard

The August 15, 2007, earthquake had a magnitude of 8.0 (Biggs et al. 2009). Over 2 minutes of intense ground shaking occurred in Ica during the lengthy earthquake's duration (Deggs and Chester 2005) and the hypocenter was at a depth of 39 km (Deggs and Chester 2005; Pulido et al. 2013). In 2007, Modified Mercalli Intensities of VII-VIII are estimated by the Peru Geophysics Institute (IGP) at Pisco, Chincha, and Ica (Degg and Chester 2005). In the affected area, there were significant landslides and liquefaction observations. In addition to causing damage to building foundations, the Pisco-Chincha earthquake's liquefaction effects also resulted in ground displacement, landslides, damage to roads and bridges, the toppling of power poles, breaks in water and drainage pipelines, and damage to port facilities, among other features of damage. Overall, this earthquake's soil impacts and geotechnical effects were extensive causing major damage to the foundations, subsurface, and surface buildings (Elnashai et al. 2008).

The 2011 earthquake had a magnitude of 6.9 and a focal depth of 24 km, the earthquake intensity in the ICA region was felt at VI on the MMI scale (NGDC/WDS 2023). On October 28, the duration of the shaking was from 60 to 100 seconds (Lazares and Aguilar 2012).

Event comparison with respect to exposure

The 2007 quake affected approximately 650,000 people (140,000 households) (Degg and Chester 2005). In the areas of Ica, Lima, Huancavelica, Ayacucho, and Junn, 80,000 homes and buildings were either partially or totally destroyed; 21,000 structures were damaged and almost 55,000 collapsed; numerous hospitals (584) and educational institutions (122) also had negative effects (Degg and Chester 2005). Cities in the regions of Ica and Lima were included in the affected area (San Bartolomé and Quiun 2008). During the 2011 earthquake over 100 people were affected (CRED 2023; NGDC/WDS 2023) and approximately 45,000 houses got destroyed (GSC 2016).

Event comparison with respect to vulnerability

According to Santa-Cruz et al. (2016), previous initiatives to enhance risk awareness and ability for emergency preparedness have targeted Lima schoolchildren. After community training and monitoring activities including teachers, parents, and students, elementary and high school children had obtained a basic level of risk awareness before the 2007 earthquake. However, they also state that government institutions, academic staff, instructors, and healthcare personnel lack the necessary skills to give information or humanitarian assistance to children impacted by earthquake occurrences. The experience in Pisco’s 2007 seismic event indicated that students' physical and psychological difficulties were exacerbated by weak communication skills.

According to Bruni (2015), the National Civil Defence System (Instituto Nacional de Defensa Civil - INDECI) oversaw the reaction to the earthquake, which was aided by the military and the business sector (local, national, and worldwide). Many contributions came from civil society and the international community, including governments, international NGOs, and United Nations agencies. Despite the fast and massive reaction, several critics have highlighted concerns about overall preparedness and coordination. This critique, recognised as a "lesson learned" by the Peruvian National Defence, has been utilised to alter the Peruvian Disaster Risk Management Plan (Bruni 2015). Cuadra and Tokeshi (2008) also state that there was no capacity or preparedness to respond. This lack of readiness and resources was related to the fact that many of the mayors had just recently been elected, and the shift of power frequently included a total staff renewal, mostly for political reasons. As a result, capacity was lost. Furthermore, disaster prevention and response were not prioritised since they lack political clout among constituents and do not produce large resources (Elhawary and Castillo 2008).

Given the country's high seismic risk, the National Safe Hospitals Policy, which includes essential vulnerability reduction initiatives for hospitals and health institutions, was authorised in 2010. As part of this project, the Hospital Safety Index was used to evaluate over 90% of Ministry of Health institutions, offering the likelihood that a hospital or health facility would be able to sustain operations during and after events, which they did in 2011 (ReliefWeb 2021). Also, with a $25 million loan from the Inter-American Development Bank, Peru, aimed to lower its vulnerability and increase its disaster response capabilities (ReliefWeb 2010d). The programme is the first in a series of three programmatic policy-based loans to help the Peruvian government adopt measures to anticipate, minimise, and regulate disaster risk factors in society, as well as provide an effective response to disasters. The programme is designed to strengthen the legislative and institutional structure in the areas of risk identification, reduction, management, and financial handling by providing support to the planned Framework Law for Integrated Disaster Risk Management (ReliefWeb 2010d).

According to Elhawary and Castillo (2008), in practise, regional and local civil defence committees were unable to effectively deal with the emergency following the 2007 earthquake, partly because many local authorities were directly affected, and partly because many committees had not been formed, and there was no capacity or preparedness to respond.

In the five months following the earthquake, the Peruvian Ministry of Housing started distributing bonds worth around 2,000 USD to those impacted who had title to their properties on the land. These bonds were intended to assist people in purchasing building supplies for new dwellings. Families without land titles are not eligible for this governmental initiative (GSC 2010). In 2011, PREVAED-PP068, the financial programme for disaster risk reduction and emergency response, received S$19 million (ReliefWeb 2021) as well as a $25 million loan from the Inter-American Development Bank to increase disaster response capabilities.

Sub-conclusion

The paired earthquake events that occurred in the Ica region of Peru on August 15, 2007, and October 28, 2011, had significant impacts on the region. The 2007 earthquake, with a magnitude of 8.0, brought about devastating consequences.

One of the key factors contributing to the severity of the 2007 earthquake's impact was the vulnerability of the structures in the region. Inadequate retrofitting of older buildings left them susceptible to damage, particularly masonry constructions made of clay and brick. Even some reinforced concrete structures suffered significant harm or collapsed due to a lack of ductile details. This highlighted the importance of retrofitting and modern seismic design requirements to enhance the resilience of structures in earthquake-prone areas.

The 2007 earthquake also exposed shortcomings in the region's risk management and emergency response capabilities. The lack of preparedness and resources at the regional and local levels hindered effective coordination and response to the disaster. Weak communication skills and a lack of capacity among government institutions, academic staff, instructors, and healthcare personnel further exacerbated the challenges in providing timely information and assistance to those affected, particularly the students.

However, the 2007 earthquake served as a turning point in Peru's approach to disaster risk management. Efforts were made to improve preparedness and coordination, as well as enhance infrastructure resilience. The establishment of the National Safe Hospitals Policy in 2010, which included vulnerability reduction initiatives for hospitals and health institutions, aimed to ensure the continuity of essential services during and after disasters.

Following the 2007 earthquake, geological hazard maps were developed to identify regions prone to seismic activity, landslides, and floods. Additionally, regional plans for disaster prevention and response were created, focusing on protecting the population and assets of the Ica region. These initiatives reflected a growing recognition of the importance of proactive risk reduction measures and strategic planning.

The 2011 earthquake, although less severe in terms of magnitude and impact, demonstrated some improvements in risk management. The development of hazard maps and the implementation of regional plans were instrumental in guiding preparedness efforts. However, challenges remained, and it was noted that the regional plan for disaster prevention and response had not been fully implemented, indicating the need for sustained commitment and adherence to risk management strategies.

Paired Event ID 6 - Indonesia

Paired earthquake event: 26th December 2004 and 28th March 2005 Earthquakes in Nias island, Sumatra, Indonesia

Short description of both events with a focus on impacts

One of the planet's most active tectonic regions is found in Indonesia (Cummins 2017). On December 26, 2004, a devastating subduction earthquake occurred off the Sumatra coast of Indonesia. The earthquake was caused by the subduction zone between the Indian plate and the Burma microplate rupturing. The Indian plate has been subducting beneath the prevailing Burma microplate at a rate of about 60 mm per year. Indonesia's Banda Aceh was located 255 kilometres south-east and 155 kilometres west of the earthquake's epicentre, respectively (Saatcioglu et al. 2005). The earthquake was the second-largest one that a strong motion seismograph had ever recorded (Stein and Okal 2005). More than 170,000 people were killed in Indonesia by the earthquake and subsequent tsunami. Also approximately 1.7 million people were displaced (Telford and Cosgrave 2006). Telford and Cosgrave (2006) state that Indonesia accounted for nearly half of the affected region's total economic cost of the damage and ensuing losses, which was estimated at US$9.9 billion.

Only three months after causing the second-largest earthquake ever to be instrumentally recorded (Stein and Okal 2005), the Sumatra abduction Zone (SSZ) produced another large earthquake that rocked offshore of West Sumatra, Nias island, Indonesia, on March 28, 2005. The consecutive hazard occurred only a few hundred kilometres south of Sumatra's most severely affected earthquake zones (Borrero et al. 2011). Between Simeulue Island in the north and the Batu Islands in the south, the event resulted in significant earthquake damage and alterations to the land's elevation (Borrero et al. 2011). Moreover, the Sumatra shoreline and nearby islands were damaged by its generated tsunami that hit Sumatra on March 28, 2005, over a 500-kilometer stretch of its coastline (Borrero et al. 2011). The earthquake claimed the lives of 839-915 people and injured more than 6300 people (CRED 2023; Beetham and Sinclair 2008).

Descriptions of processes between events with a focus on risk management

In 2004, The majority of the reinforced concrete frame structures were supported by smaller-sized columns and had sturdy, relatively deep beams. As a result, there was widespread column hinging throughout the region while the majority of the beams were elastic up until the structure collapsed, leading to frame stability failures overall. The damaged columns were investigated, and it was discovered that there were no detailed, properly spaced seismic design hoops. Column flexural failures were the result, particularly in soft stories and places where the strong-column weak-beam design philosophy had not been applied. Non-engineered building columns clearly lacked the necessary volumetric ratio, as well as the spacing and detailing of column ties, but neither did engineered building columns have enough transverse reinforcement (Saatcioglu et al. 2005). Moreover, unreinforced masonry walls predominated in the affected area. As exterior and interior infill walls, as well as partition walls, brick and block walls were utilised. The building's mass was increased by these walls, which attracted seismic forces. They could support structures until their elastic limits were reached. In response, they either experienced sliding shear failures or diagonal tension cracks followed by diagonal compression strut crushing (Saatcioglu et al. 2005).Also, due to a lack of understanding or budgetary restrictions, many property owners in Indonesia did not engage in seismic risk reduction measures such as retrofitting or strengthening their structures (Birkmann et al. 2009)

According to Birkmann et al. (2009), private property risk mitigation measures were also not executed efficiently prior to and after the seismic disasters. As a result, several susceptible structures were badly damaged or destroyed during the earthquakes. Another issue affecting non-structural risk management procedures in Indonesia was the lack of hazard maps. There was a paucity of comprehensive and up-to-date hazard maps prior to both the 2004 and 2005 earthquakes that may guide land-use planning and risk mitigation measures. As a result, authorities and property owners found it difficult to identify and prioritise regions for seismic risk reduction measures (Birkmann et al. 2009).

Event comparison with respect to hazard

The magnitude of the 2004 earthquake was 9.1-9.3 (USGS 2019b; Saatcioglu et al. 2005), whereas the magnitude of the 2005 earthquake was 8.7 (Kreemer et al. 2006). The 2004 Great Sumatra Earthquake lasted 3-4 minutes (USGS 2019b). The averaged MMI was IX in Indonesia, the most affected area, 13 other countries in South Asia and East Africa also felt the earthquake but with a lower MMI intensity (NCEI 2023).

Approximately three minutes of Modified Mercalli (MM) IX to X intensity shaking, during which people were unable to stand, were produced for the entire Nias Island by the great Nias earthquake of 2005 (2.07° N, 97.01° E), according to descriptions of those who experienced it, observations of the damage it caused, and seismic calculations (Beetham and Sinclair 2008). Because of its prolonged length, the 2005 earthquake (2.1°N, 97.1°E) triggered soil liquefaction in the impacted areas. Soft soil in the area contributed to the seismic waves' amplification (Saatcioglu et al. 2005). The 2005 earthquake had a relatively shallow focal depth of 30 kilometres (Ciu et al. 2023; NGDC/WDS (2023). The focal depth of the 2004 earthquake was the same, 30 km (Saatcioglu et al. 2005; NGDC/WDS (2023).

Event comparison with respect to exposure

Over 100,000 residences were damaged or destroyed as a result of the 2004 earthquake. Additionally, 693 hospitals or clinics, 1,662 schools, 2,580 mosques, 1,412 government buildings, 1,416 market and kiosk units, and 2,617 km of road were destroyed or damaged (Meisl et al. 2006). Millions of people were affected by the earthquake (Dilley 2005).

The earthquake that devastated Nias in 2005, which had a population of 710,000 at the time, primarily made up of rural regions, resulted 13,000 homes being destroyed, 60,000 homes being damaged, 12 ports and piers being destroyed or damaged, 400 bridges being destroyed, 1,000 km of road being rendered impassable, 760 government buildings being damaged, 720 schools being destroyed, two hospitals, 350 health clinics being destroyed, 1,940 religious structures (churches and mosques) being damaged (Beetham and Sinclair 2005). According to the risk analysis of Dilley (2005), millions of people were affected by the 2004 earthquake.

The main affected areas of the 2005 earthquakes were: (1) Nias Island, Nias Province, and the districts' capitals of Gunung Sitoli, Gido, and Teluk Dalam; (2) Simeulue Island, province of the NAD; (3) Pulau Banyak, Province of the NAD; (4) The NAD Province of Singkil (ReliefWeb 2005). The population that was impacted by the earthquake is not known accuracy. In Simeulue, 12,000 people are reportedly impacted, while 152,320 people are reportedly affected in Nias (ReliefWeb 2005), including 22,000 people being displaced as a result of the 2005 earthquake (Meisl et al. 2006).

Event comparison with respect to vulnerability

The consecutive earthquake in 2005 served to further exacerbate the region's already high level of vulnerability among the populace as a result of the severe consequences of the 2004 event (Borrero et al. 2011).

During the first earthquake there was low risk awareness (Gaillard et al. (2008). Because of the publicity surrounding the December tragedy, the local population was very aware of the threat posed by earthquakes and tsunamis; many people made the wise decision to flee to higher ground where a direct observation of the event was not possible (Borrero et al. 2011). Moreover, according to Adiyoso and Kanegae (2012), after the 2004 earthquake and tsunami event, governments, municipal, national, and international agencies, as well as non-governmental organisations, worked hard to educate people so that they would be more prepared in the event of a disaster. Governments have made attempts to provide school-based disaster education, including disaster risk reduction, because children are one of the most susceptible populations to catastrophes. It was hoped that by introducing curriculum-based disaster education in schools, students would become more conscious of disasters (Adiyoso and Kanegae 2012).

The lack of an early warning system and people's inability to prepare played a key role in the impacts of the 2004 earthquake (Adiyoso and Kanegae 2012).

Following the tsunami that rocked Aceh province on December 26, 2004, the 28 March 2005 earthquake beneath Nias Island, and the 27 May 2006 earthquake in Yogyakarta, the IFRC's capacity to help the

Indonesian Red Cross has grown significantly in terms of personnel and resources in the nation. There is currently a strong IFRC presence in-country, with 12 partner national societies (with approximately 32 experienced delegates and 320 national staff) and a Federation country team of 19 delegates and 282 national staff who support the PMI in its emergency and longer-term programming (IFRC 2010). Telford and Cosgrave (2006) state that a massive, globally coordinated response ensued, resulting in an estimated $13.5 billion in foreign aid for the 2004 quake.

Sub-conclusion

The paired earthquake events that occurred on Nias Island, Sumatra, Indonesia, on December 26, 2004, and March 28, 2005, had significant impacts on the region. The 2004 earthquake, with a magnitude of 9.1–9.3, and its subsequent tsunami resulted in catastrophic consequences. The vulnerability of structures played a role in the severity of the impact. Inadequate seismic design and a lack of retrofitting measures contributed to widespread failures in both reinforced concrete and non-engineered buildings. Furthermore, the lack of comprehensive risk management and preparedness measures before the events worsened the impacts. Insufficient understanding of seismic risks, limited budget allocations for risk reduction, and a lack of hazard maps hindered effective planning and mitigation efforts. This led to a high number of damaged or destroyed buildings and infrastructure.

The consecutive earthquake events in 2005 revealed some improvements in risk management and preparedness. Public awareness campaigns and educational programmes aimed at increasing knowledge of seismic hazards and evacuation procedures contributed to a more informed population. The media coverage and international response to the 2004 earthquake also led to a significant increase in resources and personnel for disaster response and recovery.

Paired Event ID 7 - Haiti

Paired earthquake event: 12th January 2010 and 14th August 2021 Earthquakes in the Republic of Haiti

Short description of both events with a focus on impacts

The earthquake that devastated Haiti on January 12, 2010, was one of the deadliest earthquakes in history; the most reliable assessments of victims (according to the U.S. Geological Survey (USGS) is 158,679 fatalities and more over 300,000 injuries (Kolbe et al. 2010, cited in Harp et al. 2016). In terms of the number of persons killed as a percentage of the population of the country, the earthquake was the most damaging hazard any country has suffered in modern times, according to the Inter-American Development Bank (IDB) (Cavallo et al. 2010).

Also, the USGS tracked 23,567 landslides, in a region of approximately 5,000 km^2, which were sparked by the intense shaking. These landslides occurred throughout a large portion of Haiti, leading to extensive damage to infrastructure such as buildings, roads, and bridges (Harp et al. 2016). The earthquake's direct economic effect was estimated to be $7-14 billion (i.e. approximately 100% of Haiti's GDP), with an indirect economic impact of around $4.3 billion (Cavallo et al. 2010; DesRoches et al. 2011).

The devastating 2010 earthquake in southern Haiti was followed 11 years later by the Nippes, Haiti, earthquake on August 14, 2021 (Douilly et al. 2022). The earthquake's epicentre was 13 kilometres south-southeast of Petit Troup de Nippes, and it was felt strongly throughout the entire region, including all of Hispaniola (Haiti and the Dominican Republic) and the islands of Jamaica, Cuba, and Puerto Rico (USGS 2021). The Enriquillo-Plantain Garden fault zone, the main fault structure and microplate border in the area, appears to be the faulting mechanism for this earthquake, similar to the 2010 event (USGS 2021). The quake was less severe than the 2010 earthquake. Nevertheless, the earthquake also resulted in the deaths of 2575 people (CRED 2023) and injured over 12,763 people (CRED 2023). The direct economic loss is approximately 1.6 billion USD; recovery costs were estimated to be approximately 1.98 billion USD (Whitworth et al. 2022). A total of 4,893 landslides occurred on the Tiburon Peninsula as a result of this earthquake. Because the landslides blocked roads and damaged other infrastructure, they made it difficult to respond (Martinez et al. 2021).

Descriptions of processes between events with a focus on risk management

The structures in the earthquake-affected area performed poorly due to a lack of an effective building code, insufficient seismic proportioning and detailing, subpar construction materials, and a lack of quality control. Slender columns and insufficient transverse reinforcement were just two examples of the many flaws that were known to contribute to seismic damage in typical reinforced concrete frame buildings with concrete block infill (DesRoches et al. 2011).

Buildings in Haiti are frequently made of fragile, poor-quality concrete with thin steel reinforcing bars that are lacking between columns and floors where earthquake stress is greatest, jeopardising structural integrity (Bilham et al. 2010). Following the earthquake in 2010, the Haitian government established the Housing and Public Buildings Construction Unit (UCLBP) to develop construction codes and educate masons to rebuild better and limit the risks of future disasters. However, both the UCLBP and masons have financial issues because construction materials are expensive and building code enforcement was not always a government priority (Maçon et al. 2022). The state lacked the institutional ability to enforce construction codes (Felima 2009; Caplan 2021).

According to the report of Kolbe et al. (2010), the high fatality rates during the 2010 earthquake were caused by a lack of government construction rules and health facilities before the earthquake. They also state that urban expansion happened without adequate assessment of seismic risk, resulting in the construction of buildings and infrastructure in hazard-prone locations. During the 2010 quake there was only had one outdated seismic hazard map that was too vague to be of any use (DesRoches et al. 2011). The top geological map was published in 1987 (Lambert et al. 1987). Kolbe et al (2010), also states that there was a lack of comprehensive and up-to-date hazard maps prior to the 2010 earthquake that may guide land-use planning and risk mitigation measures (Kolbe et al. 2010).

According to Felima et al. (2009) and Caplan et al. (2021), the Haitian state still lacked urban planning measures by 2021. Eberle (2021) states that, for example, Port-au-Prince was planned to contain 3,000 people but had grown to almost a million by 2015.

Event comparison with respect to hazard

The 2010 earthquake (18.4°N., 72.6°W) lasted around 35 seconds (Harp et al. 2016), 25 kilometres (km) southwest of Port-au-Prince, Haiti's capital. Hough et al. (2011) report a main shock shaking with MMI of VIII. The magnitude of the 2010 earthquake was 7.0 (Hayes et al. 2010). The focal depth of the 2010 earthquake was relatively shallow, approximately 13 kilometres (DesRoches et al. 2011).

In 2021, the Enriquillo-Plantain Garden fault zone was predominantly ruptured westward with reverse and left-lateral strike-slip action. The rupture began in the middle of the Tiburon Peninsula, about 125 km west of Port-au-Prince at a depth of 10 km (USGS 2021). Along an 80-km stretch of steep, mountainous, and landslide-prone terrain in the middle of the Tiburon Peninsula, shaking was estimated by the U.S. Geological Survey (USGS) ShakeMap to have surpassed 0.5 g (acceleration of gravity) (Martinez et al. 2021); thus the Nippes earthquake had an MMI of VII. The magnitude of the 2021 earthquake was 7.2 (Douilly et al. 2022). The duration of the ground shaking lasted 20 seconds (Calais et al. 2022), and the focal depth was around 10 km (USGS 2021).

Event comparison with respect to exposure

The 2010 earthquake displaced more than a million people, and destroyed around half of the area's infrastructure (DesRoches et al. 2011). In the city of Le'ogane, close to the epicentre of the earthquake, 80%–90% of the structures are thought to have been severely damaged or destroyed. The cities of Carrefour, Pe'tion-Ville, Delmas, Tabarre, Cite Soleil, and Kenscoff were among those badly impacted in the metropolitan Port-au-Prince area (DesRoches et al. 2011). More than 300,000 houses were destroyed or severely damaged. In addition, 80% of the nation's schools and more than 50% of its hospitals were destroyed or damaged, and it is estimated that 60% of the country's administrative and economic infrastructure was lost (Government of the Republic of Haiti 2010). The presidential palace and the parliament were among the more than 180 government structures and 15 important government offices that were destroyed. For several months following the earthquake, the response and rehabilitation were slowed by the partial devastation of Port-au-Prince's main port and the obstruction of roadways by debris. The earthquake left more than 2.3 million people without a house, at the peak of displacement, according to the Interim Haitian Reconstruction Commission (DesRoches et al. 2011).

Over 1 million people are believed to have been exposed to very strong or severe shaking levels as a result of the earthquake that struck Haiti on August 14, 2021 (USGS 2021). The overall impacted area is 500 square km (ReliefWeb 2022). Also, 137,000 homes were destroyed as a result of the quake (UN OCHA 2021; Withworth et al. 2022).

Event comparison with respect to vulnerability

Haiti was barely getting over the devastation of the 2010 earthquake when the earthquake of 2021 struck. A substantial number of people moved from the east to the west of Haiti as a result of the 2010 earthquake, changing these regions' vulnerability and susceptibility to earthquakes in the future (Whitworth et al. 2022).

Haiti is the poorest country in the Western Hemisphere and lacked an effective government and institutions prior to the earthquake, which increased vulnerability. There has not been much seismic activity in Haiti since the 18th and 19th centuries, which made people less aware of earthquake risks and prepared for them (DesRoches et al. 2011).

According to Calais et al. (2020), a study performed following the 2010 Haiti earthquake indicated that 65% of respondents said the possibility of a comparable earthquake occurring during their lifetime was "very high" or "high," showing an increase in earthquake risk awareness short before the 2021 earthquake. The survey also discovered that the great majority of respondents knew more about safety precautions to take before, during, and after an earthquake, which were mostly communicated by the scientific community and the media.

During the 2010 earthquake, a preparedness program and an earthquake contingency plan were absent, as seismic design, seismology, and the geosciences were not typically covered in university curricula (DesRoches et al. 2011). According to the PreventionWeb (2022), Haiti has benefited from the lessons learnt in 2010. The government was better prepared in 2021 as it developed a National Risk and Disaster Management System. This system was used by the government to activate the National and Departmental Emergency Operations Centres on the day of the earthquake. Local United Nations Development Programme (UNDP) personnel on the ground noticed a culture of communal togetherness. People were able to respond more promptly and efficiently after learning from the 2010 quake. For example, they observed the compassion of a group of anonymous civilians who sailed to a remote place to provide fruit and even trees to inhabitants (PreventionWeb 2022).

According to Kirsch et al. (2012), the unprecedent magnitude of the 2010 Haiti earthquake and the simultaneous loss of Haitian government and United Nations (UN) leadership resulted in a disaster response directed by the US government and military. The response was fast and large in scope, but leadership and logistical assistance were insufficient to handle the size of the response, especially in the first month following the accident, and the UN cluster system struggled with the inflow of other agencies and individuals, complicating the health care response. The health-care response was tremendous, but it was often inefficient and poorly organised, and it provided services that could not be sustained by the existing health-care system. 67 multinational urban search and rescue teams from over a dozen nations deployed to Haiti and performed 136 live rescues. The first teams came the day following the event, including one from the United States, and by day four, there were 26 teams in Haiti. The United States government sent six teams totalling 511 people, four of which were domestic teams backed by the Federal Emergency Management Agency. They performed 47 live rescues at a cost of $51 million (Kirsch et al. 2012).

Within minutes after the disaster caused by the 2021 earthquake, UNDP was collaborating with the Haitian government at the national and departmental levels to put the post-earthquake response plan into action (PreventionWeb 2022). In collaboration with local agencies, the UNDP post-earthquake project response commenced in the three impacted departments. They carried out coordination, economic recovery, and risk assessment tasks. The piling of debris in the streets was one of the most serious issues in the impacted communities. To combat it, they collaborated with local governments to organise waste removal. They aided volunteer teams in the commune of Maniche, who even utilised collected rubble to build a road (PreventionWeb 2022).

Sub-conclusion

The earthquake that struck Haiti on January 12, 2010, was one of the deadliest earthquakes in history. It resulted in extensive damage to infrastructure, including buildings, roads, and bridges. The earthquake caused significant loss of life and injuries, making it one of the most devastating disasters the country has ever faced. The earthquake that occurred on August 14, 2021, in Haiti was the second major earthquake to hit the country in the 21st century. While it was less severe than the 2010 earthquake, it still caused significant damage and loss of life. The earthquake triggered numerous landslides, which further hampered response efforts and made it challenging to provide aid to affected areas.

In terms of risk management, both events highlighted the vulnerabilities and shortcomings in Haiti's construction practises and infrastructure. The lack of effective building codes, poor-quality construction materials, and insufficient seismic proportioning and detailing contributed to the inadequate performance of structures during earthquakes. Despite efforts to establish construction codes and educate builders after the 2010 earthquake, challenges in enforcing regulations and financial constraints persisted. Regarding hazard comparison, the magnitude of the 2010 earthquake was 7.0, while the 2021 earthquake had a magnitude of 7.2. Both earthquakes had relatively shallow focal depths. The 2010 earthquake caused extensive damage and displacement of people, with a significant impact on infrastructure, including schools and hospitals. The 2021 earthquake affected a densely populated area, resulting in widespread destruction of homes and infrastructure. In terms of vulnerability, Haiti's status as the poorest country in the Western Hemisphere and its lack of effective government institutions amplified the impacts of both earthquakes. The country's limited resources and inadequate preparedness further increased its vulnerability to seismic events. However, the 2021 earthquake showed some in awareness, preparedness, and crisis management, with the government activating emergency operations centres promptly and benefiting from lessons learned from the 2010 earthquake.

Paired Event ID 8 - Chile

Paired earthquake event: 14th November 2007 and 16th September 2015 Earthquakes in Chile

Short description of both events with a focus on impacts

Chile, because of its location on the Pacific Ring of Fire, has some of the world's greatest seismic and volcanic activity (Bronfman et al. 2016). The Tocopilla earthquake that struck the northern coast of Chile on November 14, 2007, was the consequence of the South American continental plate subducting beneath the Nazca plate (Astroza et al. 2008). Significant seismic activity caused severe damage to infrastructure, including buildings, roads, and bridges. Two people were killed (CRED 2023) and 155 people were injured as a result of the earthquake (CRED 2023). Moreover, a substantial amount of structural damage to residential building caused the displacement of 29,000 people (Cimellaro et al. 2010). The economic damage was approximately 151 million USD (CRED 2023).

The September 16, 2015 earthquake in Illapel, Chile developed as a result of thrust faulting along the plate boundary in Central Chile between the Nazca and South America plates (USGS 2015). It had a larger magnitude than the earthquake in 2007 and generated a tsunami severely affecting the region. The earthquake claimed the lives of 19 people (CRED 2023) and injured 34 others (USGS 2015). The economic damage was approximately 1.1 billion USD (CRED 2023).

Descriptions of processes between events with a focus on risk management

Chile is one of the world's seismically active countries and as a result of the region's frequent past seismic activity, Chilean building codes include seismic impacts consideration, and building practice includes seismic-resistant design (Telleen et al. 2012). Earthquake-focused construction codes that aid in the prevention of collapses were developed from early on (Hart et al. 2022).

Chilean engineers responded to the first earthquake by changing design spectra, changing the triggers that determine when special boundary zone detailing in walls is required, limiting compressive strains in walls, imposing minimum thickness requirements for wall boundaries, and improving detailing provisions for wall boundaries and shear reinforcement (Telleen et al. 2012).

Event comparison with respect to hazard

The earthquake of 2015 (31.6°S 71.7°W) was more severe than the earthquake of 2007 in terms of magnitude. The earthquake of 2015 had a magnitude of 8.3 (Aránguiz et al. 2017; USGS 2015), while the earthquake of 2007 had a magnitude of 7.7 (Astroza et al. 2008). The 2015 quake had a MM intensity of VIII (Schaefer et al. 2015; USGS 2015) and the 2007 quake also had a MII of VIII (NGDC/WDS 2023).

The earthquake of 2015 also caused severe soil liquefaction in the affected areas due to its longer duration. The focal depth of the earthquake of 2007 was relatively shallow, at 39 km (Barrientos 2007), while the focal depth of the earthquake of 2015 was even more shallow, at 22.4 km (USGS 2015).

Event comparison with respect to exposure

The earthquake in 2007 covered an area of ~9,000 km^2 (Bejar Pizarro et al. 2008), and in 2015 the area affected area was ~30,800 square kilometres (Aochi and Ruiz 2021). The 2007 earthquake affected 702,763 people and the earthquake in 2015 affected 25,155 people (CRED 2023). Approximately 16,650 people were displaced after the 2015 earthquake, with thousands of houses damaged (Li et al 2016).

Event comparison with respect to vulnerability

Due to the frequency of earthquakes, the Chilean government has substantially invested in numerous earthquake risk reduction measures, , including public awareness campaigns, and has seen low levels of mortality following several quite powerful earthquakes (Hart et al. 2022)

Initiatives to create awareness and inform the public about disaster preparedness measures have also being developed in the years between the events, such as the continuous monitoring and warning system for natural hazards and the increasing frequency of simulation exercises since 2010. These activities have been attended by schools, municipal governments, police, and the military forces. Along with public events and the distribution of recommendation manuals, programmes/campaigns such as

"Prepared Family" and the "Comprehensive School Safety Plan for Nurseries and Day-Care Centres" have been established. All of this has been done to promote public awareness of natural hazards and educate them on the precautionary steps that should be taken in each earthquake event (Bronfman et al. 2016).

According to Bronfman et al. (2016), the National Policy for Disaster Risk Management, which established the National System of Risk and Emergency Management, was passed in 2014. This policy aimed to enhance institutions, monitoring and early warning systems, as well as the culture of disaster prevention and preparedness.

On November 17, 2007, 150,000 Swiss Francs was provided from the Federation's Disaster Relief Emergency Fund (DREF) to help the national society in giving assistance to about 6,250 individuals (CRC 2007). Similarly for the second hazard, the DREF provided ~160,000 Swiss Francs in 2015 (IFRC 2016).

Sub-conclusion

Both the Tocopilla earthquake in 2007 and the Illapel earthquake in 2015 were significant seismic events in Chile. The Illapel earthquake, which occurred in 2015, was more powerful with a magnitude of 8.3, while the Tocopilla earthquake in 2007 had a magnitude of 7.7. The Tocopilla earthquake caused extensive damage to infrastructure, including buildings, roads, and bridges, while the Illapel earthquake had additional impact due to the generation of a tsunami that severely affected the region. The Tocopilla earthquake resulted in the displacement of approximately 50% more people than the Illapel earthquake.

Chile, being located in a seismically active region, has implemented strict building codes and seismic-resistant design practises. Engineers made improvements to building designs and detailing provisions to enhance earthquake resilience. The government of Chile has also invested in earthquake mitigation methods, public awareness campaigns, and disaster risk management. Initiatives such as the National Policy for Disaster Risk Management, established in 2014, aim to strengthen institutions, monitor early warning systems, and promote a culture of disaster prevention and preparedness. International assistance was provided in response to both earthquakes. The Federation's Disaster Relief Emergency Fund (DREF) extended support to aid the affected population and assist in the recovery efforts. The assistance from international organisations highlights the global recognition of the significance of these seismic events and the need for collaborative efforts in response and recovery.

Paired Event ID 9 - Italy

Paired earthquake event: 6th April 2009 and 24th August 2016 Earthquakes in Italy

Short description of both events with a focus on impacts

An earthquake struck the Abruzzi region of Central Italy on April 6, 2009 (Tertulliani et al. 2011) as a result of the Paganica Fault rupturing (Çelebi et al. 2010). The epicentre occurred 85 kilometres northeast of Rome and 6 km southwest of L'Aquila, the regional administrative centre of Italy (Cimellaro et al. 2010; Tertulliana et al. 2011). Approximately 300 people were killed (Çelebi et al. 2010; Cimellaro et al. 2010; CRED 2023) and over 1,500 were injured as a result of the earthquake (Çelebi et al. 2010; Cimellaro et al. 2010). The earthquake's direct economic effect was estimated to be 4 billion USD (Rossetto et al. 2011).

The Amatrice earthquake that rocked Italy on August 24, 2016, killed 296 people and injured 400 (CRED 2023). According to the estimate from the Italian Civil Protection Department, the earthquake caused economic damages of approximately $11 billion (EERI 2023).

Descriptions of processes between events with a focus on risk management

The 2009 earthquake in L'Aquila, Italy, brought to light the fact that due to "strengthening" retrofit work carried out in the previous 50 years, the seismic vulnerability of old masonry structures and palaces had worsened (Cimellaro et al. 2010). The use of conventional reinforcement methods, such as replacing the original wooden roof structure with new reinforced concrete or steel elements, installing new reinforced concrete floors and new reinforced concrete floors, and using reinforced concrete jacketing on the shear walls, was advised by the Italian seismic standard. Because they produce deformations that are incompatible with brick walls and higher seismic forces (owing to heavier loads), these retrofit treatments have a number of limitations, as demonstrated by the L'Aquila earthquake (Cimellaro et al. 2010). The structures' collapses were caused by: (i) poor building construction quality; (ii) poor material quality; (iii) inadequate knowledge of the structure's seismic reaction and inadequate design; (iv) poor maintenance; and (v) vertical and horizontal building development without a thorough examination of the original structure's static behaviour (Cimellaro et al. 2010). Most people were asleep when the earthquake occurred, making the collapse of residential structures—primarily low-rise, unreinforced masonry construction—a substantial factor to the risk to life (Cimellaro et al. 2010). Thus, building rules were less restrictive during this time period than they are now, especially since construction in L'Aquila was not subject to the most stringent limitation (Alexander 2019). Moreover, 55 students who were housed at University of L'Aquila buildings perished in the 2009 earthquake. The university of L'Aquila lacked a pre-disaster mitigation and recovery strategy, and only a tiny number of students knew some emergency measures, stated by Magni et al. (2017).

Following the catastrophic 2009 L'Aquila earthquake, the Italian Civil Protection Department (ICPD) established the National Seismic Prevention Plan (NSPP), with a total endowment of 965 million euros provided by law (Dolce 2012). The Italian government set out to address several facets of the disaster risk cycle. Notably, it introduced a National Plan for Seismic Risk Prevention that placed a high focus on the construction of secure public structures. In order to lower the likelihood of human (rather than economic) losses, further measures included seismic retrofitting or rebuilding of structures and pushing a risk-awareness campaign targeted at the most susceptible sections of the nation (Dolce 2012).

The epicentral area of the 2016 earthquake was included in the greatest probability of seismicity on the official seismic hazard map of the Italian Civil Protection. The earthquake was consistent with the seismic history of the affected area, where the "worst-case scenario" is an earthquake with a magnitude greater than 6 (Piccardi et al. 2016). However, many buildings still severely damaged due to their fragility, since they were largely ancient masonry structures lacking sufficient anti-seismic strengthening methods (Piccardi et al. 2016)

Event comparison with respect to hazard

The magnitude of the 2009 earthquake was 6.3 (Alexander 2010), whereas the magnitude of the 2009 earthquake was 6.3 (Alexander 2010). The MMI of the 2009 earthquake was VIII (USGS 2009) and the MMI of the 2016 earthquake was X-XI (Fiorentino et al. 2018). The focal depth of the 2009 earthquake was shallow, approximately 8.8-9.5 km (Çelebi et al. 2010; Cimellaro et al. 2010), but the focal depth of the 2016 earthquake was even shallower, 4.4 km (USGS 2016b). The 2009 earthquake lasted about 20 seconds (Bressan 2012) and the 2016 quake had a duration of approximately 50 seconds (Formisano et al. 2017).

Event comparison with respect to exposure

In the Abruzzo Region of Central Italy, the 2009 earthquake caused major damage to modern reinforced-concrete-framed structures with hollow masonry infill walls as well as significant damage to centuries-old buildings of high cultural significance. Although there were serious and widespread structural flaws, analysis of the features of strong motion data from the severely afflicted region suggests that the brief duration of the violent shaking may have prevented the collapse of many more damaged structures. It is acknowledged that the infill walls may have played a significant role in averting further degradation or the collapse of many structures, with the proviso of short-duration shaking (Çelebi et al. 2010). The earthquake completely destroyed the city L'Aquila, with a population of almost 70,000; a total of 64,812 individuals were left homeless as a result of the major event, with about 32,100 residing in tents and 32,700 staying in hotels along the Adriatic coast (Çelebi et al. 2010; GSC 2010). A total of approximately 70,000 people were affected by the 2009 earthquake event (CRED 2023). Initial evaluations showed that 55% of the buildings in L'Aquila could be used, 15% could be used with minor modifications, 20% could not be used, and the remainder needed more research. 50,000 structures, including offices, factories, and public buildings, were impacted (GSC 2010).

The Accumoli earthquake in 2016 displaced 4,000 people and numerous structures in the affected region were destroyed (approximately 80000) or damaged (approximately 260,000) (Nievas et al. 2020). A total of approximately 56,000 people were affected by the 2016 earthquake event (CRED 2023).

Event comparison with respect to vulnerability

Despite the fact that the Italian region is known to be very seismic, the city and municipality of L'Aquila had been classified as having "moderate seismicity" since 1915. According to Castaños and Lomnitz (2002) it either represents a failure of probabilistic seismic hazard analysis to accurately portray the situation or it represents a deliberate move to reduce construction costs in L'Aquila city by imposing a lighter regime - putting residents at risk of structural collapse in earthquakes. In any scenario, it demonstrates legislative inertia in the face of scientific understanding of hazard. Moreover, the analysis of Imperiale and Vanclay (2019) reflected on the 2009 earthquake and revealed a widespread lack of understanding of the relationship between social vulnerability, risk, and impacts of earthquakes; a lack of risk definition in all dimensions and a lack of procedure for proper disaster risk assessment and management in regulatory frameworks; a lack of awareness about the transformative role of science for DRR purposes; and, as a result, a lack of planning and monitoring of DRR strategies.

After the 2009 earthquake, Italy was concerned with increasing the population's and decision-makers' knowledge of seismic risk, and was particularly active in fostering a culture of preventive and civil protection. Furthermore, with the assistance of the competence centres, pamphlets providing clear explanations of seismic risk and conduct norms in the event of an earthquake have been prepared and extensively disseminated. Also, various risk-awareness campaigns were advocated and participated in in Italian schools, carried out at the national level by NGOs, and has funded specialised INGV programmes (Dolce 2012).

Following the adoption of a national legislation (No. 225 of 1992) that established the Italian Civil Protection system, Abruzzo Regional legislation No. 72 of 1993 required the region to develop an emergency plan and arrange civil protection services. There is no clear reference in this legislative instrument to the necessity for towns to create preparations, and a fully-fledged emergency plan was not implemented in L'Aquila city until February 2015 (Comune dell'Aquila 2015). Although the Italian Civil Protection system is well established (OECD 2010), it is largely top-down, and it had to compensate for the weaknesses of the municipal, provincial, and regional institutions during the 2009 earthquake. Moreover, in 2009, overall there was little culture of preparing for hazards, and the majority of efforts were directed towards the emergency stage; there are no available data on the effectiveness of preparatory measures and national early warning systems (Dolce 2012).

Procedures are used when planning is inadequate or non-existent, which was the case during the 2009 earthquake. During the early crises in L'Aquila, the promptness of the nationally coordinated convergence response effectively saved the day. Medivac, or helicopter evacuation of the injured (mainly to hospitals on the Adriatic coast), compensated for serious damage to L'Aquila's regional hospital (Casarotti et al. 2009). Two field hospitals were established, one in a record time of 23 hours 30 minutes, but, as with prior catastrophes (Von Schreeb et al. 2008), they offered continuity of normal treatment rather than emergency medical surge capacity, since the surge had been dealt with once they were operational. Also, the civil protection was able to mobilise 12,000 volunteers for search and rescue efforts and following operations. Additionally, 2,300 firefighters were called to duty (GSC 2010). Moreover, the findings of Paganini et al. (2016) show that Italian Emergency Department physicians on duty had a limited understanding of key hospital disaster preparedness principles at the time of the earthquake.

A state of emergency was announced on August 24, 2016, after the rapid activation of the Civil Protection Department, and it remained in effect until August 19, 2017. On August 28, 2016, a command-and-control centre was formed in Rieti, where it remained until April 7, 2017, to coordinate emergency management actions throughout four areas. Its mission was to help the people, assess damage to structures and artistic and cultural heritage places, investigate alternative housing possibilities, and support production operations (Frigerio et al. 2019). The next day, firefighters, army forces, police forces, the Italian Red Cross, the National Alpine Corp, and Speleological Rescue were all quickly dispatched for civil protection operations, totalling 5,400 rescuers in a matter of days. Thousands of civil protection volunteers from national and local organisations were deployed in the field, mostly to assist the general public but also to support coordination centres and local health services (IFRC 2022).

The Italian government spent about one billion euros towards earthquake protection after the devastating Abruzzo Earthquake of April 6, 2009. Despite the fact that this sum is only a small portion of what is actually required, a broad-based national strategy for seismic risk reduction has been put into place (Dolce 2012). The plan's main goal was to prevent human casualties, and the Italian Civil Protection Department is in charge of its strategy and oversight. As a result, the activity was targeted particularly at high-risk and high-hazard places. According to a more comprehensive and long-term approach to seismic risk mitigation, it was implemented not only through the seismic upgrading of structures, resulting in an immediate reduction of the seismic risk of the retrofitted constructions, but also through the evaluation of the local seismic hazard and the seismic resilience of urban systems (Dolce 2012). Moreover, the European Commission provided Italy 494 million euros to assist with the aftermath of the Abruzzo earthquake in 2009. This European Union funding helped to cover the costs of the Italian authorities' emergency measures, such as the supply of temporary housing, the restoration of critical infrastructure (power stations, water distribution networks, highways), and the clearance of rubble and damaged settlements. The assistance will not be utilised to compensate for private property damage (European Commission 2009).

The Council of Ministers announced authorised 50 million euros for the relief and recovery operations of the 2016 earthquake (IFRC 2022). Following the earthquakes in 2016, the European Commission proposed to collect 1.2 billion euros through the EU Solidarity Fund (EUSF), the largest sum ever raised in a single instalment. This fund was used to aid in reconstruction following the earthquakes that struck central Italy (European Parliament 2017).

Sub-conclusion

The earthquakes that struck Italy in 2009 and 2016 shared several significant characteristics and had far-reaching consequences. The 2009 earthquake centred near L'Aquila, a historic city in the Abruzzo region, while the 2016 earthquake occurred near Amatrice in the central part of the country.

One of the most notable impacts of both earthquakes was the loss of life and injuries. While the exact figures vary, the toll was significant in both cases, with numerous individuals tragically losing their lives and many others sustaining injuries of varying severity. Furthermore, the destruction caused by the earthquakes was extensive and widespread. Buildings, infrastructure, and cultural landmarks were severely damaged or completely destroyed, leaving behind scenes of devastation and displacement. The economic consequences were also substantial, with billions of euros required for reconstruction and recovery efforts in the affected areas. The scale of the damage underscored the need for comprehensive and coordinated efforts to rebuild and restore these regions.

In response to these earthquakes, the Italian government, along with various organisations and international support, mobilised emergency response and recovery operations. The aim was to provide immediate assistance to affected communities, including shelter, medical aid, and basic necessities. Lessons learned from previous earthquakes played a crucial role in shaping these response efforts as authorities sought to improve coordination, communication, and the overall effectiveness of the emergency response. Moreover, the earthquakes highlighted the vulnerability of older structures and the need to enhance building standards to withstand seismic activity. Efforts were made to raise public awareness about earthquake preparedness, implement stricter building codes, and establish seismic risk reduction plans. These measures aim to reduce the impact of future earthquakes and protect lives and infrastructure.

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