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Damage in critical infrastructures due to natural and man-made extreme events – A critical review

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Abstract

Critical Infrastructures (CIs) play a crucial role in the normal performance of economy and society. Over the last decades the amount and the variety of CIs grew rapidly, and the interdependency between them increased constantly. Consequently more and more essential services depend on the continuous performance of one, two or even more CIs such as power supply, communications, etc. It is thus of utmost importance to ensure reliable and robust performance of critical infrastructures on a continuous basis, particularly during and after the occurrence of extreme events. This paper presents a state-of-the-art review of the contemporary state of critical infrastructures' preparedness, through a comprehensive literature review of significant extreme events that occurred in the past two decades. This paper examines the Oklahoma bombing (1995), the Izmit earthquake (1999), the World Trade Center attack (2001), the Indian Ocean tsunami (2004), hurricane Katrina (2005), the London July 7th attacks (2005), the Haiti earthquake (2010), and the Fukushima-Daiichi Nuclear disaster (2011). The review exposes insufficient preparedness of CIs in cases of extreme events and raises several root patterns which led to the severe consequences of the extreme events: a gap between the preparedness of the CIs to the actual risk; higher than expected consequences due to evolution of critical infrastructures; high and increasing interdependencies between the CIs, and high vulnerability of critical infrastructures despite the known risk. The consequences of those events reveal a mismatch between the actual risk to the CIs and between the investments that were made by decision makers for their preparedness.

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1. Introduction

Critical Infrastructures (CIs) consist of systems or assets that, if disrupted or destroyed, have a serious impact on the health, safety, security and wellbeing of society, or the effective performance of governments [9]. Subsequently,

CIs such as water supply systems, telecommunications systems, electrical power systems, and gas and oil transmission and distribution infrastructures have become a crucial component of civilized life. Thus the continuous performance of CIs is vital for the day-to-day operation of economy and society [33].

Disruptions in critical infrastructure systems occurs as a result of several causes such as operating failures, poor design and mechanical failures, physical destruction due to natural and man-made extreme events. This manuscript focuses on disruption and destruction of CIs as a result of natural and man-made extreme events. Natural and man-made (sabotage and terror) extreme events are characterized by an uncertainty in the occurrence time and the magnitude of the event. Natural extreme events include extreme climate events such as Hurricanes, Floods, Tornados and Droughts, and seismic extreme events such as earthquakes and tsunamis. Man-made extreme events include intentional sabotage by explosions, steep path racket shooting, plane crash, and cyber terror. This paper presents an examination of CIs preparedness through review of eight extreme events; Oklahoma bombing (1995), the Izmit earthquake (1999), the World Trade Center attack (2001) Indian Ocean tsunami (2004), the hurricane Katrina (2005), the July 7th attacks in London (2005), the Haiti earthquake (2010), and the Fukushima-Daiichi Nuclear disaster (2011).

2. Objectives

It is intended herein to develop and implement a quantitative method to assess risk that CIs' are exposed to in the occurrence of extreme event (natural and man-made). Different scenarios of natural extreme events (i.e. earthquakes, tsunamis, and hurricanes), terror activities (i.e. explosions, and plane crash) and their consequences are analyzed and the preparedness of CIs to extreme events are examined as a composite of three basic alternative strategies; (1) Redundancy, (2) Robustness, and (3) Resilience [15]. Eventually, alternative courses of actions are suggested to implement those strategies to effectively improve the preparedness and reduce the risk that CIs are exposed to in the case of an extreme event.

3. Review of extreme events

In order to comprehend the preparedness level of Critical Infrastructures, eight extreme events were reviewed through an examination of the contemporary preparedness of CIs to extreme events and identification of root patterns which may led to the severe consequences of the extreme events. Table 1 summarizes the eight extreme events reviewed in this study. Their return period and their annual loss are shown at the eighth and ninth columns, expressing the risk that CIs were exposed to.

3.1. Oklahoma City Bombing (1995)

The Oklahoma City terrorist bomb attack included a truck bomb equivalent to 1,800-2,300kg of TNT that exploded close to the Alfred P. Murrah Federal Building in Oklahoma downtown and claimed more than 800 victims. In addition to this, the blast damaged buildings and cars within a sixteen-block radius. Vast majority of the fatalities were as a result of the collapse of the Murrah building while glass-related injuries were the most frequently reported cause of injury [12, 16, 42]. The Murrah building was built according to building codes at the time (mid-70's), which did not require design with resistance to horizontal loads; the building had no robustness to blast and no redundant load paths [36]. Critical elements of the building were very easily accessible and exposed to such kind of attack and robustness of the surround buildings' glass could reduce significantly the amount and the severity of injuries.

3.2. Izmit Earthquake (1999)

The Izmit earthquake struck Turkey's most heavily populated and industrialized area while most of the people were asleep in their beds. Over 300,000 people suffered directly as a result of the earthquake, over 250,000 building were damaged [38, 51], and CIs were severely damaged; the electricity power failed for several days within minutes

after the earthquake, main highway bridges collapsed, and the water distribution system was interrupted. Since 1939, including the Izmit earthquake, eleven earthquakes with magnitudes equal or greater than 6.7 have taken place along the North Anatolian fault [3, 22], and several forecasts predicted high probability of occurrences of strong earthquake in the area [38,46]. The high probabilities of strong earthquake in the area combined with high density population, poor construction, and devastating consequences as a result of such event produce an extremely high risk. The earthquake's results revealed unsafe engineering and poor construction despite the high vulnerability.

3.3. September 11 (2001)

Over 10,000 people suffered directly from the suicide terrorist attacks at the World Trade Center and on Flights UA175 and AA11. As well, hundreds of thousands of people were exposed or potentially exposed to dust, particulates, and other environmental contaminants on that day, and endured or witnessed deeply traumatic events. Buildings were damaged within a radius of several kilometres [20,40] and many buildings in the area suffered from fire, pressure wave, massive projectile debris, airborne debris and layers of thick dust that required a clean-up and caused mechanical damages. The area was densely inhabited by many critical infrastructures such as underground train lines, main bus stations, electrical power system, banking and financial services. The concentrations of many critical infrastructures and the high interdependencies [29,30] between the CIs produce severe consequences in case of such attack and made the region extremely vulnerable to man-made extreme events.

3.4. Indian Ocean Tsunami (2004)

At 2004 an earthquake struck the west coast of Northern Sumatra with a magnitude of 9.1 and triggered a series of tsunami waves that spread out from the epicenter across the Andaman Sea and the Indian Ocean. The arrival time varies from 15 minutes to nearby shores (such as Indonesia and Sri-Lanka) to several hours for distant shores [1, 34, 39]. The height of the tsunami waves that struck the coastlines reached to an altitude over 20 meters and a depth of several kilometers inland [7,31,37,47,48]. The death and missing total is estimated at over 200,000 people, and over 2 million people were injured or displaced. The tsunami severely damaged the tourism and the fishing industry in the region, due to destruction of tourist sites and thousands fishing boats. Despite a rich history of earthquakes in the region and high risk of tsunami evaluations, there were no tsunami warning alert systems in the region that could notify about the oncoming tsunami. An appropriate alert system combined with evacuation routes, preparation and proper event management, could significantly reduce the loss and reduce almost entirely the amount of fatalities [44]. Most of the CIs and the buildings onshore were destroyed because of lack of robustness to tsunamis; therefore, CIs built on shores should be designed with a consideration of tsunami consequences.

3.5. Hurricane Katrina (2005)

Hurricane Katrina cross along Florida, Mississippi, and Louisiana leaving a trail of destruction and fatalities (nearly half of victims were over the age of 74) [5,10,18]. The combination of rains and winds damaged hundreds of houses, downed trees and power lines. The rain and the storm surge caused more than 50 breaches in levees across the city of New Orleans and in the navigational canal levees that caused flooding 80% of the city [19,34]. More than half a million housing units across Louisiana region were damaged and many critical infrastructures were damaged or destroyed. Katrina created a widespread shortage of electricity [49], when at the outage peak more than 2.7 million consumers were left without electric power [32].

Table 1. Extreme events summary

<i>Extreme event</i>	<i>Year</i>	<i>Type</i>	<i>Affected areas</i>	<i>Estimated damage and loss (10⁶ \$US)</i>	<i>Death and missing</i>	<i>Injured</i>	<i>Return Period of similar events (years)</i>	<i>Average annual Loss (10⁶ US\$)</i>
Oklahoma City Bombing	1995	Man-made	Oklahoma City, Oklahoma, USA	650	167	684	-	-
Izmit Earthquake	1999	Natural	Izmit, turkey	6,000	17,000	50,000	<10	600
World Trade Center	2001	Man-made	New York city, NY,USA	22,000	2,764	9,349	-	-
Indian Ocean Tsunami	2004	Natural	Several Countries among Indian ocean	11,000	228,000	500,000	<25	440
Hurricane Katrina	2005	Natural	5 Countries (mostly Florida, Louisiana and Mississippi),USA	130,000	1,833	Hundreds	<15	8,600
London July 7th Bombings	2005	Man-made	London, England	2,500	56	700	-	-
Haiti earthquake	2010	Natural	Port-au-Prince, Haiti	7,800	316,000	300,000	>100	<780
Fukushima Daiichi	2011	Natural	Fukushima Daiichi, Japan	309,000	20,350	5,314	<60	5,000

3.6. London July 7th (2005)

The July 7th bombing were a series of four suicidal terror attacks on the public transportation infrastructures lines of London. The attack occurred during the morning rush hour of July 7th 2005. Fifty-six people were killed in the attacks, including the four suspected bombers, and 775 injured, and hundreds more suffered from psychological trauma [2]. The blast destroyed the lines of the underground transportation and it took several weeks to recover all the underground lines. The economic loss as a result of the attack is estimated at approximately \$2.5Bn including direct and indirect loss (e.g. tourism industry, damage to small businesses, on-going damage, and etc.)[26,52].

3.7. Haiti Earthquake (2010)

On January 12 2010 at 16:53 local time an earthquake with Magnitude of 7.0 occurred in Haiti with an epicenter approximately 25km western of Port-au-Prince [50], followed by at least 90 aftershocks with magnitude 4.0 or greater in a range of 300km from the epicenter. Approximately 310,000 people were killed [13,21,27,43], over 300,000 people were injured and thousands of people were in need of psychological support or psychosocial supervision. As a result of the earthquake there were massive infrastructure destruction, including destruction of transportation, medical, governments, educational infrastructures and more [21]. Approximately 100,000 homes have been completely destroyed and more than 200,000 were damaged [4,11,14,41]. Over 1,300 educational establishments and more than 50 hospitals and medical centers have collapsed or became unusable. Part of the country's main port was damaged and was not operational. The combination of high density population and poor construction without seismic resistance [4] made Haiti highly vulnerable to seismic events.

3.8. Fukushima Daiichi Nuclear Disaster (2010)

As a result of a magnitude 9.0 earthquake that struck in Japan, a series of seven tsunami wave hit the Fukushima Dai-Ichi Nuclear Power Plant (NPP), with a maximum hitting wave height estimated to be 15 meters, which exceeded the design basis of the tsunami breakwater walls and was above the site grade [6,23,35,41]. As a result of

the earthquake and the following tsunami series, at least 20,000 people were killed or missing, over 500,000 residential buildings were damaged or destroyed, 2,000 roads, 50 bridges and over 25 railways destroyed or damaged by the earthquake and the following tsunamis [24]. CIs such as gas and water supplies, telecommunications and railway service were also severely disrupted. Despite the history of Japan, which include tsunami waves over 15m [8,17,25], the design of the Fukushima-Daiichi NPP consider underestimated scenarios and insufficient protection systems of critical infrastructures to tsunami event. To prevent such severe consequences, the governments and the operators have to prepare for the worst case, considering the risk.

4. Implementation of preparedness

Preparedness to extreme events was examined as a composite of three basic strategies: redundancy, robustness, and resilience [15]. Insufficient preparedness of CIs to extreme events was observed through the events review resulted by of non-implementation of those strategies.

- Robustness - Lack of robustness was found at almost all the reviewed extreme events, it is reflected substantially in the A. Murrah federal building when critical components of the building were built without resistance to blast and explosion and their destruction caused a progressive collapse of the north side of the building. Similarly, the poor construction in Izmit and Haiti, and the insufficient tsunami protective systems at the Fukushima-Daiichi NPP represents lack of robustness.
- Resilience - the ability of Critical Infrastructure to recover quickly from extreme event relies mainly on mantle preparedness for the event. Appropriate preparedness and a good and effective event management will significantly reduce the consequences of the event, prevent the rippling effect and avoid cascading effects. A resilience of power supply after tsunami hit Fukushima Dai-Ichi NPP could prevent the core meltdown. Another example of insufficient resilience was noticed after hurricane Katrina; when areas across Florida and Louisiana remained without power supply for over a month and caused disturbances and losses of the public and private sector. Another aspect of resilience can be reflected in scenario analysis in case of an extreme event and planning courses of action such as evacuation and damage mitigation, actions that were not performed in cases of WTC and Indian Ocean tsunami.
- Redundancy of critical components or functions of Critical infrastructures will increase the reliability and the performance of the CIs system, especially in case of extreme events. A lack of redundancy was noticed in the Izmit earthquake, when after collapse of bridges there were no alternative routes to the affected area which made it difficult to access for rescue operations, another lack of redundancy is reflected in lack of alternative loads paths in the Murrah Building in Oklahoma and the lack of alternative power source in Fukushima-Daiichi nuclear plant. Critical and vulnerable components of CIs must be duplicated (or even tripled in the case of Fukushima-Daiichi) in order to ensure full functionality of the critical system in cases of failures.

5. Conclusion

Eight significant extreme events that occurred in the last two decades were studied and the level of preparedness of critical infrastructures during these events was examined. The examined extreme events reveal the gap between the considered risk during the design stage of CIs and between the actual risk the CIs are exposed to at the time of the extreme event. Over the years the consequences as a result of the extreme events is getting higher, mainly due to the increasing number of CIs, the high dependancy on the CIs, and the increasing interdaoandancy between different CIs. Hence, there are discrepancies between the constant annually increasing risk and between the actual preparedness implementation of critical infrastructure to extreme events. As well, more and more different CIs are connected and dependent on each other and a damage to one critical infrastructure will presumably lead to consequential failures in one or more other critical infrastructures.

Solid evidence of lack of preparedness and lack of implementation of resilience, robustness and redundancy in the design of CIs was observed. Design of the critical infrastructure should be distinguished due to the

internalization of the CIs crucially in case extreme events. Particularly since the insufficient preparedness of critical infrastructures amplified the consequences of the extreme events considering the probability of occurrence of the rippling and the cascading effects. Better preparedness could significantly mitigate the consequences in terms of casualties, destruction, and total loss.

The nature and the randomness of extreme events prevent to predict the potential occurrence of extreme events, including location and functional scenario. Therefore, standards and regulations should take into account the increasing risk portfolio over the years and be more stringent with regard to critical infrastructures preparedness. Furthermore, the design stage of critical infrastructure should include a comprehensive scenario analysis in order to discover all potential events and vulnerabilities and propose a design that provides stability to those scenarios. The design of Critical Infrastructures should embrace resistance to variety extreme event scenarios and the required preparedness level should reflect the evolution progress of the critical infrastructures.

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