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Great East Japan Earthquake Emergency Evolution and Contingency Decision Based on System Engineering Approach

Yongjian Li*, Zhe Li

Business School, Nankai University, Tianjin 300071, China

Abstract

In recent years, unconventional emergencies that have generated widespread concern in the society have frequently occurred. In 2011, the Great East Japan Earthquake and the nuclear crisis as a result of this disaster have gained tremendous attention worldwide. The present paper used a system engineering approach, an extended event graph, to analyze this earthquake and its event evolution as well as associated contingency decisions. Some pertinent countermeasures are also presented for reference of similar emergency event evolution in the future.

Keywords: Contingency decision; System engineering; Extended event graph; Great East Japan Earthquake; Unconventional emergency

1. Introduction

There is a wide discussion about unconventional emergency in the academe [1–3]. In the present paper, we believe that an unconventional emergency is characterized by inadequate precursors, potential derivation, and evolutional events causing enormous destruction, resulting in the difficulty to address the situation using traditional emergency management methods.

The great tsunami in the Indian Ocean in 2004, the Hurricane Katrina in 2005, the Wenchuan Earthquake in 2008, and the Great East Japan Earthquake (GEJE) in 2011 have become global concerns. These unconventional emergencies have caused more and more damages, including injury and death, economic loss, and adverse effects on the society. These emergencies have a common characteristic, that is, an initial disaster occurs and then induces evolutional events leading to a chain of disasters. Once the former event is dealt improperly, the latter event will deteriorate. A typical example is the nuclear incident that followed the GEJE. Given that China experiences frequent emergencies, so reflecting on the lessons of the GEJE is advantageous to refine this country's own emergency management system. A clear knowledge of unconventional emergency and contingency decisions can significantly mitigate damages. Using the extended event graph approach [4], we analyzed the GEJE evolution and associated contingency decisions in the following sections.

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2. Event Description of GEJE

The magnitude 9.0 (Mw) GEJE earthquake that occurred at 14:46 JST on 11 March 2011 was the most powerful known earthquake to have hit Japan. After the earthquake, approximately 4.4 million and 1.5 million households in northeastern Japan were left without electricity and water, respectively.

The earthquake triggered a powerful tsunami that caused a series of nuclear crises, primarily the ongoing level 7 meltdown at three reactors in the Fukushima I Nuclear Power Plant complex and the associated evacuation zones, affecting hundreds of thousands of residents. The tsunami also created over 300,000 refugees in the Tohoku region. This then resulted in shortages of food, water, shelter, medicine, and fuel for the survivors. The earthquake and tsunami caused an extensive, as well as severe, structural damage in Japan, including heavy damage to roads and railways. The expressway did not reopen to the general public until 24 March 2011. Wireless and landline phone services suffered major disruptions in the affected area. Early estimates of insured losses from the earthquake alone were US $14.5 billion to $34.6 billion. Even worse, the overall cost could exceed US $300 billion, making it the most expensive natural disaster on record [5].

3. Extended Event Graph-Based Analysis of GEJE Emergency Evolution Chain

After GEJE, many websites have reported on this disaster and its evolutional events. In the present paper, some valuable data out of 12,572 pieces of special news reports on GEJE from the Sina website were used to reveal the evolutional process of an earthquake disaster.

To hold an overall review of GEJE and its evolutions, we adopted an extended event graph method [4] to construct associated event graphs.

The extended event graphs are divided into two related parts, one top-level graph (Fig. 1) and six separated sub-graphs (Figs. 2–6). The top-level graph represents the main events caused by the initial earthquake, and the sub-graphs represent the evolution chain of each main event. Furthermore, evolution chains among different main events are also mutually influencing. However, given the restriction on the present paper, we chose only to analyze the main extended event graphs in the following.

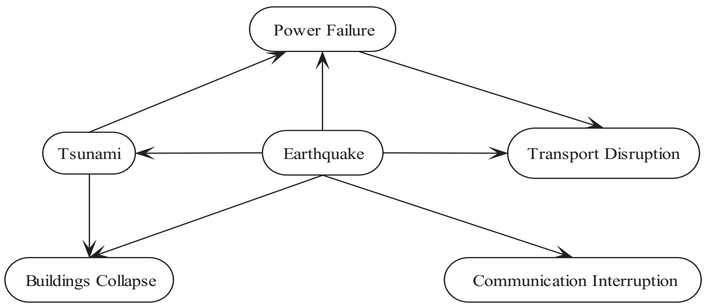

Fig. 1. Top-level Graph of Great East Japan Earthquake

The main evolution chains of GEJE are discussed along with related news reports as follows.

(1) The earthquake destroyed buildings that resulted in the displacement of people who had to move into

refugee camps. Many refugees died because of the difficult conditions in the refugee camps (Fig. 2).

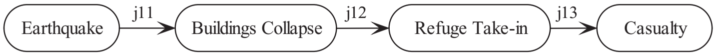

Fig. 2. Event Chain C1.

The Boolean conditions of C1 include the following: j11, the buildings are not sturdy enough to resist an earthquake; j12, the collapsed building can no longer accommodate people; and j13, the conditions of the refugee camps are difficult, such that there is poor sanitation as well as a shortage of water, electricity, medicine, and doctors. After the GEJE, local governments offered shelters to the refugees. However, the need for basic necessities was not satisfied. On 17 March, 14 patients died in one refugee camp in Fukushima[1]. According to the surveys including 56 hospitals in the disaster areas involved, patients died because their illnesses deteriorated in 24 of these hospitals. By 12 April, a statistical figure showed that 282 people died not because of the earthquake but because of the poor sanitation at the refugee camps[2].

(2) The earthquake caused damage to communication facilities, which resulted in the delay of rescue operations, thereby leading to casualties (Fig. 3).

Fig. 3. Event Chain C2.

The Boolean conditions of C2 include the following: j21, the communication facility is damaged by the earthquake; j22, the communication facility is not repaired in time; j23, no alternative communication method is taken; and j24, there are survivors to save. Communication was largely interrupted after the GEJE. 475,400 fiber-optic services were disconnected as of 6 a.m., up 76,500 from 8 p.m., 12 March, in addition to 879,500 subscribed phone lines that remained out of service in areas centering on Iwate and Miyagi [6]. Rescue personnel could not confirm the safety of some residents in the disaster areas because of the communication interruption.

(3) The earthquake caused damage to transportation facilities, which resulted in the delay of rescue operations, thereby leading to casualties (Fig. 4).

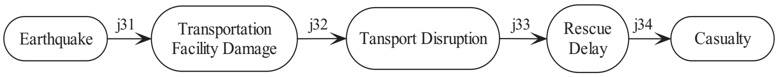

Fig. 4. Event Chain C3.

The Boolean conditions of C3 include the following: j31, the transportation facility is damaged by the earthquake; j32, the transportation facility is not repaired in time; j33, no alternative transport method is taken; and j34, there are survivors to save. The transport network in Japan suffered severe disruptions because of the earthquake. On 13 March, thousands of passengers were trapped inside the Sendai terminal. The terminal was surrounded with 3-meter high water and garbage piles, which blocked the rescue path [7]. There were also not enough helicopters to rescue so many people. Several people died because of the delay in rescue.

(4) The earthquake caused damage to electric facility, which resulted in power failure. The electricity failure paralyzed the transport, thereby leading to casualties (Fig. 5).

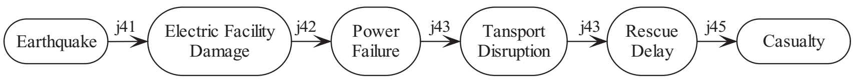

Fig. 5. Event Chain C4.

[1] http://news.sina.com.cn/w/2011-03-17/033922128946.shtml
[2] http://news.sina.com.cn/w/2011-04-12/092722277283.shtml

The Boolean conditions of C4 include the following: j41, the electric facility is damaged by the earthquake; j42, the electric facility is not repaired in time; j43, the transportation is supported by electrical power; j44, no alternative transport method is taken; and j45, there are survivors to save. After the GEJE, the power failure caused the Shinkansen to halt. Due to power shortages caused by the GEJE, rolling blackouts in the capital circle began on 14 March, which intended to fill power gaps, not only caused traffic paralysis but also caused the shortage of food, drinks, gasoline, and other supplies to disaster areas [8].

(5) The earthquake caused the failure of external electrical power. Meanwhile, the tsunami triggered by the earthquake disrupted the backup cooling system. The two events, together, enhanced the temperature of the nuclear reactors, thus leading to explosions and damage to the reactor vessel. Either the explosions or the damage of the reactor vessels resulted in radioactive leakage, leading to casualties. Moreover, the improper disposal of cooling wastewater generated nuclear pollution (Fig. 6).

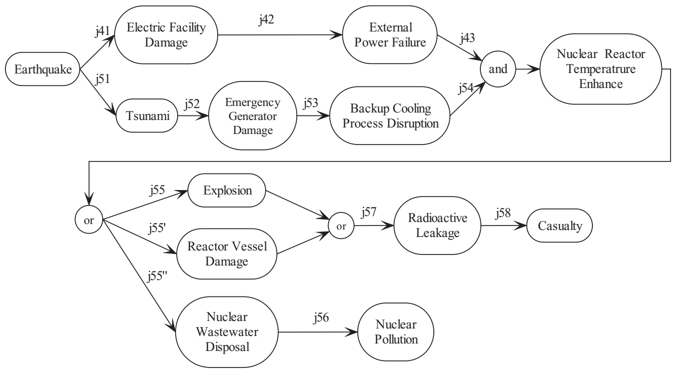

Fig. 6. Event Chain C5.

The Boolean conditions of C5 include the following: for j41 and j42, similar to the former event chain, C4; j51, the earthquake triggers a tsunami; j52, the emergency generators are damaged by the tsunami; j53, the emergency generators are not repaired in time; j54, no effective cooling method is taken to remove the heat promptly; j55, no effective method is taken to prevent explosions; j55', no effective method is taken to prevent the damage of the reactor vessels; j55", water is poured into the reactors for cooling; j56, the cooling wastewater is not disposed properly; j57, true without any preconditions; and j58, no effective evacuation is executed promptly.

After the GEJE and the tsunami, at least three nuclear reactors suffered explosions because of the hydrogen gas that built up within the outer containment buildings after the cooling system failure. Reports suggest that radioactive iodine was detected in the tap water in Fukushima, Tochigi, Gunma, Tokyo, Chiba, Saitama, and Niigata. Radioactive cesium was detected in the tap water in Fukushima, Tochigi, and Gunma. Radioactive cesium, iodine, and strontium were also detected in the soil in some places in Fukushima. Food products were also contaminated by radioactive matter in several places in Japan [5]. On 31 March, radioactive matter from the Fukushima I nuclear power plant was detected in many countries, such as Russia, South Korea, and France.

4. Contingency Decision Analysis Based on Extended Event Graph

By analyzing the associated contingency decisions of these evolution chains and by shortening these chains, the damage arising from a disaster can be significantly mitigated, especially the casualties. In this manner, we might lead the evolution to the most beneficial direction. Therefore, based on the event chain constructed, we can make contingency decisions to reduce possibilities of targeted events, especially, to avoid mitigation to a specified event.

4.1. General Decision Analysis Model

First, we can calculate the probability of one event evoluted from the event source based on the extended event graph, e.g., the earthquake in GEJE.

For the simple causality $A \xrightarrow{J} B$, e.g., event chain $C1$, the probability of event B is

$$P(B) = P(A)P(B \mid A) = P(A)P(J). \tag{1}$$

where J is the possibility of event B under the condition of event A.

For the AND causality $\begin{matrix} A \xrightarrow{J_1} \\ B \xrightarrow{J_2} \end{matrix} \otimes \rightarrow C$, e.g., event chain $C6$, the probability of event C is

$$P(C) = \max\{P(A)P(C \mid A), P(B)P(C \mid B)\} = \max\{P(A)P(J_1), P(B)P(J_2)\}. \tag{2}$$

For the OR causality $\begin{matrix} A \xrightarrow{J_1} \\ B \xrightarrow{J_2} \end{matrix} \oplus \rightarrow C$, e.g., event chain $C6$, the probability of event C is

$$P(C) = P(A)P(C \mid A) + P(B)P(C \mid B) = P(A)P(J_1) + P(B)P(J_2). \tag{3}$$

A contingency decision can be described as a set $D=(d_i, R_{i,\ i=1,2,\dots,m})$, where d_i is the decision scheme, e.g., proving water and food, repairing transport port, building temporary residence, etc. R_i is a matrix of resources needed in decision d_i and d_i is a function of R_i. Based on the extended event graph, we hope to prevent the onset of a disaster or reduce the impacts should one occur. Suppose a decision D is adopted to prevent the onset of event B, after an event chain $\{C_i, i=1,2,\dots,m\}$ evolution with the beginning of event A, then based on eq.(1)-(3), we can calculate the probability of event B with appropriate decision set $D=(d_i, R_{i,\ i=1,2,\dots,m})$, d_i is adopted to event C_i. Then a general model for the contingency decision is as follows:

$$\begin{aligned} &\min \quad \mathrm{Prob(B)} = \mathrm{P(A)P(C_1 \mid \{A, d_1(R_1)\})} \prod_{i=1}^{m-1} \mathrm{P(C_{i+1} \mid \{C_i, d_i(R_i)\})} \\ &s.t. \\ &\sum_{i=1}^{m} R_i \le W \end{aligned} \tag{4}$$

4.2. Contingency Decisions of the GEJE

Based on the general decision analysis model, we can analyze the contingency decisions of the GEJE. For reason of space, the detailed discussions are omitted and only the results are proposed as follows.

(1) For C1, the number of casualties can be reduced by improving the environment of refugee camps, storing enough water and food in refugee camps, repairing transport ports promptly, and building temporary residences as soon as possible. All of the ports of Japan were briefly closed after the earthquake, although those in Tokyo and southward soon reopened. Fifteen ports were located in the disaster zone. All 15 ports reopened to limited ship traffic by 29 March 2011 [5]. In this manner, the need of basic necessities can be satisfied.

(2) For C2, the casualties can be reduced by repairing communication facilities promptly, using an alternative communication method, and so on. After the GEJE, many online social networking sites, such as Twitter and Facebook, played important roles to help in the rescue operations. Even the Japanese government used these websites to broadcast notices [9]. From these data, the use of stable communication facilities in case of such disaster has been emphasized. Once a disaster breaks out, at least one mode of communication should work.

(3) For C3, prompt restoration of transportation facilities and considering alternative transportation to reduce casualties are important. After the GEJE, all of fifteen Japan's ports in the disaster zone were closed. By 29 March, all of them reopened to limited ship traffic, and the first ship that carried 2 million liters of petrol arrived at the port of Fukushima, which intended to fill the gaps in the lack of fuel. However, the shortage in basic necessities in the disaster areas reflects the block of supply channels [10].

(4) For C4, the crucial contingency decision is to repair electric facilities. The failure of electrical power affected many areas, such as railway, residential use, commercial use, public use, and so on.

(5) For C5, there are many measures to solve the nuclear crisis, such as pouring water to cool the reactors, releasing vapors out of the vessels to release stress, injecting nitrogen gas to prevent the reaction between hydrogen and oxygen gases, and offering electricity to the plants. After a radioactive leakage, evacuation of residents is needed.

The nuclear crisis became worse mainly because Japan made improper contingency decisions during the process. Japan did not have a long-term vision in solving the crisis. In the first stage of the nuclear crisis, Japan was busy pouring water into the plants, which led to the accumulation of 110,000 tons of highly radioactive wastewater. At first, the procedure seemed promising. However, in the following stage of the nuclear crisis, the wastewater remained in the basements of the plant, in turn, blocked the passage, which was crucial for the workers to construct electric cables [11]. On 24 March, three workers were exposed to high levels of radiation which caused two of them to require hospital treatment after radioactive water seeped through their protective clothes while working in unit 3 [12]. Therefore, the injection of cooling water delayed the overall plan to solve the nuclear crisis. Moreover, Japan initially refused international help to solve the Fukushima I nuclear power plant crisis. Until 31 March, Japan finally decided to accept technical aids from the USA and France. This phenomenon showed the necessity of having enough backup emergency generators at the plants. Moreover, prompt restoration of electric power is the fundamental solution to prevent the nuclear crisis from deteriorating, once external power fails after backup generators become damaged.

Hence, two crucial reflections may be derived from the analysis of the GEJE. First, the electric facilities should be repaired as soon as possible after a disaster breaks out. Second, enough supply of basic necessities for the survivors should be maintained while dealing with other crises.

5. Conclusion

Unconventional emergencies have become an important problem for academic and practical purposes. Through constructing extended event graphs of unconventional emergency evolution and analyzing associated contingency decisions based on the system engineering analysis approach, the present paper finally reveals several lessons on formulating contingency decisions based on the case of the GEJE. We consider these lessons to be valuable for researchers. However, the unconventional emergency management is a fresh field and its associated problems still remain to be solved, especially on how to realize the unconventional emergency theory into practical use. There is much room for improvement on how to combine the existing qualitative analysis with a more quantitative analysis of unconventional emergency.

Acknowledgments

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