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A game theory approach for assessing risk value and deploying search-and-rescue resources after devastating tsunamis

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ABSTRACT

The current early-warning system and tsunami protection measures tend to fall short because they always underestimate the level of destruction, and it is difficult to predict the level of damage by a devastating tsunami on uncertain targets. As we know, the key to minimizing the total number of fatalities after a disaster is the deployment of search and rescue efforts in the first few hours. However, the resources available to the affected districts for emergency response may be limited. This study proposes two game theoretic models that are designed for search-and-rescue resource allocation. First, the interactions between a compounded disaster and a response agent in the affected district are modelled as a non-cooperative game, after which the risk value is derived for each district from the Nash equilibrium. The risk value represents the threat, vulnerability, and consequence of a specific disaster for the affected district. Second, the risk values for fifteen districts are collected for calculation of each district's Shapley value. Then an acceptable plan for resource deployment among all districts is made based on their expected marginal contribution. The model is verified in a simulation based upon 2011 tsunami data. The experimental results show the proposed approach to be more efficient than the proportional division of rescue resources, for dealing with compounded disaster, and is feasible as a method for planning the mobilization of resources and to improve relief efforts against devastating tsunamis.

1. Introduction

The damage caused by large-scale incidents or disasters is always unpredictable. For example, in March 11, 2011, the Great East Japan Earthquake caused 15,881 deaths, 6142 injuries, and 2668 people missing across fifteen prefectures (National Police Agency of Japan, 2013). The earthquake triggered devastating tsunamis that killed 99% of all victims in the coastal areas of Iwate, Miyagi, and Fukushima prefectures. Of the total fatalities, 92.4% of the deaths were by drowning, 1.1% died of burns, 4.4% were crushed to death or died from internal injuries, and 2% could not be identified. Many adults 65 years or older failed to escape the disaster in time and were trapped by the tsunami, accounting for 56.7% of the total deaths (Shinji and Masao, 2013).

The early-warning system underestimated the powerful seismic sea waves which reached a height of 15–20 meters out at sea and 35 meters at some points after striking the shore. The devastating tsunamis destroyed most of the breakwaters along several parts of the coastline of the three most severely affected prefectures (i.e., Iwate, Miyagi, and Fukushima prefectures). People should recognize that there are limits to what could be done against high magnitude earthquakes and devastating tsunamis (Cyranoski, 2011). However, emergency response systems could certainly be improved to minimize the total number of fatalities, to not only provide economical and effective management of search-and-rescue (SAR) resources, but also quickly and accurately mobilize these resources in the most severely affected districts after a disaster or catastrophe (Fiedrich et al., 2000).

Huang et al. (2016) demonstrated a risk radar for collecting risk incident evaluation information through the internet of intelligence and monitoring emergency management information. They applied the information diffusion method for calculating the risk value in the community. The manager is able to check the online risk radar display so as to reduce risk and mitigate destruction. Cox (2009) believed that game-theoretic models could be designed to help management assess the risk of adversarial actions more explicitly and effectively by analyzing what should be modelled as decision variables of interaction between attackers and defenders. The analysis results could be used to develop useful predictive models of risk assessment and advise on resources deployment, taking into account the most serious results of the adversary's ability to inflict damage. Focusing on adversarial risk analysis

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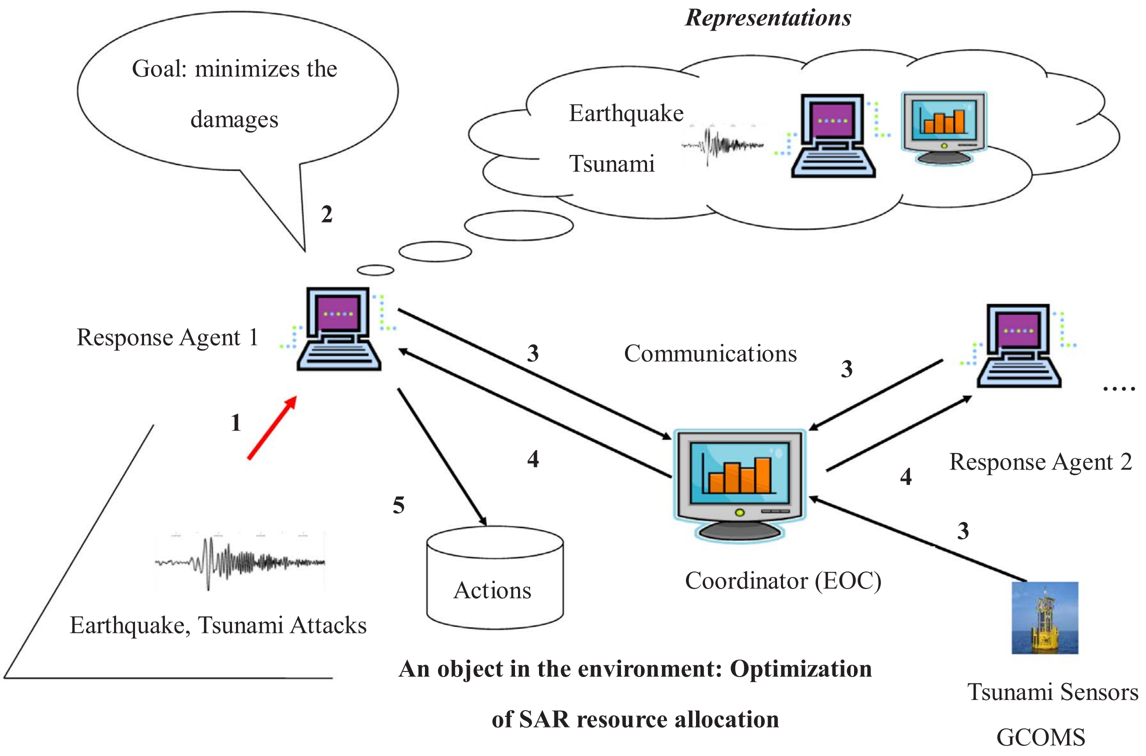

Fig. 1. An illustration representing the interactions of response agents after a disaster with an EOC.

may lead to more efficient resource deployment than the current multiplying threat, vulnerability, and consequence analysis.

Adversarial risk analysis and game theory also support each other and are deeply complementary so that they could be adapted to improve the risk assessor's ability to forecast the opponent's actions (Rios et al., 2015). Price and Macnicoll (2015) also showed that the allocation model of game theory is the same as using equal weights for the allocation of interactive risk factors. Thus, based on the interaction between various individual risks, the allocation problem uses a set of meaningful weights to allocate resources. Bier and Lin (2013) argued that interactive information must be considered in risk analysis in the environmental risk domain for pollution or safety. This interactive information is derived from cost and benefit analysis and it should be evaluated using game-theoretic methods to identify optimal regulatory strategies. They thought the game theory approach to by better than decision theory for the assessment and calculation of high and low risk levels.

In a non-cooperative game, each player tries to utilize resources at minimum cost and the coordination is not enforced externally but is self-enforcing. All players optimize their decisions which maximize their payoffs in a non-cooperative game. The Nash equilibrium (N.E.) is a solution concept for a non-cooperative game which identifies a prediction of the game outcome such that every player in the game is satisfied with respect to every other player (Osborne and Rubinstein, 1994). The cooperative game provides a suitable model for the design and analysis of response agent deployment, and it has been shown that the famous Shapley value rule satisfies many nice fairness properties. The Shapely value also identifies a socially fair, good quality allocation for all agents (Mishra and Rangarajan, 2005). Here, the individual fairness for each player is optimal and the average fairness of the multiple agent system (MAS) is high. The social optimality property ensures that each player in the game receives the best utility for himself or herself and for the complete multiple agent system.

The proposed model is applied to evaluate the risk value of the affected district (or prefecture) and to deploy SAR resources for emergency responses after strong earthquakes and tsunamis. Two game-theoretic models are constructed, representing the two stages needed for economical deployment of the available resources. In the first step, the interactive movements between the compounded disaster (i.e., two-emergency event) and the district response agent are modelled and analyzed as a non-cooperative game, after which the risk value of the earthquake and tsunami in each affected district is derived from the Nash equilibrium of game. This risk value quantifies the threat, vulnerability, and consequence of the compounded disaster for the affected districts. In the second step, the interactions of all response agents of affected districts in a whole administration region are likened to the playing of a cooperative game. All risk values of affected districts are utilized to compute each district's Shapley value. The number of response and deployment of SAR resources in the affected districts are computed from the Shapley values for all districts. Finally, the emergency operations center (EOC) launches the coordinated emergency response for the deployment of existing SAR resources in all affected districts so as to increase the survival ratio of tsunami victims.

2. Emergency responses

The EOC should command and control all SAR resources allocation in the whole region (Ryan, 2013). This study assumes that the EOC will divide a geographic region into several alarm districts. Each district deploys one response agent, who provides centralized management and monitoring during strong earthquake and tsunami events. Each response agent has a prepared set of SAR resources (i.e., ambulances, rescue-groups, fire engines, boats, and/or helicopters) that might be required for service in a two-emergency situation. For example, assume that a large-scale undersea earthquake strikes a specific region triggering two types of emergency events (i.e., earthquake and tsunami) requiring response agents to rescue victims and mitigate the destruction. The EOC provides specific district agents in a region, $A = \{a_1, a_2, a_3, \ldots, a_n\}$, where an agent is defined as a disaster response commander that monitors and minimizes the damage and assists in the recovery from multiple emergencies. Fig. 1 shows the five interaction steps among response agents faced with strong earthquakes and tsunamis.