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Earthquake induced crises: game tree approached risk communication and lessons learnt

Kouskouna Vasiliki*[1], Sakkas Georgios[2], Cecic Ina[3], Tsimpidaros Vasileios-Ioannis[4], Sakkas Stylianos[5], Kaviris George[1], Tertulliani Andrea[6]

[1] Section of Geophysics - Geothermics, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Greece
[2] Center for Security Studies, Athens, Greece
[3] Slovenian Environment Agency ARSO, Ljubljana, Slovenia

[4] campaignLAB, Brussels, Belgium
[5] European Commission - Joint Research Centre, Spain
[6] Istituto Nazionale di Geofisica e Vulcanologia, ONT, Roma, Italy

*vkouskouna@geol.uoa.gr

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1 Section of Geophysics - Geothermics, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Greece
2 Center for Security Studies, Athens, Greece
3 Slovenian Environment Agency ARSO, Ljubljana, Slovenia
4 campaignLAB, Brussels, Belgium
5 European Commission - Joint Research Centre, Spain
6 Istituto Nazionale di Geofisica e Vulcanologia, ONT, Roma, Italy

*vkouskouna@geol.uoa.gr

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ABSTRACT

Earthquakes, large or even moderate, are often followed by secondary phenomena, such as landslides, tsunamis, fires and technological disasters, leading to cascading effects that may, in turn, cause severe repercussions. Before, during and after the occurrence of these events, risk communication, currently evolved to codified legislation, is a crucial factor. Policy selection in the present study is approached by the application of the risk game tree and its formation. The events studied here in view of policy making have occurred both in the historical and the instrumental era, to account for different level of exposure and anthropogenic hazards, in Greece (1894 Atlanti, 1953 Kefallinia series, 2003 and 2015 Lefkas), Italy (1976 Friuli), Japan (2011 Tōhoku) and Slovenia (1917 Brežice). In all case studies the whole disaster management cycle is examined, i.e. mitigation, preparedness, response and recovery. Disaggregation of earthquake-related direct and cascading effects, as well as risk communication are taken into account and ethical challenges are posed both to scientists and policy makers.

1 INTRODUCTION

Earthquakes, along with other natural hazards, such as wildfires, floods and hurricanes, are considered generally high-risk events. According to the World Bank, the highest threat of all natural hazards in Southeastern Europe are earthquakes, with annual average affected population and Gross Domestic Product (GDP) at 2,000,000 and 20,000 mil US$, respectively (World Bank, 2016). These numbers are double, compared to floods. The degree and extent of earthquake effects depend on the earthquake magnitude. Usually, large and moderate-to-high magnitude shallow earthquakes are declared as disasters, triggering the need for management of the crisis they procreate, i.e. disruption of day-to-day life. This is a salience issue for emergency managers and decision-makers for a certain period of time, until community life returns to normal.

It should be noted that a number of disastrous earthquakes may encounter various secondary effects, such as landslides, tsunamis, urban fires, Natech events, liquefaction or disastrous aftershocks, which, in turn, may lead to tertiary ones, and so on. The final repercussions consist of the cumulative result of the synergy of such disasters, which would be non-existent, had the earthquake not occurred. The most sound examples are the Indian 2004 Ocean earthquake and tsunami and the 2011 Tōhoku earthquake, tsunami and nuclear accident. Thus, the problem evolves to a more complicated and multi-parametric one, given that each peril's probability of occurrence should be viewed as an independent variable and that its expected effects are of different nature and causes.

Individual hazard assessment for post-earthquake induced phenomena leads to individual risk, which must then be integrated into a multi-risk determination, incorporating the natural and anthropogenic origin of all related effects and different exposure of population and infrastructure. In such cases, the earthquake has a more dynamic behavior, as it is able to activate cascading phenomena, thus causing worse repercussions. It is, therefore, understood that managing a multi-risk event is a complex assignment to be delivered to end-users, who are responsible for its communication to stakeholders and the public.

This paper attempts to tackle the problem of communicating the earthquake and its cascading multi-risk effects. This is achieved by providing the theoretical background, qualifying, visualizing and roughly estimating the situation created and the formed risk-tree for policy selection, adopted from game theory, for past and recent earthquake case studies in Greece, Slovenia, Italy and Japan. Past events are the simplest cases, as the degree of exposure is lower and anthropogenic hazards are rare, compared to the recent ones, thus showing the dynamic change of the involved parameters. Moreover, natural disaster management of today is professionally and legally established, being a key component of policy making and economic analysis.

2 BACKGROUND

In the timeline of the Disaster Management Cycle, mitigation and preparedness phases precede the causative event, while response and recovery are directly related to its repercussions. For the scientific community involved, mitigation is the pivot, or ultimate goal of all efforts. Governments and sectors tangled to emergency management should consider public awareness and preparedness as perpetual issues that need to be justified occasionally, even during low seismic activity periods.

Ethical theories and disaster management are highly interlinked. They are divided into pre-disaster ethics, i.e. mitigation, preparedness, where scientists who develop models should decide which options maximize "the greatest happiness of the greatest number" and post-disaster ethics, i.e. response and recovery, where disaster managers are morally constrained to take the actions that will provide the best effects (LaFollette, 2014). Current ethical approaches of disaster management fall in the field of Geoethics (Peppoloni and Di Capua, 2015) and follow a risk-based approach, depending mostly on a utilitarian-consequentialism theory (LaFollette, 2014). In economic terms, where the public and private sector are involved, certain arguments arise, concerning investment in the first two phases, as the cost for the remaining two is unavoidable (Diekmann, 2013).

During the last decades, probabilistic, deterministic, stochastic and hybrid seismic hazard studies have reached a high level of accuracy of the expected ground motion at a site of interest (e.g. Giardini et al., 2014), resulting to more sophisticated National Building Codes. Seismic risk studies, focusing on its mitigation, reveal that urban areas, especially the densely populated ones, are more prone, due to insufficient communication and preparedness of society and the status of the built environment. Sophisticated algorithms, such as ShakeMaps (Wald et al., 2005) and PAGER (Wald et al., 2010) estimate in real time the expected spatial distribution of Peak Ground Acceleration (PGA) and the direct life and economic loss of each recorded earthquake worldwide, above a predefined magnitude threshold. In Greece, similar efforts for calculating in real time the expected PGA, as well as peak ground rotations (PGR) based on regional ground motions equations are also fully functional (http://macroseismology.geol.uoa.gr/realtime/, Sakkas et al., 2019). Such algorithms have proven extremely helpful in the management of earthquake emergency.

3 RISK POLICY ISSUES

Prior to a major earthquake, the involved stakeholders work together for improving the mitigation and preparedness levels. This is performed by reducing vulnerabilities and by communicating the risk through education actions and frequent notifications to the end users and the public on pending risks. The probabilistic nature of seismic hazard and risk have always placed decision makers in an awkward position, regarding mitigation and preparedness of disaster management. For these stages, the deterministic approach of seismic scenarios or a successful earthquake prediction would be preferable. Taking into account that earthquake prediction is still at research stage, deterministic seismic scenarios are not always realistic, as cost benefit analysis requires. During and after an earthquake crisis, the responsible public managers collaborate against the earthquake and its cascading effects, assuming that they possess skills in consultation and negotiation, as well as the ability to feel the public understanding and consent. The goal is to achieve both effective communication between agents and community participation during preparedness and post-disaster operations. This, according to Sylves (2015), is the Jeffersonian approach, the most recognized normative political theory for disaster management. This approach requires that the Jeffersonian public managers are skilled in consultation, negotiation and communication and must exploit their sociotechnical experience to provide what is needed for their communities and ensure strong participation.

When dealing with a disaster, stakeholders should adhere to the established common values in the field of ethics. Sylves (2015) stresses that “Disaster management relies highly on experiential learning and experimental research. In this sense, one condition needs to be appreciated by all: in disaster policy, government embodies officials and structures intended to facilitate the effective operation of democracy and political accountability”. The latter are fundamental elements for disaster management. The experiential aspect may impose a variety of mechanisms that will lead to changes of policy, regarding governmental ability to manage the preparedness, mitigation, response and recovery phases of a disaster (Pinkowski, 2008). Although a distinct differentiation is identified between disaster managers accountability and that of the earth scientists, the tying knot between them and the scientists working on seismic hazard and risk assessment is the impact related with vulnerability (physical and social) and exposure. These knots are not adequately appreciated by all disaster management theoretical models. Societal pressures and moral principles are strongly related to policy-making. Neither the seismologist, nor the geologist is confronted with moral decisions, as they are committed, in a strictly professional manner, to carry out the best possible job with the tools in hand. The assessment of geo-data may be subject to different interpretations, but it is possible to determine numerical uncertainties, thus providing engineers with probabilities for design purposes.

In this paper, we attempt to demonstrate that the merging of all four disaster management stages due to earthquake-induced effects may produce new scientific data and the results may create new approaches and responsibilities for policy-makers. The allocation of resources, for example, may need to be examined through an entirely new perspective, given that mitigation and preparedness stages may well be the decisive factor for dealing effectively with secondary disasters resulting from the main event.

4 EARTHQUAKE-RELATED RISKS AND THEIR DISAGGREGATION

Although the seismological community focuses on the delineation of the areas of expected high PGA values, recent studies wag the finger towards the disaggregation of earthquake disasters’ effects. In addition, risk communication to the public, as well as various kinds of information from the public to disaster managing authorities are also key factors nowadays. The role of secondary effects of earthquakes for damage and loss assessment has proven highly relevant through history. While 60-

75% of the economic losses are due to shaking effects, the remainder are attributed to secondary effects (Daniell et al., 2017).

Spatio-temporal variation in the disaggregation procedure is of crucial importance. For example, devastating tsunamis are more likely to occur in oceans, earthquake induced urban fires are related to the built environment and building typology, landslides depend highly on topography, damage is cumulative when important seismic events occur before or after the mainshock, respectively, etc. It is worth noting that secondary or tertiary effects may not be natural: following the Tōhoku 2011 earthquake and tsunami, technological disasters are now being seriously considered. Nuclear power plants represent a great risk to the population, when they are located near faults capable of strong earthquakes and along coasts prone to tsunamis. Out of a desire to maximize profits, estimates of seismic hazard may not be taken into account, in order to reduce construction costs (Wyss, 2015).

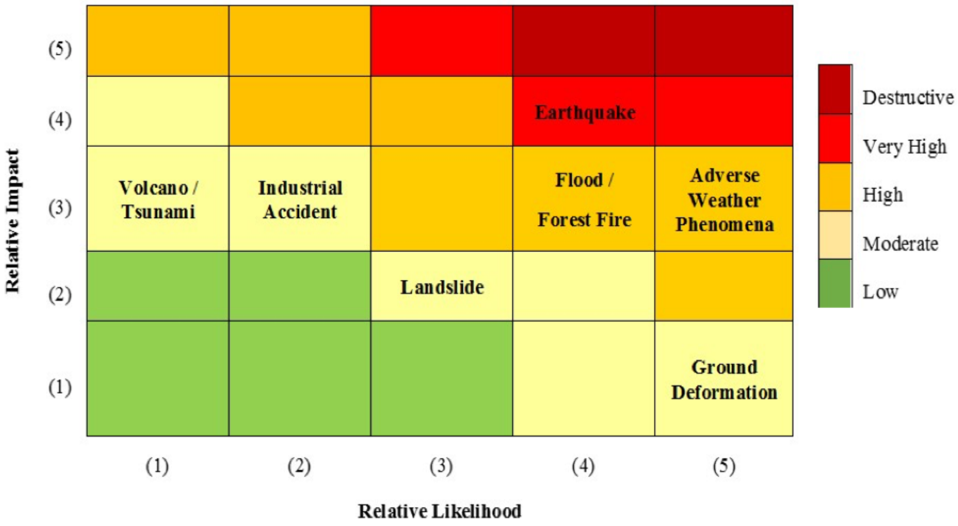


Figure 1. Risk matrix of qualitative risk estimation for Greece, for nine risk modules (Kouskouna et al., 2014)

In the earthquake disaster literature, the term disaggregation applies both for pre-disaster exposure and post-disaster losses. In the first case, studies deal with the disaggregation of expected fatalities based on probability of exceedance of spectral acceleration (Yeo and Cornell, 2004), vulnerability of all exposed elements (Gunasekera et al., 2015) and asset values spatial distribution (Wu et al., 2018). Regarding post-disaster losses, Marano et al. (2010) discussed the global losses due to earthquake cascading effects within the PAGER software. Spence et al. (2011) geographically disaggregate building damage data and Pomonis et al. (2009) assessed vulnerability and collapse probability from past earthquakes in Greece, disaggregated into rural and urban areas. Daniell et al. (2017) discuss the level of preparedness for primary, secondary and tertiary earthquake effects and note that, although most historical losses have been earthquake-shaking related, the influence of the 2011 Tōhoku earthquake has changed the historical percentages significantly for tsunami, as have the Kobe 1995 and Christchurch 2011 earthquakes with regard to liquefaction.

Therefore, the disaster management mechanism faces a complex problem: the response stage coincides with individual preparedness stages of secondary effects, often within minutes, or few hours after the occurrence of the mainshock. In addition, secondary effects may occur outside the shake area, which attracts most concern. In the cases of earthquakes studied in this paper, disaggregation of effects is attempted, when applicable.

According to the EU directives, the risk matrix methodology provides the expected risk as the convolution of probability of each disaster. An example of qualitative risk estimation, which combines the relative likelihood and impact on society and the built environment of earthquake, flood, extreme weather, forest fire, volcano, tsunami, landslide, ground deformation and industrial accident for Greece is presented in Fig. 1. This risk matrix is the final product of individual estimations for each disaster, either probabilistic or deterministic, followed by experts' judgement, and is deliverable of the Greco-Risks project (Kouskouna et al., 2014).

5 SEISMIC RISK COMMUNICATION

Environmental risk communication has developed from a management model to codified legislation (Peters et al., 1997), following the worldwide need for establishment of the environmental law in the late '60s – beginning of '70s, as a basic component of civil law. However, and due to the increasing degree of natural disaster effects, there has recently been an intense demand for the development of "disasters law", to accommodate disaster prevention, response and recovery (Dacoronia, 2015). Communication of information on an impending disaster, or immediately after a disaster, aims for the safety of the public, through evacuation, direct or indirect damage mitigation and self-protection measures.

Regarding earthquakes, geoscientists have not yet provided specific answers to the question "when, where and how big will be the next earthquake". These questions pose a serious ethical problem, on how to use their scientific results in risk-communication (e.g. L'Aquila case, Stucchi et al. 2016). In practice, geoscientists and decision makers follow different approaches, deontology (right) and consequentialism (good for society), characterized by their dissenting views of the relation between right and good, according to the ethical theory.

In this paper, seismic and cascading phenomena risk communication is related to the preparedness (risk) and response (crisis) stages of the disaster management cycle. Reynolds and Seeger (2005) distinguish the two stages, outlining their differences in detail: in the preparedness stage, good understanding of the impending risk is a prerequisite, however against the public's fatalism towards a distressing event. Public campaigns through mass communication channels inform the public on an impending risk in a controlled and structured way, based on scientific and technical knowledge and respecting diverse cultures. In the response stage, the messages are spontaneous and reactive, depending on the emergency management decisions and the progress of the crisis itself. In the case of a damaging earthquake, their main difference is that the seismic risk communication is based on probabilities, whilst crisis communication is based on the progress of seismic activity.

The public seems eager for scientific information, in an analogous way to the disaster magnitude. Nevertheless, this geo-information must be provided in a way that is understood by the general public, taking into account various social factors. A summary of guidelines on best practices in risk and crisis communication is found in Veil et al. (2011).

At present, communication on seismic activity through newspapers and radio is outdated. In past times, this was carried out by ringing the church bell in the village. Although the public has confidence in the authorities' managerial ability, it is now able to be informed on earthquake alerts along with official information dissemination, due to the growth of internet and continuous development of new technologies. As the role of the media is crucial, the scientific community, civil protection officers and the media should use a common "risk language", in order to avoid media ignorance, which may lead to the "command post" view of disaster (Quarantelli, 1991). The development of technology with speedy communication (e.g. Internet of Things, 5G networks), more efficient computers, new algorithms, application of science to every-day life with continuous deployment of new, portable, low cost seismometers and accelerometers, has led to the development of modern seismological networks capable to record minor earthquakes ($M \leq 0.5$).

Earthquake Early Warning Systems (EEWS) and Tsunami Warning Centers (TW), based on dense seismic or tide gauges networks, are now operating in several countries. Automated post-earthquake ground shaking maps are issued in real-time with the use of various algorithms (e.g.

Sakkas et al., 2019; Wald et al., 2010), with online and continuous reporting from seismological academic and research institutes worldwide. In contrast to literature associating EEWS to risk communication and therefore to probability, we stress here the fact that such a system is activated following the earthquake rupture, thus taking advantage of the P-wave arrivals at the nearest to the epicenter stations. In this sense, EEWS express the certainty of an earthquake occurrence. The same applies for TW, but with a much longer expected arrival time.

With the huge amount of overwhelming information, the way seismic risk is communicated does matter, as the earthquake makes the stability of our everyday life extremely vulnerable. The various technological tools not only provide information on risk in the pre- and post-disaster periods, but can also give feedback to crisis managers for reassessment of current situation, response and re-organisation of the civil protection mechanism, and also providing scientific data for post-disaster processing. For example, the USGS "Did you feel it" or EMSC "Testimonies" applications (Wald et al., 1999; Bossu et al., 2011), respectively, engage the public to participate in on-line earthquake damage assessment, thus providing important feedback for rapid and ample macroseismic intensity assignments and distribution. In situ collection of macroseismic data are costly and time consuming.

Risk communication policies need improvement and should be applied to all public bodies and institutions engaged with emergency management, as well as to media and communication professionals (Alexander, 2014; Stucchi et al., 2016). The authors stress the need for a better seismic risk awareness in the Italian society, on the occasion of the ending of the "L'Aquila Trial" by the Italian Supreme Court in 2015, following the L'Aquila 2009 earthquake in Italy.

In previous years, we have observed the increase and dynamics of information technologies, specifically social media, that in cases of disasters assist in the interpersonal communication and cooperation using such platforms (Lindsay, 2011). The importance of the use of social media on such occasions is vital, since Facebook and Twitter have been used in many natural and man-made disasters as means to inform on their occurrence and to their next of kin that they are safe. The "Twitter - faster than an earthquake" advertisement (https://www.youtube.com/watch?v=ug-vjWEKBGg), following the August 23rd 2011 Washington DC earthquake is an example. This leads to the conclusion that social media are gaining heightened significance in regard to civil awareness and public involvement which necessitate that policy-makers should take into account their potential and effects. From that, we can suggest that there is further ground for fostering such relationships between the public and disaster managers. Such two-way communication will in turn prove vital for the better management of scenarios and reducing risk and losses or damages.

Greece, the country with the highest percentage of seismic energy released in Europe, has experienced many strong earthquakes since the antiquity (e.g. Ambraseys, 2009), as well as during the instrumental era (e.g. Makropoulos et al., 2012). Nevertheless, due to the fact that most earthquakes are located offshore and to the adequate building stock which has improved over the years according to strict building codes, the number of fatalities by earthquakes is considered low (Guha-Sapir et al., 2017), but with significantly higher economic loss, compared to the other natural disasters.

On 19 July 2019, a moderate earthquake of M_w5.1 shook the entire Athens metropolitan area, affecting almost half of the country's population. Immediately, this awakened memories of the Athens 1999 M_w6.0 catastrophic earthquake with 143 fatalities. Looking back at the seismic history of Athens, earthquakes date back to 1889 and 1805 (Ambraseys, 2009), when Athens was very small compared to today's extent, which imply a return period of at least 100 years for a magnitude M_w6. Despite the moderate magnitude of the recent earthquake, daily life was halted. People run outdoors from the possible danger of another shock. Telecommunications were interrupted, and the need for information on the epicentral area was crucial for everyone. Thanks to the infrastructure invested for the seismic networks, in a couple of minutes the epicentre was located and shake maps providing the possible affected areas were produced. A directive for evacuation of public buildings was issued. In the next hour, the largest aftershock was recorded. A major traffic jam was observed, lasting two-three hours. Public concern started to spread whether this was the mainshock or a bigger one would follow. Seismologists issued reassurances that the aftershock sequence seemed to be “normal”, but they also suggested that caution should be exercised for at least the next 48 hours. Soon the seismological community made clear that the western branch of the Parnitha fault (around 15km west of the Athens centre) was activated and the probability of an earthquake similar to that of 1999 was extremely low. Telephone numbers of relevant bodies were provided for building inspections in cases of potential damage. New rumours spread for a possible activation of the Alkyonides fault (around 80km West of Athens) that generated the 1981 sequence. Due to the fact that the earthquake did not produce significant damage (Kouskouna et al., 2019), a few days later the earthquake was forgotten and the discussion on upcoming events faded out.

This recent event, in a society used to living with earthquakes, pointed out the need for simplified and effective communication of scientific information. Technology can provide useful tools for communicating risk, and at the same time avoiding the spread of rumours. Education and culture, the understanding of the earthquake as a natural phenomenon and not necessarily as a natural disaster, are the means to confront the negative aspects of technology. As such, the Sendai Framework defines a new social contract between the hazard scientist and the wider public (Ismail-Zadeh et al., 2017).

6 GAME TREE APPROACH

In game theory terms, in an earthquake crisis the players, or actors, involved are the earthquake, which is the “attacker who moves first” and the disaster managing mechanism as the “defender”. The attacker (earthquake) is not a stable “dummy” player, attacking once and for good, but it has a more dynamic behavior, as it is able to activate the attack of its “fellow players”, thus causing worse repercussions. The successful response of the defender is highly dependent on the level of preparedness of all involved parties.

In natural disaster management research, game theory models consider government agencies and private companies interacting as players in a disaster relief game. Usually these models are two-player models, but when there is a multi-agency collaboration, the models become multi-player games. A two-player game between an attacker and a defender can be defined as: (1) sequential where attacker moves first, (2) sequential where defender moves first and (3) simultaneous (Seaberg et al., 2017). Furthermore, regarding the application of game theory in social sciences “as long as one human is present, the phenomenon at hand is arguably as complex as it can get, and a game’s rules do not only constrain agents; in a manner, rules also play a constitutive role in that they help agents (re)define the game” (Varoufakis, 2008).

In the case of an earthquake, in order to describe the game between players, i.e. the earth (dummy player) and the human being (defender), Wu (2015) formulated the game tree for policy selection related to earthquake prediction, considering the simplest extreme cases: a prepared and an unprepared community. In this paper, we adopt Wu’s game tree formulation, with certain modifications. Instead of taking into account earthquake prediction, we classify the preparedness levels also including risk communication. When the earthquake process is initiated, various scientific automated mechanisms are activated as defense actions (e.g. real time PGA - PGV distributions, EEWS, population exposure and vulnerability distribution). For defenders, the response phase has begun.

However, the involved defending actors often face a challenge: are they prepared for a synergy of disasters? If we consider the earthquake as the “main player” and a high level of preparedness, what is the relative level of preparedness for an earthquake-induced landslide outside the area with maximum earthquake shaking effects, or a fire caused by a short circuit as a result of the earthquake? With certainty, in tsunami prone areas, the level of preparedness should be higher, considering the arrival delay of tsunami waves, in comparison to seismic waves.

The level of preparedness in confronting more than one players is subject to various factors: the existing legal context of each country for civil protection, the structure of the defense mechanism, the accuracy of hazard estimation, the detailed vulnerability assessment and existing population exposure, the reliability of seismic risk assessment, the education of the public, the past experience and the experts' judgement. Furthermore, in temporal and spatial terms, the phase of preparedness for a major inland aftershock or for an expected tsunami in coastal areas, coincides with the phase of response corresponding to the mainshock, etc. This may decrease the level of successful management, as the defenders have to face consecutive crises. In the event that the earthquake response mechanism is successful, in the first minutes or hours (e.g. the well-known 48 hours period), there may exist certain indicators, such as absence of aftershocks, specific earthquake spectral characteristics and past experience, leading scientists to identify the event as a foreshock. In this case, the preparedness for the "Big One" coincides with the response actions to the foreshock. Likewise, detailed knowledge of the seismic behavior of an area or a fault will warn the authorities on the probability of occurrence of the earthquake's cascading phenomena.

A general formulation of the game tree for policy selection is proposed by Wu (2015). In this paper, we modify this formulation for risk communication purposes, by taking into account the synergy of the earthquake and its cascading effects, without considering a prediction for the mainshock. Both cases of a prepared and an unprepared community are considered.

In our study, secondary and tertiary effects may be expected, as opposed to the mainshock itself. The symbols for "Hit" (H), "False alarm" (-F), "Miss to hit" (-M) and "Not taking actions for prediction" (-N) are adopted according to Wu (2015), and their relation is investigated. For example, an earthquake alert issued by a EEWS in prepared or unprepared communities is considered a Hit (H). On the contrary, a false alarm is considered a "negative" or "no correct" (-F) prediction in prepared communities, with an insignificant meaning in unprepared communities (0). In addition, a "Miss" for alert could mean little to prepared communities (0) and "negative" to unprepared ones (-M). In prepared communities, "not expected" will make no difference (0), while in unprepared communities this could be "negative", similar to a "no prediction" (-N). Similarly, earthquake-induced landslide susceptibility could also be a "Hit" (H) and tsunami alert systems are definitely a "Hit" (H). The complexity of the game tree depends on the existence or knowledge on secondary or tertiary effects.

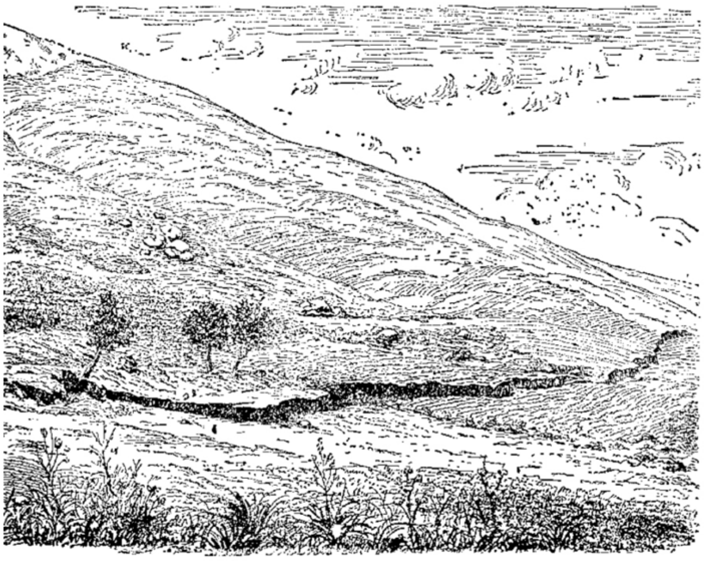
This grading is not based on the infrastructure that can make a community "prepared", but on the social aspect, and more precisely on the public education and preparedness against natural phenomena. Some of these different aspects and approaches may be at a marginal level and not easy to distinguish.

7 EARTHQUAKE CASE STUDIES

In this section, seven historical and recent earthquake case studies with induced phenomena are presented in chronological order. Special attention is paid to the preparedness and response level of the event itself, as well as of its secondary effects. In all cases, the corresponding game trees were formulated.

7.1 Atalanti, 20 (M_w6.7) and 27 (M_w6.9) April 1894

On 20 April a destructive earthquake, followed by another on 27 April occurred in Locris, Central Greece (Albini and Pantosti, 2004; Kouskouna and Sakkas 2013; Table 1). The two earthquakes heavily damaged or destroyed around 70 localities in Locris, damaged many telegraph lines and were strongly felt in Athens and Piraeus, where they caused some minor damage. The two events triggered extended secondary phenomena (Table 1, Fig. 2).



Τὸ μέγα ῥῆγμα, τὸ γεννηθὲν κατὰ τὸν σεισμὸν τῆς Λοκρίδος 1894.

[Κατὰ φωτογραφίαν τοῦ Καθ. Δρος Θ. Γ. Σκούφου.]

Figure 2. The great surface rupture due to the 20 and 27 April 1894 Atalanti earthquakes, drawn by T. Skouphos (“Helios” Encyclopedia, 1957)

In order to examine the risk communication aspect of the earthquakes, we peer reviewed the daily newspaper “Oi Kairoi” (i.e. The Times), for the period 9/21 (Julian/Gregorian calendar) April to 16/28 May 1894. For 6 days after the first event and 5 after the second, the earthquake was front page news.

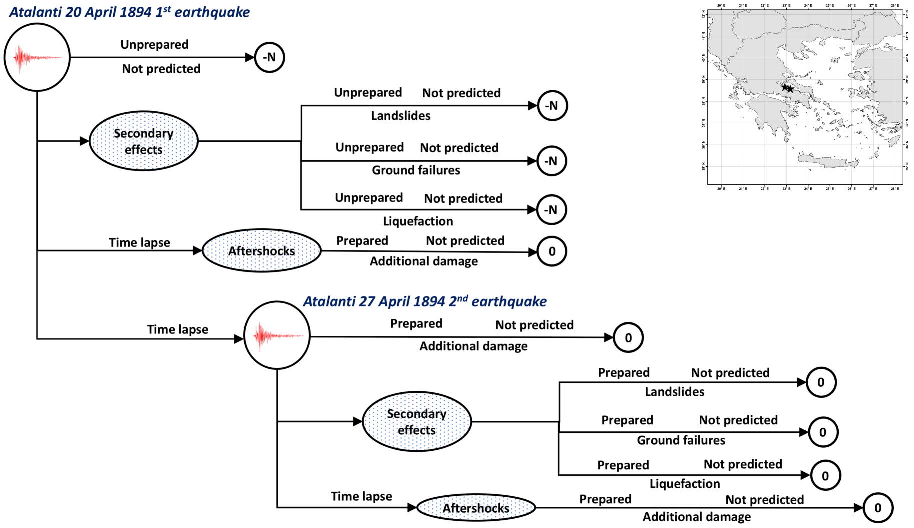


Figure 3. Game tree for the 20 and 27 April 1894 Atalanti earthquakes and related phenomena

King George I of the Hellenes arrived at Atalanti three days after the first event and the first supplies in food and tents arrived the following day. The King, accompanied by the royal family, returned after the second shock, thus acknowledging the severity of the situation. Meanwhile, those affected had abandoned their ruined houses and camped in the open, under improvised shelters made of tree branches and ropes. Permanent timber shelters were built a month after the earthquakes. International aid from Italy, France, Russia and England was also provided.

Three state geologists arrived for field observations four days after the first shock until early May. On 12/24 April, the news that the famous Austrian "seismologist" Rudolf Falb, an empirical natural scientist, having developed the lunisolar flood hypothesis of earthquakes and volcanism, had predicted the first earthquake arrived. Although the Greek geologists disagreed with this theory, the public was afraid that another earthquake was imminent and many people in Athens and Piraeus slept outdoors for several days. Similar to recent earthquakes (e.g. L'Aquila 2009, Athens 2019), the negative role of the media in disseminating non-scientifically grounded information, played a key part in causing public anxiety and decreased the credibility of Greek scientists. Whatever the impact, this "prediction", in combination with the destroyed houses, kept the people outdoors when the second event occurred, destroying what was left standing. This can be interpreted to a "prepared" community in terms of game tree approach (Fig. 3), both for the second event and its secondary phenomena. The disruption of everyday life led to minimization of losses due to the second earthquake.

The case of the Atalanti 1894 earthquakes is typical for destructive cumulative effects of earthquake shaking produced by the synergy of two large, consecutive shocks. The time lapse of 7 days between them is considered enough for the preparedness of disaster managers and communities.

In the game tree for the two Atalanti earthquakes (Fig. 3) the community is characterized as "unprepared" and the first event "not predicted" (-N). For the second earthquake and the aftershocks and despite all the disagreements between the scientific community and other empirical observers, the community can be characterized as "prepared" as the people remained outdoors, but the event itself as "not predicted" (0). For the various secondary effects of both earthquakes they could not have been predicted, as no specific knowledge existed. However, in the second earthquake the community can be considered as "prepared", as people stayed in the open.

7.2 Brežice, 29 January 1917 (M_w5.7)

This Slovenian early instrumental era earthquake occurred on 29 January 1917, during the First World War (WWI), without any foreshock activity. The epicentral area is located at the seismically active Krško basin, SE Slovenia, which accommodates the Krško Nuclear Power Plant (NPP) since 1983. Maximum intensity was observed in Brežice and three more localities (Table 1, Fig. 4, Left). The strongest aftershocks occurred on the same day, with cumulative damage. Hundreds of people were left homeless and in a very difficult situation due to the war, poverty and low winter temperatures.

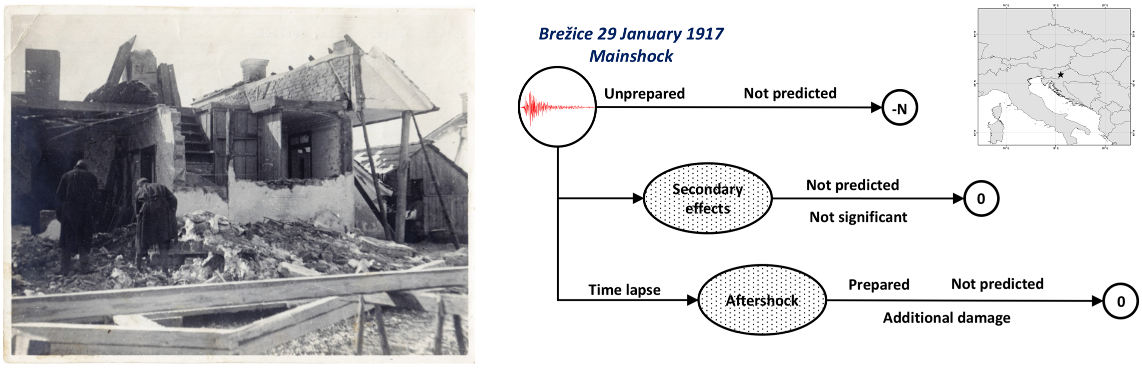


Figure 4. Left: Damage in Kajuhova due to the 29 January 1917 Brežice earthquake (Nečak and Cecić, 2018). Right: Game tree for the 29 January 1917 Brežice earthquake and related phenomena.

Some empty railway coaches were used as a first solution for the homeless and the army built three tent camps, but this was not a good solution due to low night temperatures that went deep below 0°C (Nečak and Cecić, 2018). An eyewitness remembers that he was woken up several times during the night by the soldiers for hot tea to prevent freezing. In the following days, the people were encouraged to leave the town; out of 1200 inhabitants only 300 of them remained in their houses, the others found temporary shelters at friends or relatives outside the damage zone and waited for the restorations to be finished.

Regarding population exposure and response, the situation was difficult for the locals. Although there were no WWI frontlines near the epicentral area, most of the adult men were mobilized away from home, or returned ill or crippled. Poverty due to the war was extensive, food was expensive and not easy to obtain, as well as wood and coal for heating. The reparation process was complicated; it was very difficult to obtain the material for restoration (as it was needed on the frontlines), as well as to hire skilled people to do them.

In the case of this earthquake, both preparedness and response proved inadequate, due to circumstances irrelevant to the event itself (WWI, low temperatures). An exhausted community is considered unprepared for the earthquake (Fig. 4, Right).

In the Brezice case (Fig. 4, Right), the earthquake could not have been predicted neither an alert system existed. The community is characterized as "not prepared" and the overall score for the earthquake is "-N". As there were not significant secondary effects and the community is considered as "not prepared", the overall score is of minor importance (0).

7.3 Kefallinia, 9 (M_w6.4), 11 (M_w6.8), 12 (M_w7.2) August 1953

Known as the "Great Kefallinia (or Ionian) earthquakes", the 1953 series is the landmark of natural catastrophy in Greece (Fig. 5), closely following the Second World War (WWII) and the Greek civil war, which led to the implementation of the first seismic code in Greece. The Ionian Islands, specifically Kefallinia, exhibit the highest seismic hazard levels in Greece and Europe, having experienced historically several destructive earthquakes.

Figure 5. Lixouri, 9, 11 and 12 August 1953 earthquakes. The undamaged standing building on the far left is the primary school designed and built in 1933 by the Kefallonian renowned architect Thucydides Valentis (private archives of Maria Valenti and Fangiskos Tsourlos).

Within four days, three major events devastated the Ionian islands of Kefallinia, Zakynthos and Ithaki (Makropoulos et al., 2012). A late aftershock occurred on 21 October, M6.3. Kefallinia, Ithaki and Zakynthos were turned into ruins. Main towns and villages, including infrastructure, on the three islands were completely ruined, apart from the northern part of Kefallinia, which suffered less damage (Theotokatou, 2019; Guha-Sapir et al., 2017). Big rockfalls of several tons were reported in Ithaki. Following the earthquakes, fires in Argostoli (Kefallinia) and Zakynthos town completed the destruction. Historical monuments, art works, invaluable treasures and archival material were lost in the ruins of the earthquakes and fires. The first two events are regarded as major foreshocks; most destruction is due to the ground shaking they produced. The mainshock contributed to the complete collapse of the damaged, still standing buildings. Fires in Argostoli and Zakynthos followed the August 12 mainshock.

Regarding the response by the government, the contemporary press in Athens reports on the complaints from the Ionian islands. When King Paul arrived in Zakynthos on August 14, he was coldly received, arriving in the island after the battleships with international aid. Response, aid and clean-up operations came from local army units and naval ships, as well as by nearby sailing vessels from Britain, Italy, France, United States, Sweden, Norway and Israel. Rescue operations were halted due to the second foreshock and the mainshock, without being able to save the lives of those trapped in the ruins. Although prohibited to abandon the islands by the central government, it would have been a solution for the locals to evacuate the ruined towns, in order to avoid additional death tolls and injuries after the first event. Eventually, a total number of 100,000 residents abandoned the islands as refugees, to the coasts of western Greece, from Corfu to Kythera. The total cost of damage (Guha-Sapir et al., 2017; Table 1) was unaffordable for a country recently recovering from a decade of international war, occupation and civil war.

Although the three events are interlinked, the high magnitude of the first earthquake and the short time period between all three events did not allow for any preparedness actions or disaggregation of the effects. Thus, an unprepared community is considered for all three events and their related phenomena (Fig. 6). The Kefallinia 1953 earthquakes proved the level of unpreparedness of the local community, despite the island's seismic history. Based on the government's lack of response, the community is characterized as "unprepared" and the three shocks unexpected (-N), as well as the secondary effects. A similar situation would be extremely difficult to deal with even today.

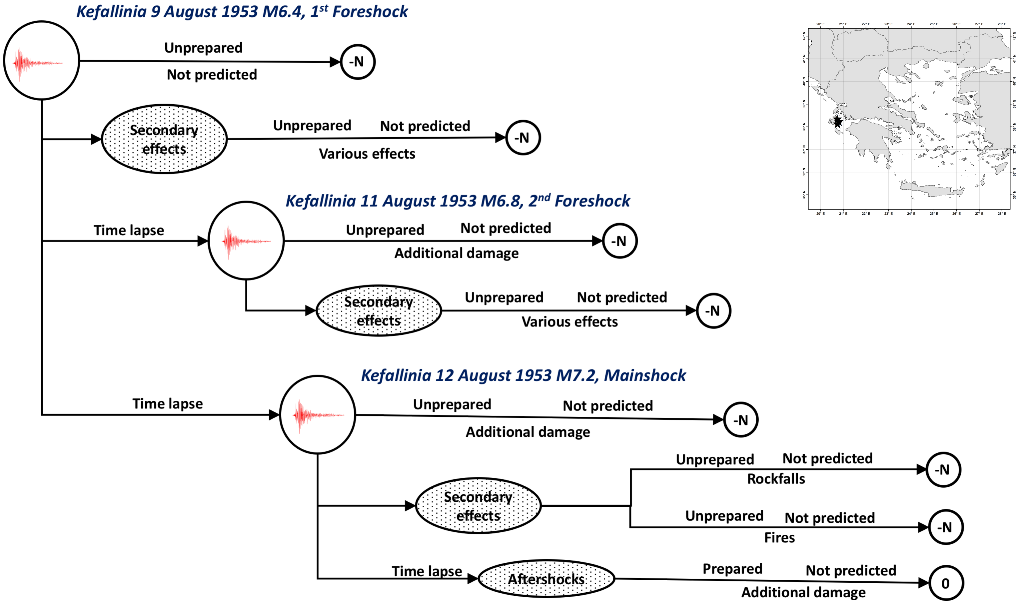


Figure 6. Game tree for the 9, 11 and 12 August 1953 Kefallinia earthquakes and related phenomena

7.4 Friuli, 6 May 1976 (M_w6.4)

This earthquake is known for provoking a very large resonance in 14 European countries, ruining towns and villages in northern Italy. Three strong aftershocks on September 1976 caused additional damage and interrupted restoration works. Maximum intensity was reported at several localities near the epicentre, as well as high intensities from Slovenia, Austria and Croatia (Tertulliani et al., 2018, Table 1), in many cases due to cumulative damage from the mainshock and the aftershocks. The total impacted area was inhabited by nearly half a million people and close to 100,000 needed temporary relocation. The loss of architectural and monumental heritage was huge. The absence of significant foreshock activity leads to the assumption that the authorities and community were not expecting this disaster and the seismological instrumentation of the time was not able to issue accurate and rapid epicentral location, which would have assisted the emergency response and informed the population.

Most of the houses in the affected region were centuries old constructions (Ambraseys, 1976). In general, the building stock was vulnerable, regarding age, maintenance, construction type and materials, such as irregular stones or round pebbles with weak and aged mortar. Tertulliani et al. (2018) assert that in the 1976 earthquake area, there were very few earthquake-resistant constructions, while modern buildings were almost intact.

Secondary effects due to the earthquake were the landslides and rockfalls observed at several sites, especially in the north, close to the mountainous borders with Austria. However, there is no information on how these effects contributed to the damage of buildings.

Following the 1976 Friuli earthquake, Italy improved progressively the procedure and techniques for ensuring the protection and upkeep of historical buildings and monuments affected by earthquakes. This earthquake gave impetus to the country for improved knowledge of its seismic hazard and risk and their impact to society.

The mainshock and its aftershocks were unexpected and the community was unprepared (-N). Due to lack of further information, it is assumed that significant induced phenomena were also unexpected (Fig. 7) and therefore the community could not be alerted (-N).

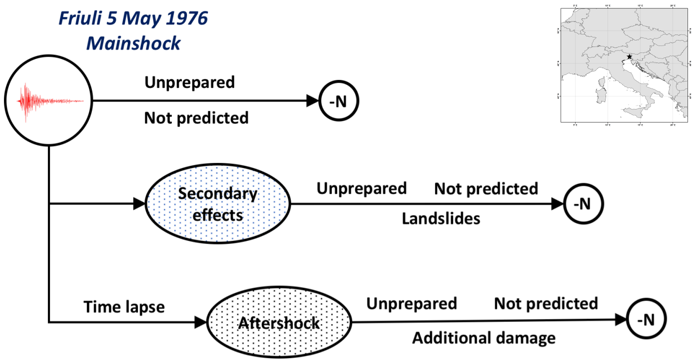


Figure 7. Game tree for the 6 May 1976 Friuli earthquake and related phenomena

7.5 Lefkas, 14 August 2003 (M_w6.3) and 17 November 2015 (M_w6.5)

The broader area of Lefkas, one of the seven Ionian islands in Greece (Fig. 8), is characterized by a remarkably high seismicity with a frequent occurrence of strong earthquakes ($M_w \geq 6.0$). Villages located at western Lefkas have been repeatedly damaged by earthquakes since the 17th century, always triggering landslides and massive rockfalls (Makropoulos and Kouskouna, 1994; Kouskouna and Sakkas, 2013; Sakkas et al., 2016). In this sense, the local population is traditionally familiar with, and psychologically prepared for the earthquake phenomenon.

In 2003, a shallow damaging earthquake occurred in Lefkas. It is considered one of the most recent destructive in the region, but no life loss was recorded and only 50 people were injured, 4 of whom seriously (Table 1). Immediately after the earthquake, an emergency camp was set up at a football field in Lefkada town (Psarris, 2016). Many secondary effects were reported such as landslides, rockfalls and liquefactions. Damage also occurred to the road network, especially on the western part of the island, while almost all ports suffered considerable displacements (Papadopoulos et al., 2003).

In 2015, another shallow damaging earthquake with 2 fatalities shook Lefkas (Table 1). An adequate level of preparedness in terms of building vulnerability and regional/national response is considered for this event (Kassaras et al., 2018), implying low seismic risk. The multiple landslides, rockfalls and liquefaction, triggered by the earthquake, were again located on the western part of the island. The protection measures against slope failures constructed after the 2003 earthquake, operated in a satisfying manner in most cases, preventing the spreading in larger areas/volumes (Kleanthi, 2017). However, it seems that the fatality and related damage due to rockfalls was not anticipated, as it contributed as "landslide risk" to the total risk estimate due to the earthquake.

In general terms, in both cases, local community was in a good level of preparedness, considering the direct effects of the two earthquakes. Although for the landslides of the 2003 event the level of preparedness was poor, for the 2015 event efforts and measures were taken to avoid significant damage. Overall, the preparedness level of the 2015 event is moderate due to the fatalities and cut-off roads, but the fact that protective measures existed and, in most cases, operated successfully, should not be neglected. The cut-off of minor roads, closing of beaches and the fatality due to rockfall, are lessons for the future, pointing out that protective measures should be enhanced.

From seismic hazard point of view (Sakkas et al., 2010), the two Lefkas earthquakes can be considered as "expected". Due to the existence of the local non-engineered traditional construction system (casa baracata or pontelo buildings), designated as earthquake resistant by the European Council Cultural Heritage Unit (Kassaras et al., 2018), the community is considered "prepared" for the mainshocks and their aftershocks, although no EEWS existed. Earthquakes are in the daily life, not easily disrupted at significant extent (0). Regarding the triggered landslides, the community was better "prepared" (0) for the 2015 event (Fig. 8).

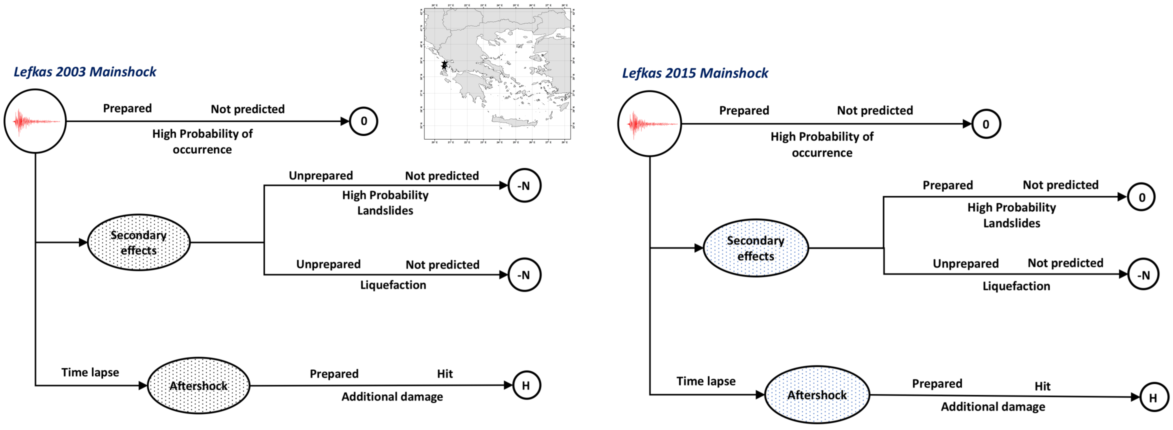


Figure 8. Game trees for the Lefkas 2003 (left) and 2015 (right) earthquakes and related phenomena

7.5 Tōhoku, 11 March 2011 (M_w9.0)

The thrust 11 March 2011 Tōhoku mega-earthquake is considered as the most studied in recent years in all aspects and "the most important event of the beginning of the 21st century in the advanced industrial world" (Zaré and Afrouz, 2012). As a consequence of the offshore event, a

38.9m tsunami, the highest run-up ever measured in Japan, was generated, responsible for an extremely large number of fatalities and missing (Daniell et al., 2011; Table 1), complete collapse or partial damage of thousands of buildings, lengthy power blackouts and water cut off at millions of buildings. This was the first time that an earthquake-generated tsunami caused a nuclear accident, the worst nuclear emergency since Chernobyl, with explosions and leaks in three reactors at the Fukushima I (Daiichi) Nuclear Power station, approximately 150 km from the epicentre.

One minute before the earthquake was felt in Tokyo, the EEWS of Japan (more than 1,000 sensors) operated sufficiently by sending out warnings of impending strong shaking to millions, thus saving many lives. In the tsunami aftermath, JMA was criticized for issuing an initial tsunami warning that underestimated the size of the wave, as sea engulfed the cemented barriers. The overall estimated cost led to significant fluctuations in the global financial markets.

The 2011 Tōhoku earthquake is the ultimate example for the synergy of most earthquake related cascading effects. The outcome of the Third UN World Conference on Disaster Risk Reduction (Sendai Framework for Disaster Risk Reduction 2015-2030) is the Sendai Declaration (UNISDR, 2015).

Japan is probably one of the most prepared countries worldwide in terms of earthquake direct effects, as well as tsunamis. In general terms, the preparedness level of Japan for direct and cascading effects is characterized as high. Nevertheless, this earthquake inserts a big barrier, the mega-quakes. Thus, new questions arise: Are the measures adequate enough to protect from the next mega-earthquake? Had the tsunami height been correctly estimated, would the catastrophe in Fukushima, which affected the whole world, in one way or another, have been avoided?

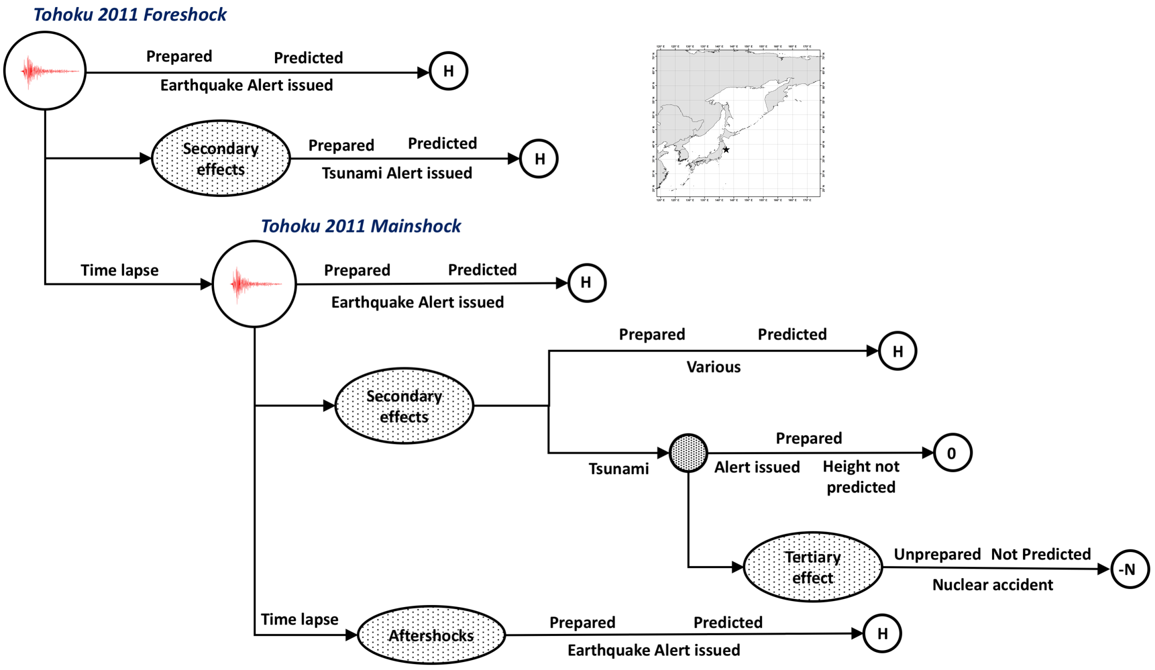


Figure 9. Game tree for the Tōhoku 2011 earthquake and related disasters

Based on the policy selection formulation (Wu, 2015), there is no doubt that Japan is characterized as a prepared community and the Japanese society as one of the most "earthquakes trained societies". EEWS locate earthquakes and issue relevant alerts to the community, thus the resulting utility in the game tree is equal to H (Fig. 9). Up to 2011, Japan's seismic hazard model had not considered low-probability mega-earthquakes of magnitude 9.0+ (Fujiwara and Morikawa, 2012). Due to the fact that Japan is a prepared community, "Miss to hit" or even "Not predicted" events are, at certain extent, tolerated by society (score of prediction policy 0), as it recognizes the difficulties and assumptions taken for seismic hazard and risk estimation (Wu, 2015). At the same time, a tsunami alert was issued in 2011, meaning a successful prediction (score H). However, the tsunami height was underestimated and incorrectly predicted (score of prediction policy 0). In total, tsunami alerts in Japan are always characterized with more hits than false alarms, thus satisfying the equation H-F>0 (Wu, 2015). Wrong warnings or no warnings do not change the fact that H>0. This mega-event is a perfect example on how the most "prepared" community against earthquakes and cascading events paralyzes, and how it can affect the whole world. Concerning foreshocks and mainshock, the community was prepared and efficiently alerted (H). It was also alerted and sufficiently "prepared" for the tsunami following the foreshock. For the tsunami following the mainshock, measures were taken and infrastructure existed, however life loss and huge damage was unavoidable. In the end, the tertiary effect showed that such a Natech disaster was unexpected (-N).

In the case of the Tōhoku earthquake, it should be admitted that measures were taken for mitigation of the effects and that predictions were issued. If there were no tsunami warnings, the fatalities and the economic losses would be undoubtedly extremely larger.

Table 1 summarizes the aggregated and disaggregated fatalities and effects, associated economic loss and preparedness level of the studied earthquakes and their related disasters. Fatalities and economic losses due to secondary phenomena are documented since historical earthquakes, when the level of preparedness was practically inexistent. However, in recent earthquakes, their percentage seems to follow an increasing trend. There is, therefore, a need for improved earthquake multi-risk approach models including secondary effects of recent earthquakes, in parallel to a comparative study with the historical ones.

8 DISCUSSION AND CONCLUSIONS

In this paper the synergy of earthquakes and their cascading effects, in terms of policy selection and risk communication is studied: the earthquake and related phenomena are treated as "attackers" in a 2-players game, with the emergency management mechanism being the "defender". It is noticed that secondary and tertiary effects may lead to overlapping of the four stages of the disaster management cycle, thus producing new scientific data in the field of earth science, economics, emergency management and finally, new input for policy-makers.

Risk communication, which was extremely poor in historical times, has improved in an extraordinary way during the last decade. EEW and TW systems are, or are in the process of being established, and platforms operated by seismological centres provide real-time or near-real-time earthquake information, aided by the social media and the electronic press. The platforms developed by geoscientists are extremely useful tools for emergency managers to "gather in situ information on an earthquake's effects within 10–20 minutes of its occurrence—at a time when any such information is critical to evaluating its impact" (Bossu et al., 2011).

The game tree formulations presented may be a valuable tool in the hands of relevant stakeholders. The classification between an unprepared and a prepared society with the relevant grading schema "Hit" (H), "False alarm" (-F), "Miss to hit" (-M), "Not taking actions for predictions" (-N) and "no difference" (0) are options easy to be used and interpreted by policy makers at local, regional, national, even international level. We deliver such formulations for selected recent or past earthquake case studies in Greece, Slovenia, Italy and Japan, which provide some hints for the evolution of policy and communication of earthquake risk.

In the cases of Atalanti 1894 and Kefallinia 1953, the time lapse of a few days or hours between successive destructive events, and fires following, halted the disaster management efforts, thus testing the local society significantly. Especially in Kefallinia 1953, disaster management froze for several days, because, within a span of four days, three destructive events occurred. The Brezice

1917 earthquake affected an exhausted society, due to WWI, a dominant factor irrelevant to seismic activity. Since 1983, the epicentral area is considered a high-risk area due to its vicinity to the Krško NPP. Then and now, the efficacy of disaster management systems is tested during challenging periods of crises, such as the current COVID-19 pandemic, which absorbs all the resources of crisis management, at the expense of allocating resources in the event of a major earthquake. The Friuli 1976 case involved 14 central European countries, leading to a demand for coordination on an international level (e.g. the 2019 rescEU mechanism). Cross-border issues arising in such cases affect the response systems of neighboring countries and reveal possible variations of each country's disaster management system. In the Lefkas cases, where the time lapse was in the order of years, the first event was considered a valuable lesson for the next, where improvements in infrastructure and management were apparent. Buildings responded better to the earthquake shaking, and the impact from the cascading effects in 2015 was lower, compared to 2003. Finally, the Tōhoku 2011 mega-earthquake is a showcase example of how an earthquake can affect a modern, well equipped and prepared society against earthquakes.

Through the six earthquake case studies covering a time period of more than a century, the evolution of risk policy and risk communication is manifested. Along with the decisions taken by policy makers for the improvements on infrastructure and management, which are vital steps towards the advance of societies, another equally important step is their preparedness in terms of communicating risk and how well it is perceived by the general public. Continuous training, easy to understand messages and an education of risk are crucial for the preparedness of a society against earthquakes. When the public does not react properly to their alerts and messages, warning systems can be of minor importance. Acting properly requires time, effort, communication, and continuous training.

The contribution of seismic hazard models to risk communication, in parallel to the evolution of risk policy is manifested in Table 1. Each case study provides lessons to be learnt for the future. Therefore, the game tree approach may assist the existing models of policy-making for disaster management in focusing on shaking, as well as specific cascading effects threatening earthquake prone areas, in order to minimize risks, thus contributing in efficacy of planning and responding to earthquake disasters.

In summary, the policy selection for earthquake risk mitigation needs a thorough study of historical earthquakes in retrospect and an analysis of the development of best practices of risk evaluation and communication tools. This calls for disaggregation of earthquake related effects and may entail mathematical solutions for quantification of the preparedness level of public and private stakeholders and communities. Emergency management theory demands for generalized knowledge, which will assist the researchers go beyond single case studies. However, several case studies signify that each disaster is unique and the experience gained from certain past events will constitute an essential tool to confront the future ones, especially in areas with unique characteristics. This paper's findings may transform the negative effects of past earthquakes to positive lessons learnt, thus posing new ethical challenges for the decision-makers that will need to be addressed. Lastly, we conclude that tailor-made tools and approaches can be developed to improve response in earthquake prone communities, and to be able to confront natural disasters in a cost-benefit manner reducing the risk of lives and costs related to disasters in terms of logistics.

Table 1: Summary of effects (aggregated and disaggregated), associated economic loss and preparedness level of the studied earthquakes and their cascading effects

Earthquake	**Casualties Dead**		**Casualties Injured**		**Damage**			**Economic Losses (in million US$ current value)**	**Preparedness Level**	
	Direct	**Secondary**	**Direct**	**Secondary**	**Direct**	**Secondary**	**Tertiary**		**Direct**	**Secondary**
Atalanti **20 April 1894** **Sources:** Albini and Pantosti (2004) Kouskouna and Sakkas (2013) Dunbar et al. (1992)	228	Not available	161	8 (landslide)	I_{max} 10 EMS98	Small ruptures, cracks, landslides and coastal liquefaction	No	10-50 Cumulative	-N	-N
Atalanti **27 April 1894** **Sources:** Albini and Pantosti (2004) Kouskouna and Sakkas (2013) Dunbar et al. (1992)	5		11+		I_{max} 10EMS98 (Cumulative damage: at least 1.337 buildings collapsed at 70 localities)	Long ruptutres (35 km), sea wave, landslides, liquefaction Cumulative: massive rockfalls, significant increase and/or decrease of the hot springs level, subsidence of coastal villages, water level changes of wells			0	0
Brežice **29 January 1917** **Sources:** Nečak and Cecić (2018) Dunbar et al. (1992)	1	1 (ground failure or liquefaction)	20-100	Few	I_{max} VIII EMS98 (2 destroyed, 57 very heavy damage, 99 heavy damage)	N/A		10-50	-N	0

Kefallinia **9 August 1953** **Sources:** Theotokatou (2019) Makropoulos et al. (2012) Guha-Sapir et al. (2017)	455 + 21 missing (Cumulative)		2,500 (Cumulative)		I_{max} X+ Houses and buildings: out of 33,300, 27,659 totally destroyed, 2,780 seriously damaged, 2,394 slightly damaged, 467 survived			100 Cumulative	-N	-N
Kefallinia **11 August 1953** Theotokatou (2019) Makropoulos et al. (2012) Guha-Sapir et al. (2017)									-N	-N
Kefallinia **12 August 1953** Theotokatou (2019) Makropoulos et al. (2012) Guha-Sapir et al. (2017)									-N	-N
Friuli **6 May 1976** **Sources:** Tertulliani et al. (2018) Guha-Sapir et al. (2017)	1,000	8	2,300	Not available	I_{max} 10 EMS98 Towns and villages within an area of $1800km^2$ were devastated	Landslides, rockfalls		3,600	-N	-N
Lefkas **14 August 2003** **Sources:** Papadopoulos et al. (2003) Psarris (2016)	0	0	46	4	I_{max} VIII MM, EMS98	Significant landslides and rockfalls mainly in western Lefkas, liquefaction		Ca. 50	0	-N

Daniell et al. (2015)										
Tōhoku-Oki **11 March 2011** **Sources:** Khazai et al. (2011) Daniell et al. (2011) Daniell et al. (2017)	268	18,500 (tsunami) 110-220 (earthquake collapse) 250 (fires & landslides) 600 (indirect causes) 2,587 (missing)	6,157		I_{max} 7 JMS, 10 or 10+ MMI 13,721 – 28,147 (destroyed) 113,227 – 194,367 (partially destroyed) 705,198 – 771,616 (damaged)	Tsunami: 98,697 – 112,402 (destroyed) 78,294 – 158,636 (partially destroyed) 31,225-95,254 (partially damaged) Fires: 345 Damage to infrastructure: 3,559 areas along roads, 77 bridges, 29 parts of the railway system	Nuclear accident, tsunami-triggered fires	194,000-290,000 (Earthquake) 176,000-258,000 (Tsunami) 109,000-162,000 (Powerplant)	H (Total)	
Lefkas **17 November 2015** **Sources:** Kassaras et al. (2018) Psarris (2016) Daniell et al. (2015)	1	1 (rockfall)	10		I_{max} VIII (Small percentage of the building stock affected, mainly non-engineered traditional structures)	Damage to houses due to rockfalls, some of the most renowned tourist beaches destroyed		20	0	0

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