Anatomy of cascading natural disasters in Japan – main modes and linkages

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Abstract

In order to contribute to the development of risk assessment, cascading natural disasters which are sequences of natural hazards was studied and the patterns of the interactions between natural disasters were investigated. The data was collected from the database of Japanese newspaper. The relationships between each natural hazards were emerged and divided into four modes: striking, undermining, compounding, and blocking modes. Striking mode means a primary disaster provides sufficient energy to move a significant mass or to propagate the energy through media. In undermining mode, a primary disaster lowers the resistance or weakens a system maintaining mass and caused to collapse. Compounding mode of the linkage shows that a primary disaster reduces the strength of a system. The difference from undermining mode is that this mode adds to the amount of mass affected. Blocking mode is found in an event blocking steady flows. The results are important for an understanding of the impact of these types of cascading natural disaster and so are valuable as a basis for the identification, description, and development of countermeasures.

Keywords

Cascading natural disaster, risk assessment, interaction patters, striking, undermining, compounding, blocking

Introduction

Since natural disasters have massive power to threaten human lives, property and social and cultural systems, immense effort has been made throughout human history to control such hazards, limit consequences, or mitigate loss and damage. When a natural disaster happens, the damage can be devastating and ruin civilization. History records how humans have tackled these threats and developed countermeasures to mitigate the massive power and enormous loss. For instance, some monarchs regarded flood control as their highest responsibility. Hammurabi, an ancient king of Babylon, devoted most of the last nine years of his reign to such projects and maintained canals for flood control as well as irrigation (Bertman 2003; Levin 2009). Even now, a few thousand years since Hammurabi, governments seek to combat the risk caused by both the old types of hazards and also new ones emerging in the wake of the expansion of habitat and the development of human activities.

Recently, sequences of disasters triggered by natural events have been highlighted. In the sequences, one or more primary hazardous events trigger one or more secondary hazardous events so that the initial disaster is compounded by the secondary event. These situations are referred to as "*multiple*", "*cascading*", or "*domino*" disasters by different authors in the relevant literature but in this paper we will use "***cascading***" to denote this type of situation. One of the reasons for the current attention to these situations is the massive impact of the earthquake and the subsequent tsunami which caused so much destruction and a humanitarian crisis in Japan, 2011 (Krausmann and Cruz 2013).

The 2011 disaster in Japan is also considered as a "*Natech*", which denotes accidents triggered by natural events that create technological calamities (Showalter and Myers 1992). Natech risks can be found particularly at industrial sites storing hazardous materials due to the concern about the loss of containment by destructive natural hazards. Moreover, natural disasters can trigger multiple and simultaneous losses of containment and then require simultaneous response efforts.

However, most of these studies have been limited to technological accidents initiated by a single natural disaster. But, there are risks that the countermeasures against each individual natural event, such as floods, tsunami, lightning, typhoon, earthquake, and so forth, may be less effective when the initial event is coupled with another unexpected type of event. For instance, remaining in an underground structure is considered relatively safe in the event of an earthquake (Ohbo et al. 2004) but poses serious risks if a flood occurs (Shao 2010). For the reliable risk management of natural disasters and their consequences, cascading natural disasters should be investigated and incorporated into management strategies. This study will focus exclusively on cascading natural disasters rather than Natech disasters.

So far, there have been some studies of cascading natural disaster. The importance of risk assessment models applicable when several events have occurred at the same time or in a successive manner has been emphasized by many. However, as yet, there are no international standards and not even the basic knowledge to establish such standards. The lack of a good data foundation hinders progress in this field. As cascading natural events have the potential to expand the damaged area, increase the number of affected people, and result in a much greater impact on society than individual natural hazards, the linkages between natural disasters needs to be unravelled.

This study investigates cascading natural disasters and seeks to find patterns or links which show the connections and interactions between natural disasters. The study will look particularly at events recorded in Japan since Japan is one of the most natural hazard prone countries in the world and therefore many records of natural disasters and their consequences have been recorded there. These records serve as histories in which citizens went through hardships, as warnings for preparation and as lessons which should be learned. These records are considered very useful resources to create a holistic picture of how primary natural hazards can trigger secondary hazards.

It should be noted that the linkages and relationships in cascading natural hazards found in this study may not be directly applicable to other countries, or to regions with different geographical and meteorological features since the occurrence of natural disasters depends on the local conditions. For instance, earthquakes are rarely experienced in areas on stable tectonic settings while Japan experiences earthquakes frequently. On the other hand, wild fires are less of a problem in Japan but are more of a problem in Australia, USA and Russia. Again, floods in Japan tend to be shorter lasting, fast flowing flash floods, whereas elsewhere, such as in Thailand (Aon Corporation 2012), there may be deepwater floods which are longer lasting (Nagai et.al. 2010). Thus the earth shows a wide variety of geographical and meteorological features, and natural hazards can occur in a different manner and with different frequency depending on the area. However, studying the features found in Japan should contribute to an initial understanding of cascading natural disasters and help establish an effective system for intervention.

In the next section the relevant literature on natural disasters will be reviewed and this is followed by a section explaining how the data for this study was collected and analysed from Japanese sources. The analysis of the data leads to the identification of four modes of links or interactions which are presented and explained in the following section, while the final section presents some concluding remarks.

Literature review

The literature survey found that many existing studies about cascade/domino disasters belong to the domain of the chemical processing industries (Abdolhamidzadeh 2011). Some academic studies have dealt with problems spreading through elements or units physically connected to each other such as infrastructure systems (Harper 2007) and logistic networks (Brimer 1995). Significant attention has also been paid to the propagation of phenomena through financial, political or health systems, or various types of communities. These studies have focussed on the vulnerabilities of the entities in question, transition features, and their consequences, and seek to analyse the phenomena, so that lessons may be learnt to prevent recurrence and to establish intervention strategies.

In those studies, a natural hazard is seen as a triggering event which is the initiator or the initial condition which sets off a chain of damaging events in industrial situations, social systems, and so on, but is not considered as a natural event which leads or causes one or more other damaging natural events so leading to cascading natural disasters. These studies clearly present the significance of disasters caused by natural hazards and note the ensuing continuous efforts to mitigate the losses. The information for assessing estimates of likelihood, severity of hazards, vulnerability data are indispensable for setting up a proper mitigation system (Hamiltom 2000). But they varies with the types of hazard because specific vulnerability depends on the hazard providing an impact. Since for a single natural hazard the vulnerabilities, the sequence of events following, and the mitigation measures can differ from one natural hazard to another, the independent method treatment of a single hazard cannot always cope with multiple natural hazards. The overall risks are not just the sum of single individual risk analyses. The characteristic features, analysis methods and the influence of each hazard are different, and multiple hazards can compound impacts from single hazards by mutual interaction and interrelation.

In 2010, the European Commission adopted the Commission Communication on “an all-hazards approach to threat and risk assessment” based on a multi-hazard and multi-risk approach for disaster management (European Commission 2010). They noted multi-hazard or multi-risk situations should to be considered in the risk identification which should consider all possible hazards, their probabilities of occurrence and their possible impacts. Multi-risk assessments in this context means determining the total risk from several hazards. There are two types: First, those occurring at the same time or following shortly after each other, because they are dependent on one another or because they are caused by the same triggering event or hazard. Second, those threatening the same elements without chronological coincidence. Those in the first type are referred to as domino effects or cascading events. An expert group established by the OECD analysed the current problem of multi-hazard risk modelling (OECD 2012). Their survey resulted in some findings, such as *strong demand for data mining and standards, lack of matured multi-risk/multi-hazard assessment models,* and *rarity of consideration of potential cascading/domino effects in natural-man-made systems*.

As an effort to establish a methodology which combines multiple risks, integrated multi-risk maps were developed to assist spatial planning procedures in areas prone to natural disasters in AROMNIA (Applied multi Risk Mapping of Natural Hazard for Impact Assessment) project (AROMNIA project, 2007). The project produced a risk index for a particular hazard by combining the consequences on different receptors. The NaRAs (Natural Risk Assessment) project aimed at producing a quantitative estimation of individual and coupled events based on the concept of a Bayesian event Tree (Marzocchi 2009). Scenarios composed of a few hazardous events were quantified. They concluded that the probability of a single risk was underestimated while the probability incorporating other types of risk showed greater magnitude (Marzocchi 2012). Schmidt et.al. prepared a prototype software for assessing the risk due to a generic natural hazard. The system is capable of calculating risks for different types of hazard but, the system does not permit modelling the interactions among multiple hazards (Schmidt 2011). Mignan et.al. describe a probabilistic approach or Monte Carlo Method aimed at providing numerical data to compare risks from different origins (Mignan 2014). Despite these efforts, Kreibich et.al., reported German cases and found that the present event and risk analyses, as well as risk management, focussed on only one single hazard, and did not consider conjoint or cascading events on an interrelated multi-hazard basis approach (Kreibich 2014). Kappes et. al. emphasized the necessity of considering a whole range of natural hazards and their management from the viewpoint that all potential threats should be taken into account for risk management (Kappes 2012). The possible interaction among cascading effects has yet to be fully understood, represented, and fully integrated in risk assessment.

This literature survey has shown that the interacting features of different hazards and their cascading effect has been less studied than expected in the light of its importance. Some examples of cascading natural effect are known to researchers and those communities which have been historically affected. For example, studies on earthquakes leading to landslides are found in various journals (Miles 2011; Rodrı´gueza 1999; Pearce 1986; Meunier 2008; Ju-Jiang 2000). Xu et al., point out that there is a chain of natural hazards in most catastrophic disasters and introduce Chinese literature on geological, meteorological, and geological-meteorological hazard chains (Xu 2014). However, the knowledge is not systematic and is dispersed. Research methods have been established for each hazard, but there is no overall perspective for the whole range of natural hazards due to the separation of disciplines.

Data Collection Methodology

In this research, the interactions between individual natural events leading to disasters are investigated and the cascading phenomena which emerge are categorised. One of the challenges in starting this research was to find good sources of information. In most available research databases, natural disasters are recorded as single independent events, making it difficult to investigate any relationships connecting these natural hazards. Moreover, as many researchers have pointed out, the lack of internationally standardised reporting and record keeping is a major hindrance (Krausmann 2008; Wirtz 2014). So, it is not possible to find a reliable scientific record of linked natural events leading to disasters

To overcome this problem this study focused exclusively on Japanese cases. Since the study focussed on the interactions between natural events there is no need to investigate each natural disaster in detail. Instead the focus is on the linkages between different disasters using a qualitative approach. Since there are few previous studies of cascading, it is worth trying to compile data on observed cascading natural hazards.

For this study, the Kikuzo II Visual for Libraries was chosen as the main source of information. It is an online commercial database provided by the Japanese newspaper Asahi Shimbun. Asahi Shimbun was first published on 25 January 1879 in Osaka and now has a domestic news gathering network organised by 4 head offices and 2 offices and a global news gathering network consisting of 34 bureaus (The Asahi Shimbun 2012). In October 2014, its circulation was about 7 million for the morning edition and 2.3 million for the evening edition (The Shimbun Joho 2014). The database contains full text coverage from 1985 to present, as well as articles from AERA and Shukan Asahi which are weekly magazines published by a subsidiary of Asashi Shimbun. The image data or pdf files of articles for earlier years, going back to 1876, are also contained in the database, but this study did not use these since text search is not applicable to this data. Clearly this approach excludes the consideration of events that were not reported in the newspaper. It also limits the depth of understanding of these events, since the newspaper reports can be influenced by speculation about the cause of disasters which had not been fully determined at the time the article was published. To overcome these shortcomings, the study also drew on formal documents and online resources and utilised research reports from research institutes and articles in domestic/international academic journals to establish that it is likely that a causal relationship exists between the apparently cascading events under consideration. In addition some related in-depth articles were studied to gain a better understanding of the occurrences and the causes of the events.

Data was retrieved from the Kikuzo II Visual for Libraries using the search system provided in the database. The key words used for searching were combinations of a few words meaning “countermeasure” or “damage”, and the name for each natural hazard event in the Japanese language. The number of hits for each such natural event is summarised in Table 1. The articles found included various types of information such as death toll, interviews with victims, physical and economic damage, the response of the affected local community, etc. In total the search generated 94,228 articles which were skimmed for relevance. Some natural disasters were described multiple times and in more than one location from various aspects because they had wide spread and long-term effects. Some records found in the search had nothing to do with actual natural hazards. In such records, a natural hazard appears as a metaphor for some other aspect of life. Since this study was focussing on cascading natural disasters, all the other records were read and suitable ones were selected to consider the linkages and interactions between the natural events.

Some keywords in table 1 consist of more than one search term. For example, two Japanese search words Yamakaji (fire in mountain) and Shinrin Kasai (fire in forest) are included in wildfire. Needless to say, there are some overlaps in each set of search results because some of the articles relate to cascading natural disasters. For instance, some articles describing earthquakes also mentioned tsunami. Therefore the sum of the number of all the search results does not match the net number of individual articles reviewed. When a search was conducted, options were utilised to exclude other keywords for time reduction. Despite this effort, there still remained a large number of articles for each natural event. All the articles were carefully read and inappropriate articles removed. For the remaining articles, when the article writer clearly mentioned or implied a linkage, the article was read to look for linkages between the hazards described in the article, and then reread to avoid missing valuable information. As noted before, the linkage mentioned in each article can involve speculation. However, most of those writing these articles have previous experience to draw on and often interview local people about their historical knowledge and experience. Also, the articles had to include two or more natural phenomena occurring in a reasonably short time frame, allowing the researchers to suspect there was a connection between the phenomena rather than these being just two or more individual unrelated phenomena. We consider that these criteria combined together were be enough for the first stage process to filter out inadequate information prior to checking with academic papers, research reports, or other resources providing scientific researches.

Table 1 The keywords and the number of articles

Geological			
Earthquake	46290	Volcanic eruption	5284
Land Slide/Collapse	21045		
Meteorological			
Hurricane	1712	Heavy rain	12081
Heat wave	6678	Heavy snow	5866
Lightning	1156	Strong wind	5792
Hydrological			
Tsunami	21219	Flood	7723
High tide	2089		
Other			
Wild fire	804		

The extent to which a complicated or compound natural event can be divided into separate elements needs to be considered. In this study, any event which can cause some physical destruction is regarded as a relevant fundamental event. For instance, some natural phenomena involve more than one element; a typhoon can involve extreme winds, heavy precipitation, and storm surges. A typhoon is a combined phenomenon of elements which are caused by low pressure. This study deals with the fundamental events rather than the compound event since each fundamental event itself can cause disastrous consequences. As another example, volcanic activities involve many processes and can be considered as comprehensive phenomenon. Volcanic activity is directly related to plate tectonics and produces magma, which is molten rock. It penetrates through crust because of the gas pressure dissolved in it. Volcanic activity is associated with one or more of the following phenomena: lava effusion, ash and ejection of pyroclastic rocks, poisonous gas release, shockwave and seismic tremolo (Johnson 2011; Miyabuchi 2013). Debris flows, mudflows and other mass movements are categorised as secondary effects in some text books (Keller and DeVecchio 2012). Although each process has links to other processes, this study does not seek them in-depth. The interest of this study lies in the connections between different types of events each of which itself can be a cause of physical destruction.

Since this research was focussing on cascading natural disasters causing physical destruction, events leading only to the disruption of social systems and biological issues were omitted. Chapman wrote that natural hazards might be defined as an interaction between a system of human resource management and an extreme or rare natural phenomenon which may be geophysical, atmospheric or biological in origin (Chapman 1994). Since such a natural hazard can have massive impact, consequential events can arise in various areas and, in particular can cause disruption to various systems developed by humans. For instance, massive physical impacts caused by natural hazards can destroy systems for maintaining public health and hygiene. The event itself can also push human beings towards a serious crisis. When we add biological threats into our scope, natural hazards affecting critical infrastructure would be listed because infrastructure plays a major role in maintaining public hygiene. However, such hazards are not within the scope of this study. On the other hand, natural phenomena interacting with each other and showing massive power to cause physical destruction can be described as a natural disaster in this research even though no harm is caused to the human habitat; maybe due to the large distance of the events from any human habitat.

Many natural events can trigger technological accidents: volcanic ash can cause clogging in filters or pipes in critical infrastructure (Wilson et al. 2010). Snow makes railway lines slippery causing derailment (Zhou 2013). However, these events do not cause any further natural disasters so are excluded from the current definition of cascading natural disasters. Similarly some cascading natural disasters are phenomena involving highly destructive and wide ranging events but we limit our scope to only the physical aspects of these natural disasters.

Data Analysis Methodology

After selecting the appropriate and relevant articles containing descriptions of cascading natural hazards, we used the Grounded Theory approach to conduct our analysis (Corbin and Strauss 1990). A growth in the use of the Grounded Theory approach has been seen in recent years as a qualitative research method. The Grounded Theory approach uses a set of data collection and analysis procedures to develop inductively derived theories, concepts, patterns, and categorises from data (Eaves 2001). In the Grounded theory approach, data collection and analysis are interrelated and the analysis begins as soon as the data is collected. This is a central feature of the approach and is often referred to as the constant comparative method. The Grounded theory approach allows a researcher to identify patterns, and relationships between these patterns. The Grounded Theory approach in this study was applied to identify relationships between the natural events and develop higher-abstraction level type categories of cascading natural disasters.

Grounded Theory techniques were used to identify categories as they emerged from the data (Reddya et al. 2009). Concepts that are common to several phenomena may be grouped to form categories. In the analysis process, we read the article carefully, extracted data of natural events comprising cascading phenomena. We mapped individual events and the linkages between events. Each causal relationship in the linkage was verified to test if it was plausible by examining other scientific resource such as academic journals and technical reports open to public. Then, as concepts start to appear in our mind that captures properties of the data, we consider the nature of each event and linkages carefully. This process aims at conceptualising and articulating the set of linkages. For example, snow appears to work as storage of potential energy when it starts an avalanche. This gave the concept "depositing" at first, since accumulated snow increases the risk of the following phenomenon. However, during the process of conceptualisation, it became apparent that this relationship could be included in "undermining" which is a higher-order conceptualization. The study continued until the conceptualization became "saturated", meaning no new data or linkages appear and all the linkage could be included in the conceptualization. The final core categories (called modes in this study) that emerged from the data are presented here.

Results and Discussion

In this section the main features of cascading natural disasters are analysed and the relationships that emerged are presented in a series of figures (Fig. 1).

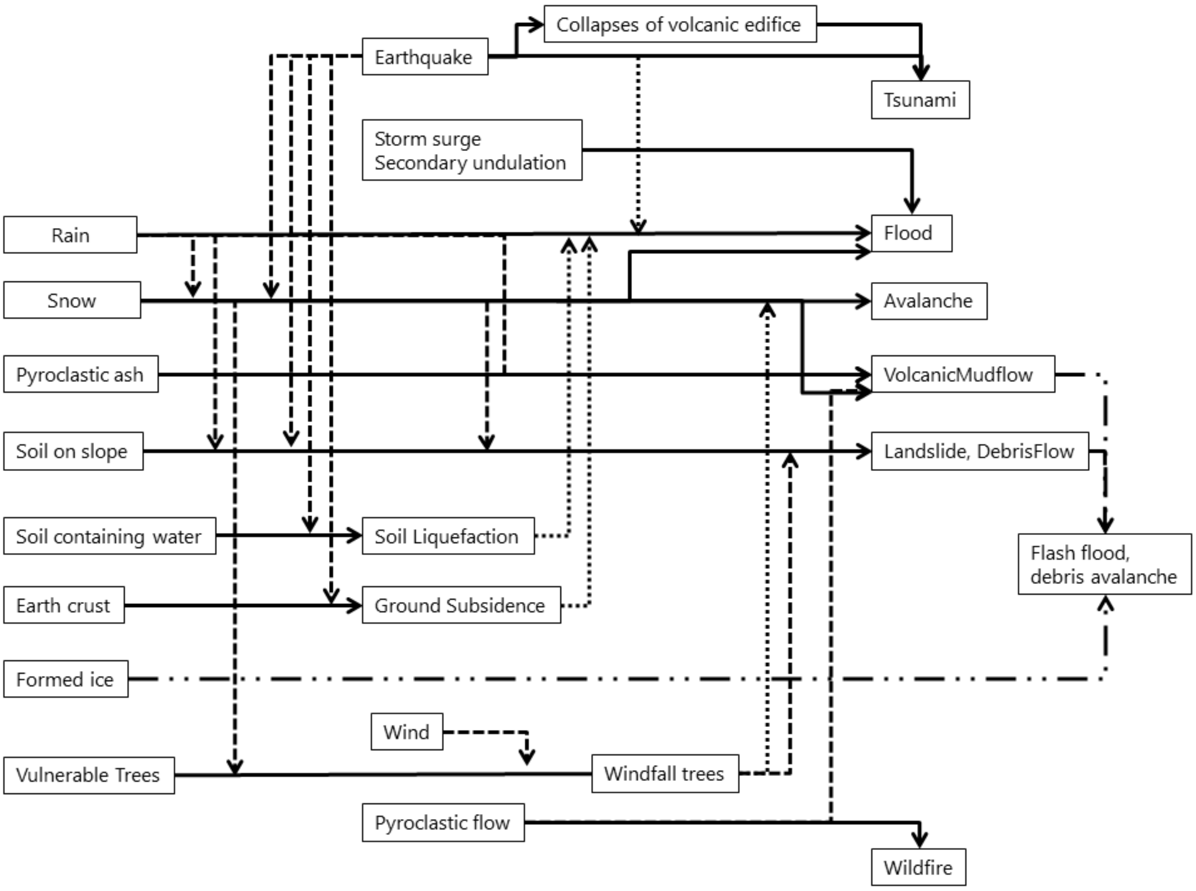

Fig. 1 Relationships of cascading natural hazards

The relationships emerged from considering cascading natural disaster appeared in articles up to October 2014. As many sources as possible were considered so that few, if any, relevant incidents are missing. The figures may not include all the cascading effects that have occurred in Japan, but we believe all the significant ones are included.

Some common natural disasters are not included in the figures because they were not found in the database as either a trigger or a result of any cascading natural disaster, although by themselves each can be harmful and destructive. For instance, the shockwave produced in a volcanic eruption can break nearby windows (Kato and Yamasato 2013), but the searches conducted found no data in the database to indicate that it was triggered by or occurred with another natural hazard. As another example, lightning is known to cause fires or secondary effects such as bound charge, electromagnetic pulse, electrostatic pulse, and earth currents (Changa and Lin 2006). But it does not usually cause a widespread wildfire or any other natural disaster.

The interaction between natural disasters can be divided into four patterns, or modes. In the following section, the numbers in each figure indicate the count of cases appearing in articles. Some cases are latest news coverage at that time and others are historical disasters discussed so that lessons can be learned.

“Striking” Mode; in this mode a primary disaster has significant further physical impact by imparting sufficient energy to move a significant mass or to propagate the energy through media which can then cause significant destruction during the process. The moving mass and propagating energy are secondary natural hazards and sources of destruction in addition to the initial primary hazard (Fig. 2).

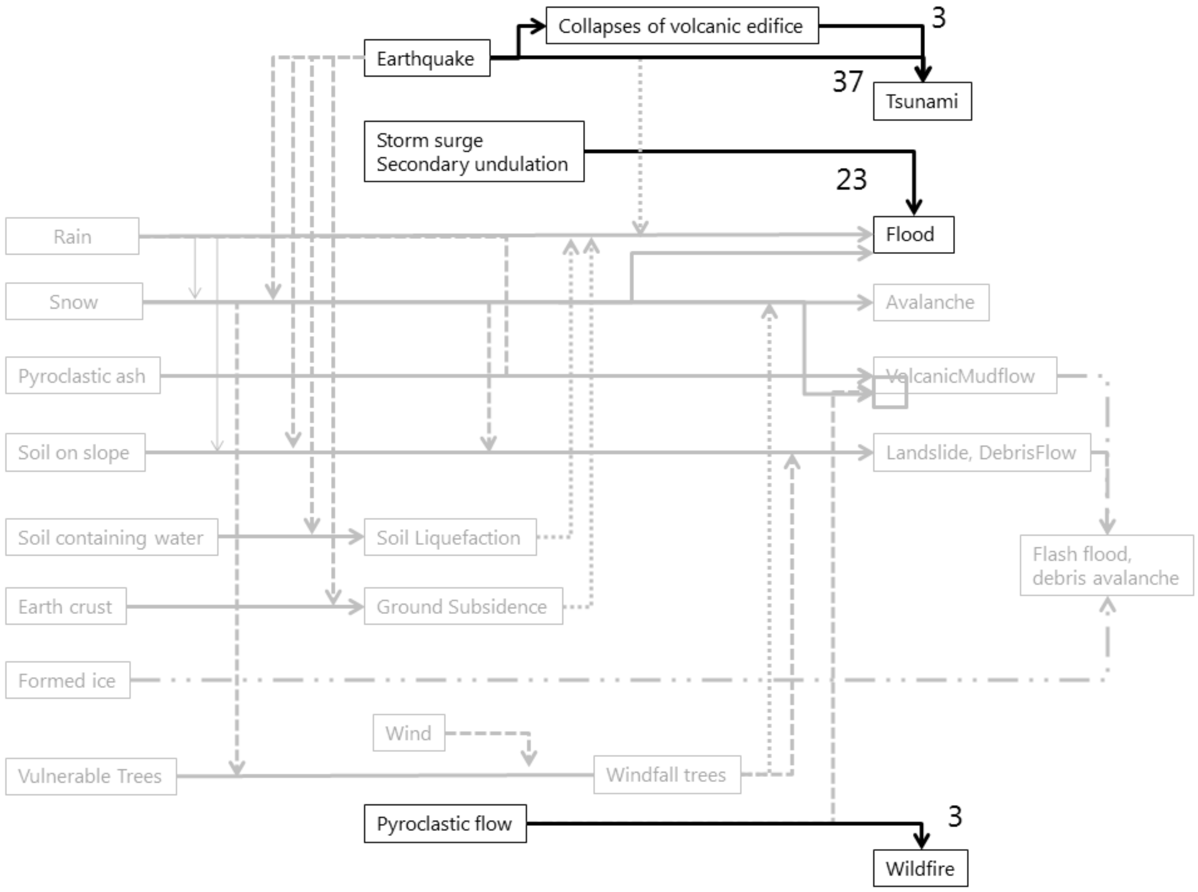

Fig. 2 Cascading natural disasters categorised as “Striking” mode

This mode includes the cases of cascading natural disasters caused by the power of geological and meteorological phenomena. Enormous amounts of energy are released by the initial event which is then transmitted through some mass, or transports some mass.

The major events constituting the primary disaster for this mode are: earthquakes, collapses of volcanic edifice, storm surges and secondary undulations, and the secondary hazards are tsunami, and flood.

When the seismic power imparts energy to sea water through movement of the sea floor, the secondary event is a tsunami (Nirupama 2013). Even an earthquake with a relatively small magnitude can generate large and widespread tsunamis (Kanamori 1972). Initially the tsunami wave moves rapidly in the deep ocean, but it slows down as the depth decreases and the height of water increases as it reaches the coast. The height of the tsunami at landfall directly affects the scale of the resulting damage.

Other events which provide impact energy to elevate the sea surface are storm surges (Nirupama 2013) and secondary undulation (Honda et al. 1908). Although tsunamis propagate through deep oceans, storm surges do not exist in the deeper part of the oceans but are found in shallower ocean areas and are caused by meteorological phenomena. Secondary undulation (one kind of seiche), is also a meteorological phenomenon which has been found in harbours (Hibiya and Kajiura 1982). Atmospheric-pressure variation cause these long waves with extraordinary amplitudes which can reach 1.5m. Secondary undulation results when long waves come into a harbour with amplitudes close to the natural modes of oscillation of the harbour (Kakinuma and Fukita 2011). The subsequent strong currents caused by a secondary undulation in 2009 caused floods and severe damage to cargo-vessels, fish reserves, banks and so forth (Kakinuma et al. 2009). Another natural event inducing transportation of mass and causing a secondary effect is the collapse of a mountain hill side (collapses of volcanic edifice). In 1792, Mt. Mayuyama collapsed following earthquakes generated by volcanic activity and a large section of the mountain fell into Ariake Sea (Kawamata et al. 2005). This shock induced a tsunami and the death toll is said to be about 15000. So, this incident involved three consecutive disasters: first, the earthquakes as a primary effect, second, the hill side collapse as a secondary effect, and third, the tsunami as a tertiary effect. These three events comprised the cascading natural disasters.

An example of energy propagating through media is thermal energy which can cause a wildfire. Wildfires are frequently reported as damage resulting from a volcanic eruption (Annen and Wagner 2003). Since high temperature magma dominates volcanic activity, its products, lava, pyroclastic surge and flow, supply heat to set fire to surrounding forests. Wildfires following volcanic eruption were observed at Mt. Asama, September 2004, Mt. Unzen, May 1993, June 1991, Mt. Mihara, November 1986 and in several earlier events.

“Undermining” Mode; in this mode of the linkage, a primary disaster lowers the resistance or weakens a system maintaining mass and the mass ends up collapsing (Fig. 3).

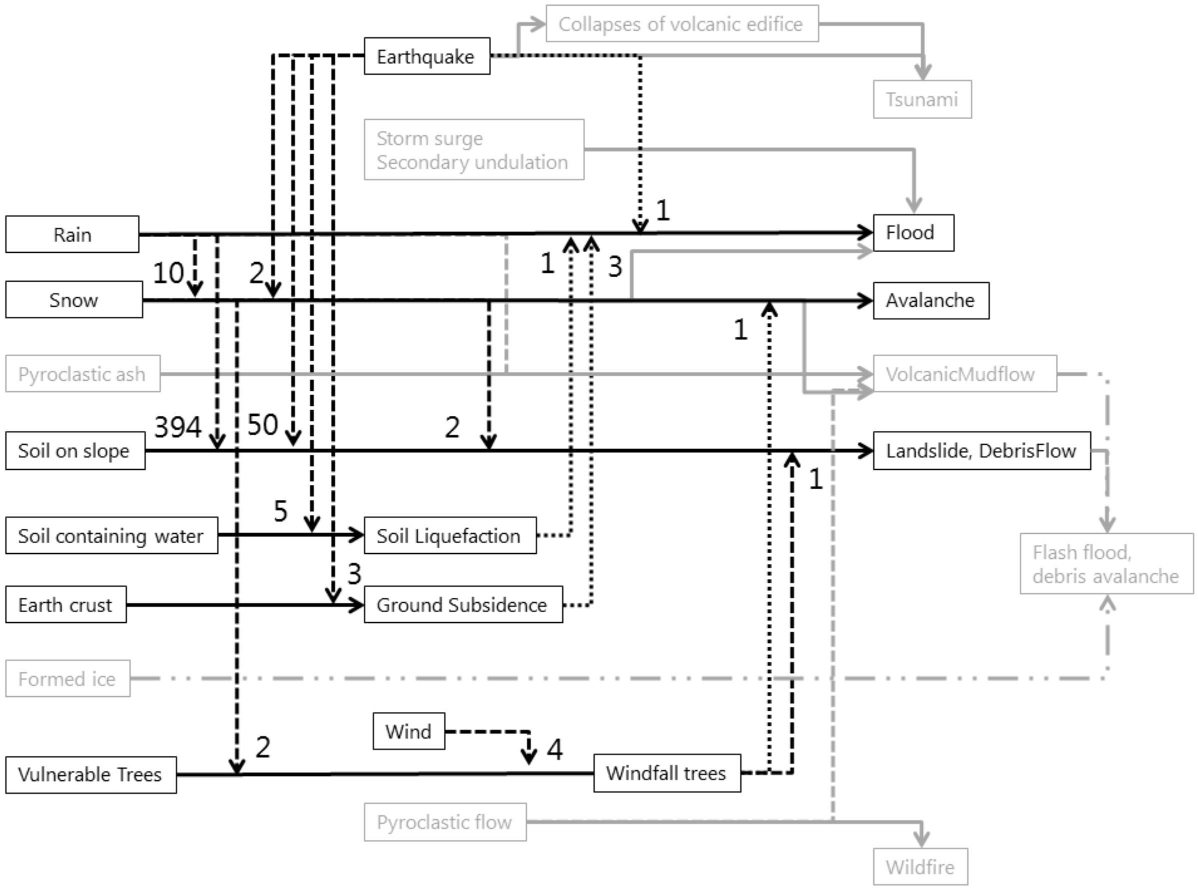

Fig. 3 Cascading natural disasters categorised as “Undermining” Mode.

There are various systems which support or retain mass. The natural events in this mode reduce the strength or the capacity of such a system, or make such a system fragile. The system can be artificial. An example is an earthquake which occurred in Nara in 1854 which caused a reservoir to collapse and the water released caused a flood. Similarly earthquakes can damage river banks or sea walls which are structures to support and channel streams of water.

The system affected by “*undermining*” can be natural. In the natural system, internal forces, such as friction, connect elements and can help retain mass stability on a steep surface. Such forces help maintain the stability of soil or snow because the force keeps each particle together. The mass of soil or snow will distort and may be displaced when an external strong force is applied. Similarly, when the natural hazard applies a greater force to the system than the retaining force, such a system will become unstable.

In the figure, deposited systems are placed on the left side. Broken lines indicate the natural hazards action to perturb the “deposited” system shown on the left side in figure. The natural hazards affect the internal forces within the deposited system. Dotted lines represent the natural hazards action in reducing the strength or capability of supporting or reinforcing system to maintain the mass. For example, accumulated snow can result in avalanche from rain (indicated with a broken line, Stimberis and Rubin 2011) or earthquake (Podolskiy et al. 2010) by breaking the connection between grains or chunk of snow, while strong winds upturning trees increases the risk of an avalanche because the trees function to stabilise the snow cover (Bebi et al. 2009). In the same vein, a landslide can be caused by rain (Inverson 2000, Montrasio and Valentino 2008) or earthquake. Both of them disturb the forces maintaining soil reinforcement. The most common landslides following an earthquake are shallow disrupted landslides on steep slopes, but the Mid Niigta prefecture earthquake in 2004 triggered more than one hundred deep landslides (Chigira and Yagi 2006). Damage to tree roots by strong winds contributed to reducing soil reinforcement and shear strength as well (Abe and Ziemer 1991, Afforestation and Forestry-Road Association of Hyogo 2008.). In this case, the link from “windfall trees” is represented as a broken line. In another example, there were landslides linked to the problem of trees destroyed by several typhoons in Hyogo, Japan 2004. Several typhoons struck the area in that year and trees were uprooted by the typhoon on 19 October which was not the strongest typhoon. Thus, the subsequent landslide was considered to occur because of significant damage to trees by the preceding typhoons in the year. It is argued that the ground support system had been reduced by the tree damage of the earlier typhoons. When trees are expected to act as protective system to mitigate avalanches, wind damage to trees is a severe problem.

Another example is ground subsidence. Ground subsidence per se is a problem when it lowers the ground unevenly. Facilities on the uneven ground can lean dangerously or fall. The subsistence caused by an earthquake or pumping water out from the ground can also cause a secondary natural hazard. For example, the earthquake in Japan, 2011 led to ground subsidence in a wide area. Oga moved by about 5.3m horizontally and was lowered by about 1.2m (Geospatial Information Authority of Japan). The phenomena made the affected area more vulnerable to flood or tsunami (Udo et al. 2012).

Another example of this type of undermining is soil liquefaction which can be found in some landfill sites after an earthquake. An earthquake shakes the soil, loosens the connections between the soil particles and causes water distributed in the soil to rise up to the surface. The ground in the area becomes a suspension and the soil particles eventually settle under water (Fiegel and Kutter 1994). This situation arose in the wake of the earthquake in 1964 Niigata and Alaska (Seed 2003). Solid liquefaction can be a severe problem particularly if there are buildings standing on the ground affected. The unstable ground can cause the buildings to lean and fall down.

In this first sense, soil liquefaction is a secondary natural hazard caused by an earthquake. It can also be seen as a primary natural hazard in the “*undermining*” mode. As mentioned above, water trapped in soil is released as soil liquefaction and inundated the affected area for 7 hours. (Tohno and Shamoto 1986). By another mechanism, it can also reduce the strength of the foundations of critical infrastructures such as river banks or walls (Yoshitake 1992), so in the face of a natural disaster these facilities are no longer capable of preventing a flood, a secondary natural disaster.

This mode is characterized by some event reducing the capability of a system to support mass, and so the resulting system failure maybe preceded by a process which deposits and builds up mass.

“Compounding” Mode: in this mode of the linkage, a primary disaster reduces the strength of a system and adds to the amount of mass affected (Fig. 4).

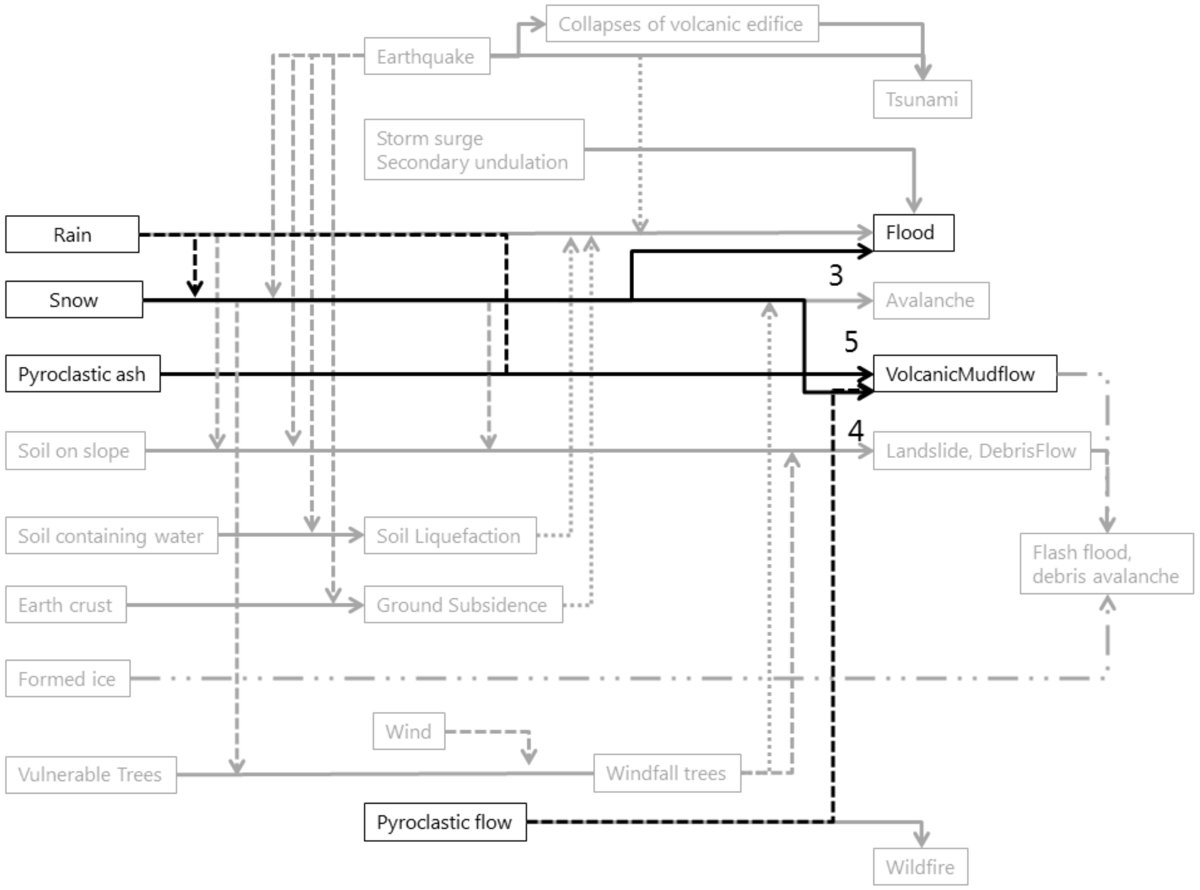

Fig. 4 Cascading natural disasters categorised as “Compounding”. Dotted lines indicate the primary natural hazards action to perturb the system and increase mass affected.

A primary event categorized as a *compounding* itself causes a disaster. Moreover, the impact of the primary event increases when it interacts with a deposited mass. For instance, the impact of the pyroclastic flow significantly increases when it contacts deposited snow and the resulting increased volume of fluid magnifies the problems as volcanic mudflow (Waitt et al.1983). Pyroclastic ash is also a product of volcanic activity and can be deposited on the affected area. If it then rains on the ash, the mixture of ash and rain leads to a mud flow (Young et al. 1998). Snow thaws as the temperature rises and heavy rain in that season can cause a rapid thaw leading to floods (Sui and Koehler 2001). The combination of snow and rain is also found in undermining mode, but this case results in a flood rather than an avalanche.

Blocking: in this mode of the linkage, an event blocks steady flows (Fig. 5).

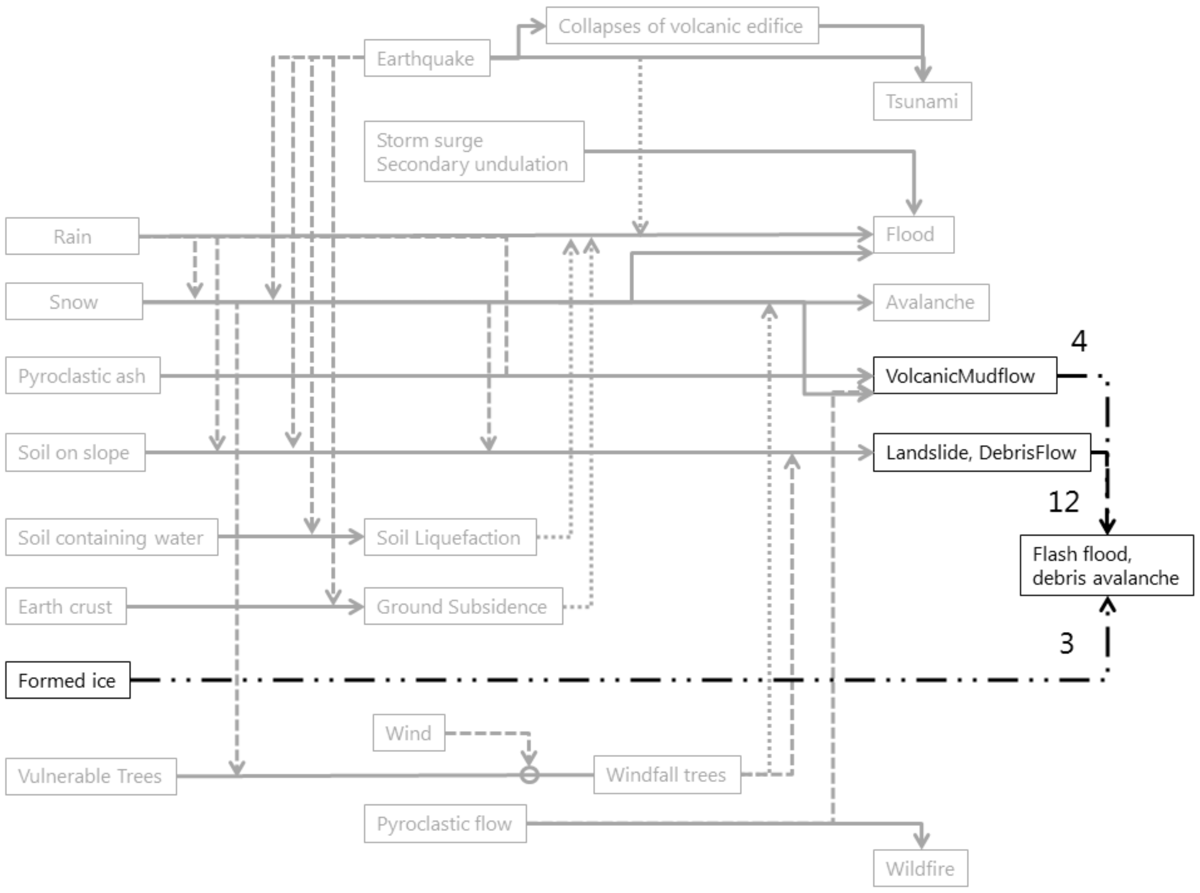

Fig. 5 Cascading natural disasters categorised as "Blocking" Mode

In this mode, a mass collapses and blocks a river causing a hazardous situation which can result in flooding upstream or a sudden break of the barrier and a flash flood downstream. Volcanic mudflow, landslide and debris flow can create a dam by falling into a river (Costa and Schuster 1988). A river can be clogged by partially melted ice which is known as an "ice jam" (Beltaos and Prowse 2001; Hirayama et al. 2002). In this mode the risk of the secondary event takes time to increase as sufficient mass has to accumulate either to flood upstream or cause problems downstream beyond the temporary blockade.

Edward Bryant discusses hazards in environmental studies in terms of two timeframes. One is *chronic* which refers to long term and slowly developing hazards such as desertification or soil degradation that may be caused by human activity or by global warming. The second time frame is called *episodic* or *periodic*. This second timeframe considers people as living within a hostile environment over which they have no control. These sorts of hazards are large magnitude events that last for a short period of time like an earthquake (Bryant 2006). These ideas suggest that for cascading natural disasters it is important to incorporate the idea of a time frame for natural events, and, in particular, allow for time delays between the primary and secondary events. Especially in the case of the blocking mode, it is important to note that whilst the primary event can result in significant destruction itself it can, by blocking a flow, cause a secondary disaster to build up gradually over a longer period of time than is normally thought of in cascading natural disasters.

Concluding remarks

The linkages between natural disasters in cascading natural disasters have been presented and discussed in this paper. The results are based on reviews of nearly 100,000 newspaper articles reporting damage and loss caused by natural disasters in Japan. Attempts were made to explain the links between these natural disasters and this led to the identification and definition of several modes to categorise different types of linkage connecting the natural disasters which form part of a cascading natural disaster.

Four modes of interaction emerged from the investigation. The mode termed “Striking” occurs when a primary natural event imparts sufficient energy to transport a large mass of water or solid material or to transmit energy through media. These phenomena are regarded as secondary natural disasters and cause disruption additional to the primary disaster. The mode termed “Undermining” represents cases where a primary natural event damages the sustaining system of some mass, which may then disintegrate causing a secondary disaster. The third mode is termed “Compounding” and occurs when a primary event interacts with a sustaining system of mass, damaging the system and merging itself into the mass to create a greater secondary disaster. The mode termed “Blocking” represents a pattern in which a mass in motion blocks an existing flow of water temporarily until the increased mass bursts or overflows the obstruction leading to a flash flow of water and debris down steam.

This collation and categorisation of cascading natural disasters has led to a greater understanding of their nature. The results are important for an understanding of the impact of these types of cascading natural disaster and so are valuable as a basis for the identification, description, and development of countermeasures. The results will be beneficial for personnel considering overall risk management by providing them with a better perspective on cascading natural disasters.

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