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ORIGINAL ARTICLE

A classification of mitigation strategies for natural hazards: implications for the understanding of interactions between mitigation strategies

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Abstract The unexpectedly poor performances of complex mitigation systems in recent natural disasters demonstrate the need to reexamine mitigation system functionality, especially those combining multiple mitigation strategies. A systematic classification of mitigation strategies is presented as a basis for understanding how different types of strategy within an overall mitigation system can interfere destructively, to reduce the effectiveness of the system as a whole. We divide mitigation strategies into three classes according to the timing of the actions that they prescribe. Permanent mitigation strategies prescribe actions such as construction of tsunami barriers or land-use restrictions: they are frequently both costly and "brittle" in that the actions work up to a design limit of hazard intensity or magnitude and then fail. Responsive mitigation strategies prescribe actions after a hazard source event has occurred, such as evacuations, that rely on capacities to detect and quantify hazard events and to transmit warnings fast enough to enable at risk populations to decide and act effectively. Anticipatory mitigation strategies prescribe use of the interpretation of precursors to hazard source events as a basis for precautionary actions, but challenges arise from uncertainties in hazard behaviour. The NE Japan tsunami mitigation system and its performance in the 2011 Tohoku disaster provide examples of interactions between mitigation strategies. We propose that the classification presented here would enable consideration of how the addition of a new strategy to a mitigation system would affect the performance of existing strategies within that system, and furthermore aid the design of integrated mitigation systems.

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1 Introduction: the problem of interaction between mitigation strategies

Mitigation strategies are policies or procedures that lead to more or less pre-planned actions that operate before or during a hazard event to reduce its impact on vulnerable populations. Common examples include land-use and development planning; engineering strategies such as tsunami barriers, river or tidal flood defences, and seismically resilient buildings; and warning systems that foster education, evacuation plans, and communication to enable mitigation actions at the time of hazard events or in anticipation of them. Different types or classes of mitigation strategy require differing timescales and methods of implementation according to both the nature of the hazards and the vulnerabilities of the exposed societies. Critically, it is normal for multiple mitigation strategies to be developed and applied together or, more commonly, added in a progressive sequence reflecting technological and socio-economic developments rather than any systematic ab initio plan (one starting from a state of no mitigation). Although in principle one integrated system could provide for mitigation of multiple hazards (especially those that commonly occur in association such as earthquakes, landslides and tsunamis), we consider it more convenient for the analysis presented in this paper to define separate but interlinked and interacting mitigation systems each addressing a single hazard.

As a first step to understanding these interactions, we introduce the concept of a **mitigation system**, which consists of all the mitigation strategies implemented together to ensure “the lessening or limitation of the adverse impacts of hazards and related disasters” (UNISDR 2007). The authors expand this UNISDR definition of mitigation as follows:

> The adverse impacts of hazards often cannot be prevented fully, but their scale or severity can be substantially lessened by various strategies and actions. Mitigation measures encompass engineering techniques and hazard-resistant construction as well as improved environmental policies and public awareness.

We use the UNISDR definition of mitigation in preference to the more restrictive definition of mitigation used in, for example, the USA (Lindell et al. 2006). Importantly, the inclusion of “public awareness” in the UNISDR definition implies that mitigation, as well as involving actions taken long before hazard event occurrence such as engineered flood defences, also includes measures that enable impact-reducing actions taken immediately before or at the time of the hazard event: an example might include a flood warning siren and education of the population around it to respond to sounding of the siren by evacuating a potential flood inundation zone. Both the physical flood defence strategy and the siren-plus-education strategy are mitigation strategies: a key point that we aim to make in this paper is that these strategies, although decided upon by policy-makers well in advance of the hazard event, result in mitigative actions in different time frames relative to the hazard event. The distinction between mitigation strategies, as decided upon by policy-makers, and the mitigative actions taken by a wide range of actors in response to the prescriptions of the strategies, is an important one in this paper.

These multiple mitigation strategies are expressed in associated legislation, policy, infrastructures and government processes, as well as in physical structures, that together form the mitigation system. Individual mitigation strategies may use complex technologies that are themselves commonly referred to as systems; for clarity, we refer to these as technological sub-systems to distinguish them from the overall mitigation system. The general definition of a system used here is that of a group of interacting, interrelated, or interdependent elements forming a complex whole (Kim 1994). A mitigation system is thus a set of interacting, interrelated or interdependent mitigation strategies implemented for the purpose of mitigating the effects of a particular hazard or group of hazards. We emphasise that the integration of multiple mitigation strategies as a system should be analysed as a complex system by focusing on interactions between the elements of the system in operation under constraints of time and uncertainty (Mileti 1999, p 107). Importantly, these interactions can take place through time in different stages of the disaster management (DM) cycle; four temporal phases or stages of disaster management commonly adopted and applied by emergency practitioners and policy-makers (mitigation, preparedness, response and recovery). Such interactions across time present a problem for the standard model of the DM cycle (Lindell et al. 2006), which is commonly implemented (Coetzee and van Niekerk 2012) with the simplifying assumption that, within one circuit of the cycle, the stages of the cycle exist in relation to each other only as a linear sequence of processes.

An important consequence of this idea of disaster management as a linear series of processes that occur in sequence during each circuit of the DM cycle is that it may lead to the assumption that when adding new mitigation strategies, the effectiveness of the system as a whole will always be a linear product of the component mitigation strategies. However, this assumption does not allow for the possibility that actions prescribed by these strategies will interact with each other in ways that are not anticipated or allowed for by their designers and operators. Unexpected destructive interactions (or “interferences”) can damage the effectiveness of the strategies, or even render particular combinations of strategies actively dangerous. Conversely, it is possible that constructive interaction may occur between mitigation strategies so that the whole system is more effective than the sum of the parts; but in the absence of conscious design for constructive interactions, such occurrences are fortuitous.

The concept of destructive and constructive interaction between mitigation strategies raises further questions that we also consider in this paper:

1. How can mitigation strategies be classified?
2. How do the limitations of our knowledge of hazards affect our choice of mitigation strategies and combinations of strategies?
3. How do different classes of mitigation strategies interact with other classes?

We are primarily concerned here with mitigation systems designed to mitigate the effects of rapid-onset geophysical hazards such as earthquakes, tsunamis, windstorms and volcanic eruptions. Nevertheless, we consider that the concepts outlined may also be relevant to the mitigation of extended hazard events such as droughts.

2 Classification of mitigation strategies

2.1 Classification criteria

The classification that we present here is based upon two criteria that relate to the mitigative actions that result from mitigation strategies:

1. *Timeframe* when do the mitigative actions resulting from the strategy occur—does it produce actions (such as construction of flood defences) long before the hazard event whose effects are then permanently operative (or at least continuously operative over a specified time period), or are these actions triggered either by the successful detection of the source event that generates a hazard (or an early manifestation of the hazard such as first landfall of a tsunami), or by successful detection and interpretation of precursors to the hazard source event that are recorded and interpreted by observers or by some form of warning technology?
2. *Adaptability* does the strategy enable the actions resulting from it to be modified or adapted immediately before or during an unfolding hazard event by *optional* decisions made following observations of the hazard or its precursors (we use the word optional here to emphasise that a potential decision maker may choose not to intervene and rely upon decisions made by others), or are these actions fixed in advance of the hazard event? The latter applies most obviously in the case of permanent physical hazard defence structures, but also in the case of automated responses as discussed below. The optional decisions involved in modifying or adapting the actions may take many forms and may be made by different people ranging from individuals within directly vulnerable populations through professional emergency managers to political leaders.

An important feature of these two criteria is that they encompass the possibility that, once implemented, a mitigation strategy may require no further decision-making or actions unless and until public, political or scientific opinion seeks to change it as a result of social, economic, environmental, political changes, or changes in knowledge of the hazard, that have occurred since implementation of the strategy. This feature, which applies most obviously in the case of permanent physical defences against a hazard, presents problems for the concept of “early warning systems” as it has developed in recent years. The definition of “early warning system” has developed from the more narrowly defined “means of getting information about an impending emergency, communicating that information to those that need it, and facilitating good decisions and timely response by people in danger” (Mileti and Sorenson 1990) to the broadly defined “systems that link risk knowledge, monitoring and warning services, dissemination and communication, and response capability” (UNISDR PPEW 2006, p 2). This expansion presumed that mitigative actions necessarily involve communication and decision-making based upon information provided by monitoring and warning technologies leading to actions in response to that information, but this is not always true as illustrated in our Tohoku disaster case study (Sect. 3). Therefore, we argue that the policy choice to introduce mitigation strategies that rely on such technologies and associated communication and decision-support technological systems as a basis for mitigative actions should be recognised explicitly as such, and that alternatives should at least be considered. Whilst the concept of a mitigation system presented here resembles the broadest definition of an early warning system (EWS) as used by Garcia and Fearnley (2012), we regard the change of terminology as important: it focuses upon the aim or purpose of the system, and makes no presumptions about how this aim or purpose is to be achieved.

Given the two criteria identified above, we identify three classes or categories of mitigation strategy: permanent, responsive and anticipatory.

2.2 Permanent mitigation strategies

Permanent mitigation strategies involve actions that are put in place long before hazard events and remain in place at all times, at least within specified periods (as for example in the case of an annual insurance policy). Their operation is not dependent upon human decisions or actions shortly before or at the time of the hazard event, and so cannot be adapted in the light of observations of impending or occurring hazard events, to mitigate those events. Although of course they may be changed after an event to take advantage of lessons learned and in the hope of mitigating future occurrences of the same hazard (for example the renewed interest in relocation of coastal communities to higher ground after the 2011 Tohoku tsunami, following a pattern seen after earlier tsunamis: Shibata 2012; Suppasri et al. 2012, 2013, 2015), these changes only occur in the following circuit of the DM cycle. The simplest examples of permanent mitigation strategies involve implementation of permanently in place measures such as: physical defenses like tsunami and storm surge coastal defenses, and river flood defenses building regulations designed to reduce the vulnerability to seismic shaking of buildings, constructed or retrofitted in accordance with them; building regulations designed to reduce the vulnerability to seismic shaking of buildings, constructed or retrofitted in accordance with them; reductions in exposure to the hazard through development planning and land-use restrictions, or discouragement of development through measures such as denial of public funding for infrastructure and services in high-hazard zones; and compensatory reliefs such as insurance. The first of these are "structural" mitigation strategies in the sense used by Godschalk et al. (1989), whilst the second and third are "non-structural" strategies: we emphasise, however, that in all three cases implementation of these measures takes place long before hazard events and does not involve decision-making during, or shortly before the hazard event. They are instead based on decisions made in advance, on yearly to multi-decadal timescales.

More subtly, permanent mitigation strategies also include automated systems such as shutdowns of power systems and railways in response to initial seismic shaking (Fujinawa and Noda 2013). No human intervention is either required or possible in the operation of these systems during disasters. Other mitigation strategies may be dependent on automated infrastructural systems to be functional, for example the automated systems for rapid communication of data and warning messages around large-scale instrumental monitoring networks. Automated systems frequently have preset responses, varying according to measured criteria of the hazard event, that are fixed in advance and do not involve optional decision-making—potentially leading to novel actions—at the time of the hazard event. Given there is no capacity to respond to observations that do not fit those measured criteria (that is to say, new or unexpected observations), we therefore include automated response strategies in the category of permanent mitigation although they share some characteristics of the responsive or (more rarely) anticipatory mitigation strategies discussed below. A similar point applies to insurance and similar compensation schemes. Even though insurance payouts are triggered after a disaster, in the recovery phase of the DM cycle, the parameters of an insurance contract are all fixed at the time of its agreement. In our framework, insurance is therefore also a permanent mitigation strategy.

These features of permanent mitigation strategies mean that their operation is constrained by the prior beliefs and scientific understanding of the nature of the expected hazards, in terms of probabilistic hazard occurrence and intensity distribution that are used to design the strategies and their physical manifestations. There is therefore strong pressure upon the scientific advisors to the designers of permanent mitigation strategies to get their hazard estimates "just right" and furthermore to state these estimates with a precision that may be greater than is justified by their knowledge. Thus, permanent mitigation strategies are inherently bad at coping with the unexpected, especially if their designers fail to make allowance for their imperfect, uncertain knowledge of the hazard or hazards concerned.

On the other hand, since the hazard mitigation measures that result from a permanent mitigation strategy, once implemented, are always in effect, no advance knowledge is required of when an individual hazard event will occur, or with what intensity; nor does it require any ability of individuals to act in response to observations of the hazard event or precursors to it. Permanent mitigation strategies and the mitigation systems that depend on them are, therefore, very much the product of institutional rather than individual knowledge; with all that that implies regarding the capacity of these strategies and systems to respond to new knowledge of the hazard that they are designed to protect against.

2.3 Responsive mitigation strategies

Responsive mitigation strategies involve decisions and actions in response to the detection and interpretation of a hazard event once the source event has occurred and taking advantage of the time gap compared to the time needed to implement changes to the plans previously devised in accordance with the mitigation strategy between the source event and its impact on vulnerable populations and environments. Responsive mitigation strategies therefore have a potential for adaptation of actions on the basis of the observations of the hazard event, although the capacity for adaptation may be severely limited by the short duration of this time gap. They may be based upon complex technological sub-systems or relying on simple direct sensory (non-instrumental) observations made by groups and individuals within vulnerable populations. These strategies require capacities to: recognise the signs that a hazard-causing event has occurred, or is about to impact vulnerable exposures; to interpret those signs in terms of the intensity of the hazard and if necessary communicate that interpretation to distinct decision-makers; to optionally decide what action to take to mitigate the hazard; and to carry out those mitigative actions in a timely fashion so that they have a positive effect (we note that the confusion caused by late changes to, for example, evacuation routes and plans, may reduce rather than increase the effectiveness of a strategy for responsive mitigation by evacuation). Several aspects of knowledge of the hazard event are therefore involved in the successful implementation of a responsive mitigation strategy, which must be determined, interpreted and processed in the short time between the hazard-causing event and the impact of the hazard. These time intervals can range from seconds, in the case of earthquakes, to tens of minutes in the case of near-field tsunamis and tornadoes, to many hours in the case of far-field tsunamis and hurricanes. Furthermore, this rapid process needs to be reliable, avoiding both underestimation of the hazard event on the one hand (leading to insufficient mitigative actions in this particular event) and overestimation on the other, that may lead to a "false alarm" or "cry wolf" syndrome that is liable to hinder responsive mitigation of future similar events.

Provided the knowledge base that underpins observation and interpretation of the hazard is sufficiently profound, the operators of responsive mitigation strategies can modify the actions prescribed by the strategy to cope with the unexpected, particularly unexpectedly high-hazard intensities. However, short time intervals available for effective action can require complete or partial automation of key technological components of responsive mitigation strategies. An example is the automated processing of detected signals to generate warning messages that are then evaluated by a scientist to reduce false alarms, before being transmitted further. The difference between such a case and the completely automated shutdown systems that we have argued to be permanent mitigation strategies (Sect. 2.2) may be slight or significant, according to the range of interpretative judgments and optional actions available to, respectively, the scientists (or other observers) and emergency managers under the protocols and cultures that govern their work. There is, therefore, a gradation between responsive mitigation strategies and permanent mitigation strategies reflecting a trade-off between adaptability and timeliness. We emphasise that the key distinction between the two is that actions prescribed by a responsive mitigation strategy can be adapted in near real-time during a hazard event, on the basis of decisions made in response to new observations and interpretations of the hazard, whereas the actions involved in implementation of a permanent mitigation strategy cannot.

2.4 Anticipatory mitigation strategies

Anticipatory mitigation strategies involve actions that are implemented on the basis of observations and interpretations of precursory phenomena to hazard-causing events, in the time period in which those precursors occur (which may vary from hours to days, in the case of many meteorological hazards, to months or even years in the case of volcanic eruption hazards). These actions may be adapted to allow for new information about the nature, intensity and extent of the anticipated hazard event that is gained as a result of interpretation of the hazard precursors. Anticipatory mitigation strategies therefore depend fundamentally upon the knowledge base used to reliably identify precursory phenomena to the hazard-causing event, and to interpret those phenomena in ways that provide indicators of the location, time and magnitude of the hazard-causing event with sufficient certainty to enable prediction of the timing and intensity distribution of the resulting hazard in a form that provides a basis for mitigative actions. In the case of complex hazard events, such as volcanic eruptions, there may also be uncertainty about the nature of the hazards that are about to occur, and the occurrence and intensity distributions of secondary hazards such as landslides, dam break floods and fires.

Anticipatory mitigation therefore depends, more than the other types of mitigation strategy, upon an understanding (normally, at least in the modern era, but not necessarily a scientific or deductive understanding; traditional beliefs may also form a basis for anticipatory actions) of the processes and mechanisms that underlie the hazard-causing event and precursory phenomena. It also depends on the level of tolerance of uncertainty by decision-makers and others stakeholders, who must be prepared to accept the social, economic and reputational costs of false alarms. In general, the interpretation of precursors becomes more certain as they accumulate with time, whilst the time available for anticipatory action decreases in proportion. Whilst some societies and individuals live in a mental state of "constructive paranoia" (Diamond 2012, pp 243–275) that enables anticipatory actions to mitigate a wide variety of hazards in response to the slightest warning signs, in developed societies the limits of anticipatory mitigation are constrained by the institutional state of scientific knowledge of precursory phenomena for particular hazards, as well as by the level of awareness of those particular hazards amongst vulnerable populations (Esteban et al. 2013). Therefore, anticipatory warnings are normally communicated to vulnerable populations in a "top-down" fashion opening the potential for failures of communication, or for refusals to act as expected on the basis of the information communicated.

The advantage of anticipatory mitigation strategies, as compared to responsive mitigation strategies, is that in general they provide longer time intervals for interpretation, warning communication, decisions and consequent mitigative actions, and therefore also greater scope to adapt the actions prescribed by the strategy to the unfolding hazard event within the limits of available resources. These resources may well have been determined long in advance and in these cases, there is an overlap between anticipatory and permanent mitigation similar to that between responsive and permanent strategies discussed above. The key feature and potential critical weakness of anticipatory mitigation strategies are, however, that these decisions and actions have to be made under conditions of greater uncertainty than is the case with responsive mitigation strategies.

Whilst the boundary between responsive mitigation and anticipatory mitigation is clear for those hazards that have a clear onset time (most notably earthquakes and tsunamis), the distinction is less clear for those in which the hazard is caused by an evolving event such as a hurricane. Hurricane warnings and consequent mitigation activities, such as coastal evacuations, begin with many features of anticipatory mitigation—coping with uncertainties in the track and strength of the hurricane—and only gradually evolve into responsive mitigation as the hurricane approaches landfall.

2.5 Knowledge of natural hazards and the choice of mitigation strategies within a mitigation system

Decisions relating to a proposed mitigation strategy and its place within a mitigation system depend on a wide range of factors from technological and economic through to social and political factors. The complexities of these interactions between the mitigation strategies, vulnerabilities and exposures, and how decisions are made within these interactions are beyond the scope of this paper. However, we emphasise the importance of the scientific or other knowledge of hazard that underpins the design and operation of a mitigation strategy. As discussed in the previous sections dealing with each type of mitigation strategy, the aspects of knowledge of the hazard that are most critical differ systematically between the three types of mitigation strategy that we have defined. Whilst in all cases there must be some consensus regarding the threat represented by recurrence of a hazard, the different types of mitigation strategy have different knowledge base requirements. The classification presented applies to mitigation strategies for different hazards and may operate on different scales, so the details of the knowledge base differ widely. Nevertheless, we argue that some common features of the knowledge base apply to all the mitigation strategies in a particular class that are characteristic of that class and differ between classes (Table 1).

In consequence, the scientists who provide important aspects of that knowledge base play different roles, and need to provide different types of knowledge (data and interpretation) at different times, in support of the different classes of mitigation strategy. Table 1 summarises the different types of mitigation strategies and contrasts the knowledge tasks (normally science tasks) that underpin them. It is especially important to recognise that within this classification framework, different mitigation strategies are either effective or ineffective in part as a function of the present state of knowledge of the hazards concerned.

Finally, it should be noted that whenever a mitigation strategy is dependent upon hazard knowledge, its effectiveness in the long term depends on the willingness to invest in the collection of that knowledge, for example in the updating of probabilistic hazard assessments, or in the monitoring and detection equipment networks that form critical elements of hazard warning systems, and in the intellectual capacity to interpret and use that knowledge as a basis for mitigative actions. In the long term, this willingness to invest in hazard knowledge will depend upon the awareness of the hazard in the populations that are

Table 1 Classification of mitigation strategies by the criteria used in this paper and the relative importance of different aspects of knowledge of hazard as a basis for different classes of mitigation strategy, as indicated by sizes of crosses in table

		Mitigation strategy classes and their defining characteristics		
		Permanent	Responsive	Anticipatory
Timing of implementation actions prescribed by strategy		Long before hazard event	In response to detection and characterisation of hazard event	In response to detection and interpretation of precursors to hazard event
Adaptability of implementation actions to characterisation of individual hazard events		None	Some (limited mainly by time available)	Some (limited mainly by uncertainty)
Key science tasks	Long-term spatial frequency/magnitude distribution	**X**	**X**	x
	Understanding mechanisms and interpretation of precursors			**X**
	Rapid detection, event quantification and communication		**X**	x
	Accurate alert information and avoidance of false alarms		**X**	**X**

vulnerable to it, as indeed will the effectiveness of mitigation strategies based upon that knowledge—especially mitigation strategies that rely upon the vulnerable populations to take decisions and act upon them, often in short time frames and in the face of uncertainty. This point has been made in relation to tsunami hazard mitigation by Esteban et al. (2013) but applies much more widely; we return to it in the discussion section below.

2.6 The concepts of "brittle" and "flexible" mitigation strategies and the importance of the scientific basis for choosing mitigation strategies

An additional concept, distinct from our classification, that we find useful in analysing the interactions of mitigation strategies is that of **brittle** mitigation. This, by analogy with brittle materials, means a mitigation strategy that reduces losses associated with hazard events up to a limit of hazard intensity; but that fails, in ways that are associated with high levels of loss, in events where that hazard intensity is exceeded or where the area affected by the hazard is larger than that anticipated by the mitigation strategy. Such failure can be literal and physical, as in the case of the collapse of a flood defence under pressure of water, or the inundation of a built-up area above the expected maximum flood level used to define a zone of land-use restriction around a river flood plain. However, it can also be a system or process failure, for example the breakdown of a communications system upon which a responsive mitigation strategy depends, under the impact of the hazard event that it is designed to mitigate. Some strategies may have the potential to fail in both ways: for example, provision of community shelters to which people can retreat during or after a hazard event should their houses be damaged may be a brittle mitigation strategy either because the shelters themselves may be unexpectedly vulnerable either to the primary hazard or to secondary hazards, leading to both direct casualties and to the loss of emergency supplies stored in the shelters; or because provision of the shelters discourages investment by families or individuals in more hazard-resistant homes and in emergency supplies: the combination of these effects could produce a particularly brittle mitigation strategy. Again by analogy with brittle materials, which are often more rigid or have greater strength up to their failure than do similar more ductile materials, brittle mitigation strategies may actually be more effective below their limiting hazard intensity than more flexible mitigation strategies, but far less effective above this limit. Further, the term does not necessarily imply failure at low hazard intensity and for this reason we prefer the term brittle to the alternative “fragile”.

In contrast to brittle mitigation strategies, a **flexible** mitigation strategy is one that retains a significant degree of effectiveness even when faced with a hazard intensity greater than that assumed in its design, either through inherent features of its design (as in “fail-safe” technologies that can form the basis of flexible permanent mitigation strategies) or through the design into the strategy of a capacity for adaptation of actions in response to the observation that the design hazard intensity has been, or is about to be, exceeded. Thus, a feature of a well-designed responsive or anticipatory mitigation strategy, is that it is operated by individuals, groups or organisations with a level of education and technology adequate to observe and interpret observations that indicate that the impending hazard event will be of unusually high intensity. In such a case, the strategy is likely to have a high degree of flexibility and so will be less dependent on any probabilistic assumptions made about the likely intensity of the hazard. It should be noted that use of advanced technology or highly educated professional operatives is not a prerequisite for flexibility. The basis of observation and interpretation may be very simple—for example observation of large approaching tsunami waves, or of an unusually extended period of strong felt seismic shaking, may be adequate for correspondingly urgent responsive mitigation (running faster and further) by hazard-aware populations in or close to tsunami source zones.

We emphasise that our distinction between “brittle” and “flexible” mitigation strategies is not the same as that between “hard” (engineered structures) and “soft” (mainly, warning and evacuation-based) protection measures that have been emphasised in the context of tsunami hazard mitigation in Japan both before and, with greater intensity, after the Tohoku 2011 earthquake and tsunami (Shibayama et al. 2013). In the case study below, we illustrate how particular types of mitigation strategy can tend to be brittle or flexible, as well as how the failure of brittle mitigation strategies can have exceptionally severe consequences when the failure is unexpected. This is typically because the assumption of effectiveness of the failed mitigation strategy may have reduced the effectiveness of other mitigation strategies within the overall mitigation system or even led to the exclusion of those alternative strategies from the design of the mitigation system. In such situations, the presence of a brittle mitigation strategy within the mitigation system can be said to have *embrittled* the system as a whole, or other particular strategies within it where it has particular effects upon these. Thus, the adoption of a brittle mitigation strategy, and its detailed design, are more likely to have dangerous consequences when it is not based upon a good understanding of those features of the hazard that affect its performance and in particular its limits of effectiveness. We emphasise, however, that anticipatory and responsive mitigation strategies are not necessarily flexible (for example, if vulnerable populations are simply told to perform predetermined actions without explanations, they are not given the capacity to vary their actions in response to their observations of the hazard event), and that permanent mitigation strategies are not necessarily brittle if the failure of structures or processes implementing those strategies is “fail-safe” or gradual.

3 Retrospective analysis of interactions between mitigation strategies in the 11 March, 2011, Tohoku earthquake and tsunami

In this section, we use the concepts developed in the previous section to retrospectively analyse, in the spirit of analysis and retrospection promoted by Voight (1990), the causes of malfunctions in the operation of exceptionally complex seismic and tsunami hazard mitigation systems in the 2011 Tohoku earthquake and tsunami disaster. In our analysis, we mainly deal with interactions between mitigation strategies that belong to different types, but also include interactions between mitigation strategies of the same type. The interactions discussed are negative interactions, but we note that positive interactions, where efforts to pursue one mitigation strategy have positive effects on the implementation or operation of another, can also occur. An example may be found in the Mt Pinatubo 1991 volcano eruption disaster, where efforts to ensure continuity of instrumental monitoring of the volcano during the impending eruption to enable evacuation in response to increasing levels of activity even during the eruption (a near—responsive mode anticipatory mitigation strategy) may have contributed to the change in perceptions on the part of emergency managers at Clark Air Base that led them to order a pre-emptive (i.e. anticipatory) evacuation of the base prior to the start of the eruption proper (Punongbayan et al. 1996, p 81; Anderegg 2000, p 30).

Whilst this section is not comprehensive (with our three classes of mitigation strategy, we would need a minimum of 24 examples to cover both positive and negative interactions (in either direction) between the six combinations of pairs of mitigation strategy types), we aim to present an illustrative example of how the concepts developed in this paper might be used to improve the effectiveness of mitigation systems as a whole. The designers of this example mitigation system placed emphasis upon the implementation of permanent physical defences and automated systems, so our comments focus upon these and the interactions between them and other mitigation strategies, but in other cases the emphasis might for example be upon the interaction between land-use planning and awareness education mitigation strategies.

The 2011 Tohoku earthquake and the resulting tsunami impacted densely populated and highly developed regions in Japan, where more financial, technical and scientific resources have been put into a greater variety of hazard mitigation strategies than in any other country. Two mitigation systems were involved: one that mitigated seismic shaking hazards and the other that mitigated tsunami hazards. These were partly connected and were dependent on the same hazard assessment, but had distinct areas of coverage and involved distinct strategies (that nevertheless sometimes interacted with each other). The earthquake mitigation system—dominated by the permanent strategy of high construction standards to give buildings good resistance to seismic shaking—was generally successful as shaking intensities from the very large but offshore Tohoku earthquake were within the limits expected from smaller but closer earthquakes in the upper crust of Japan (Ye et al. 2013). However, the tsunami mitigation system is widely seen as having been at best a partial success (Suppasri et al. 2013) and by some as a major failure (Noggerath et al. 2011; Stein and Okal 2011). This is in large part because of two aspects of the disaster:

1. The high mortality rate in the tsunami inundation zone was higher than expected especially in view of the large investment in mitigation measures. The mortality rate was

3 % of the population in the inundation zone as a whole, and locally over 10 % (Suppasri et al. 2012, 2013). These were around one-fifth to one-tenth of the corresponding mortality rates in entirely unprepared but otherwise comparable inundated coastal regions of Sumatra in the 2004 Indian Ocean tsunami (Suppasri et al. 2012: note that the latter mortality data include people killed, or trapped in and subsequently drowned, in buildings that collapsed in the earthquake; but these do not account for the large difference in mortality rates) but, surprisingly, orders of magnitude more than is seen in major tsunamis affecting traditional coastal communities in undeveloped coastal regions of South Pacific countries where the only mitigation strategy is community based self-warning and voluntary evacuation based upon traditional (and, more recently, taught) knowledge of how to recognise and respond to strong felt earthquake shaking and the sighting of approaching tsunami waves (e.g. McAdoo et al. 2009).

2. The reactor accidents and radiation releases at the Fukushima nuclear power plant (NPP) that followed limited earthquake damage and then major tsunami damage to the reactor buildings and, critically, emergency support and safety technology systems (Lipscy et al. 2013). In contrast, and despite experiencing significantly higher tsunami waves than at Fukushima, the Onagawa NPP on the Sanriku coast suffered only relatively minor damage that did not prevent safe shutdown of the reactors, for reasons relating to the use of a local hazard assessment including local run up data from a wider range of past tsunami events as the basis for detailed design and layout of the NPP site (Sasagawa and Hirata 2012). As a result of this local hazard assessment, the Onagawa NPP was built with its safety critical components some 5 m to 10 m higher above sea level than the corresponding components at Fukushima, and so remained sufficiently functional to enable safe shutdown of the reactors.

A root cause of these aspects of the disaster was the discrepancy between the sizes of the earthquakes and tsunamis that were anticipated to occur on the NE Japan subduction zone, and the size of the earthquake and tsunami that actually occurred. We do not propose to enter the discussion about the reasons for this discrepancy (Geller 2011; Stein and Okal 2011; Kanamori 2012; Lay 2012; Stein and Geller 2012). For the purposes of this paper, it is instead important to examine how the discrepancy between expectation and the reality experienced on 11 March, 2011, affected both the performances of individual mitigation strategies and, in particular, the interactions between those strategies.

In addition to the most important and largely effective permanent mitigation strategy of building to high standards of earthquake shaking resistance, the earthquake hazard mitigation system contained numerous implementations of more or less automated equipment shutdown technologies (permanent mitigation strategies) such as the stopping of high-speed trains and the powering-down of operating nuclear reactors. There are indications, discussed below, that some of these automated strategies may have interfered with the operation of other mitigation strategies aimed at reducing the effects of the tsunami. A more truly responsive mitigation strategy, that of training individuals to “duck and cover” or take similar immediate action in response to alarms or felt seismic shaking, seems to have produced no comparable interferences (Fujinawa and Noda 2013).

The tsunami hazard mitigation system in NE Japan was (and is) unusual in the variety and scale of mitigation strategies used. In addition to the responsive mitigation strategies of evacuations following local and international warning system alerts, a variety of permanent mitigation strategies were also implemented in the region. These are summarised in Table 2 where two general trends can be observed at least for the locations in which key studies (notably, Ando et al. 2013) were carried out.

Table 2 Mitigation strategies used in the Tohoku 2011 earthquake and tsunami, their classification and effectiveness

Mitigation strategy	Category (and subsidiary elements)	Comments on effectiveness in 11 March, 2011, tsunami disaster	References
Engineered tsunami barriers (and gates)	Permanent (but with gates closed in response to tsunami warnings)	Barriers designed to protect towns and ports against moderate-sized tsunamis collapsed or were overtopped by the actual tsunami waves that were larger than allowed for in the design	Earthquake engineering research institute (2011); Suppasri et al. (2013)
Coastal tree plantations ("soft" or permeable tsunami barriers designed to slow inundations)	Permanent	Trees in plantations were broken or uprooted by the tsunami waves, increasing debris damage in the areas behind the plantations that were inundated by tsunami floodwaters choked with tree debris	Suppasri et al. (2013)
Restriction of development in anticipated inundation zone, based upon experience of historic large tsunamis (869 AD, 1896 AD, 1933 AD in particular) preserved in local knowledge and expressed in carved marker stones along the limits of previous inundations	Permanent	Based upon prior local experience rather than the national tsunami hazard assessment and highly effective in protecting villages on the Sanriku coast that had relocated inland or to high ground beyond the inundation limits of the 1896 AD tsunami in particular, as inundations from that event were broadly comparable to those in 2011. The Onagawa NPP site was also laid out on the principle of minimising, as much as possible, the elements of the installation located below the inundation limit of the 1896 AD tsunami at Onagawa: this was effective in ensuring the safe shutdown of the installation	Suppasri et al. (2013); Sasagawa and Hirata (2012)
Evacuations in response to messages originating from Japan Meteorological Agency rapid-response instrumental tsunami warning system	Responsive (with Permanent monitoring and communications infrastructure forming technological sub-systems)	Initial warning based on incomplete data underestimated tsunami size, indicating that it would not be large enough to overtop tsunami defences. JMA earthquake magnitude estimates (and tsunami predictions) not upgraded until 2–12 h later. In some areas, few people received the JMA warning messages due to breakdown of communications infrastructure as a result of the earthquake and power outages	Ando et al. (2013)

Table 2 continued

Mitigation strategy	Category (and subsidiary elements)	Comments on effectiveness in 11 March, 2011, tsunami disaster	References
Evacuations in response to local warnings, or self-warning in response to felt seismic shaking and/or observation of approaching tsunami waves	Responsive (with Permanent warning infrastructure forming technological sub-systems)	Effective in many places on the Sanriku coast in particular, reflecting prior community experience of tsunamis, except in cases where people believed they were safe behind tsunami defences, or evacuated to tsunami shelters that were subsequently inundated. Some people did not evacuate as the tsunami waves neared the shore because tsunami barriers blocked their view of the sea; others did not evacuate because they were above the level of tsunami shelter roofs, and so believed that they were safe; or evacuated only to the edges of tsunami hazard zones as defined in official maps and were caught by tsunami waves larger than those allowed for in the maps. In some cases, the local warning systems depended on emergency workers remaining at their posts within the inundation zone, and so effective operation of these systems was at the cost of the lives of the emergency workers concerned	Earthquake Engineering Research Institute (2011), Ando et al. (2013)
Provision or earmarking of tall buildings as tsunami vertical evacuation shelters within expected inundation zones to reduce evacuation time to reach safety	Permanent	Many of these shelters were designed to protect against the moderate tsunamis predicted by the hazard assessment, but were largely or completely inundated by the actual tsunami, resulting in high mortality rates amongst people trapped in the shelters	Earthquake Engineering Research Institute (2011), Suppasri et al. (2013)

First, since the tsunami was very much larger in scale and intensity than expected in almost all of the engineered (or "hard"; Shibayama et al. 2013) permanent mitigation strategies, these strategies generally showed brittle behaviour. In some cases, this was physical brittleness (e.g. tsunami barrier walls that collapsed under loads in excess of design limits or due to design faults), and in others brittleness in the sense of a drastic decrease in effectiveness beyond the design hazard intensity (e.g. the overtopping of tsunami barriers and complete inundation of tsunami shelters). Large numbers of deaths amongst people in inundated tsunami vertical evacuation shelters highlight the point that the brittle behaviour of the permanent mitigation strategy manifested in these structures also reduced the overall effectiveness of the mitigation system not only by the direct physical consequences of their failures but also by their interferences with the operation of the responsive mitigation strategies. Thus, the effectiveness of the evacuation strategies (whether based on the permanently in place technologies of national or local warning systems, or even on self-warning as discussed below) was destroyed if, on the basis of these warnings, people evacuated to vertical evacuation shelters that were subsequently inundated, becoming traps rather than shelters (Earthquake Engineering Research Institute 2011; Ando et al. 2013). Other interferences between elements of the physical structures that were manifestations of the permanent mitigation strategies, and actions prescribed by the responsive mitigation strategies, are also indicated in Table 2.

In contrast to the brittle behaviour of permanent mitigation strategies designed on the basis of the national seismic and tsunami hazard assessment, permanent strategies designed on local knowledge of past tsunami events were highly effective (Mori et al. 2011). Examples include the relocation inland of villages after previous tsunamis in 1896 and 1933 and prohibitions on building downslope and seaward of traditional tsunami inundation markers (Shibata 2012; Suppasri et al. 2012, 2013), as well as the design of the Onagawa NPP (Sasagawa and Hirata 2012) where the simple decision to build as much as possible of the installation above the inundation limit of the 1896 tsunami was a highly successful permanent mitigation strategy, fundamental to the survival and safe shutdown of this NPP. This highlights the critical sensitivity of permanent (or "hard"; Shibayama et al. 2013) mitigation strategies to errors in assessments of long-term hazard occurrence and intensity distributions.

A second trend, although not as clear, is that some responsive mitigation strategies may have interfered with others. From Table 2 [see especially the study by Ando et al. (2013), albeit a very small survey], it is evident that a variety of interferences between responsive mitigation strategies occurred during the Tohoku disaster. Initial underestimation errors in the official bulletins (the basis for the responsive mitigation strategy of instrumental warning system based evacuation) caused this strategy to interfere with the more basic responsive mitigation strategy of evacuation based on individual or community knowledge, observation and warning. Continued operation of the instrumental warning system was disrupted by the power failures resulting perhaps in part from interference from the earthquake hazard mitigation strategy of automated shutdown of nuclear power plants. However, given that the JMA underestimated the predicted size of the tsunami up until it actually struck the Sanriku coast (Ando et al. 2013), it may be that the collapse of the broadcast communication system ultimately reduced rather than increased casualties, by removing a source of erroneous information that conflicted with other information that correctly indicated that a major tsunami was about to strike, such as the strength and duration of seismic shaking and the direct observation of approaching tsunami waves.

We emphasise that much further work needs to be done on collecting and analysing data relating to the actions, and the reasons for those actions, of people who were in the inundation zone of the Tohoku tsunami. Nevertheless, present indications are that destructive interactions or interferences occurred both between different responsive mitigation strategies, and especially between permanent mitigation strategies and responsive mitigation strategies, that greatly reduced their effectiveness as parts of the overall mitigation system with the result that some of the responsive mitigation strategies were as brittle as the permanent mitigation strategies. Rather than operating together to enhance the effectiveness of the tsunami mitigation system as a whole, the application of science, technological ingenuity and considerable investment of economic resources to a wide range of mitigation strategies appears to have produced an embrittled mitigation system that experienced serious malfunctions under hazard intensities greater than the maximum which its component strategies—especially most permanent mitigation strategies—had been designed to resist.

4 Summary and reflections

4.1 Summary

This paper has advocated the analysis of mitigation systems in terms of the mitigation strategies that they contain and the interactions between those strategies, in an approach similar to that of a systems analysis more generally. As a key step in this process, it has presented a classification of mitigation strategies into permanent, responsive and anticipatory strategies. The classification is based on the two criteria of first, when the strategy operates (permanently, at the time of the hazard event, or in the anticipation of the event in response to precursors), and second, on whether or not the strategy can be modified or adapted, in response to near real-time observations of the hazards or its precursors. Permanent mitigation strategies do not require such observations or the warning systems needed to make and communicate them, and it is for this reason that the paper has adopted the mitigation system terminology in place the concept of the early warning system.

The boundaries between these classes of mitigation strategy are gradational, and the position of any given mitigation strategy within the gradation depends on the extent to which any actions involved are predetermined or optional and based upon observations of the hazard event. As a result, the viability and effectiveness of particular types of mitigation strategy in dealing with particular hazards are strongly dependant upon the capacity to observe the hazard and interpret those observations in time to adequately implement the mitigation strategy. The current state of knowledge of the hazard may be sufficient to support some classes of mitigation strategy but not others.

An additional property of mitigation strategies identified as important is that brittle mitigation strategies may be more effective below their limiting hazard intensity than more flexible strategies, but are far less effective above this limit. It follows that adoption of a brittle mitigation strategy is more likely to have dangerous consequences when it is not based upon a good understanding of those features of the hazard that affect its performance.

4.2 Reflections upon the Tohoku 2011 case study

The Tohoku 2011 example shows that interactions between mitigation strategies have profound effects upon the overall performance of the mitigation system. Since these interactions have not been previously been systematically recognised and allowed for in the design of mitigation systems, they have usually been destructive and have greatly reduced the effectiveness of complex mitigation systems such as the tsunami mitigation system in NE Japan. In particular, permanent mitigation strategies like those emphasised in Japan prior to 2011, are often inherently brittle, since once implemented they lack the capacity to adapt to new hazard observations. It is arguable that they should only be used when there is no knowledge base that enables responsive or anticipatory mitigation strategies (such as the mitigation of earthquake hazards where the main strategy is that of building to high standards of seismic resistance). A key problem that should be addressed whenever a permanent mitigation strategy is included within a mitigation system is how to ensure that people execute effective responsive or anticipatory mitigation despite their expectations of the performance of permanent mitigation strategies. It is critical to ensure that vulnerable populations have realistic expectations of the performance of permanent mitigation strategies and in particular understand that they lose their effectiveness above their design hazard intensity limit: this point is now emphasised in awareness education in Japan by the division of tsunami hazards into high- and low-intensity cases (Shibayama et al. 2013). We consider that, in order to further reduce destructive interactions between permanent and decision-action dependent (responsive and anticipatory) mitigation strategies, there is a need to understand the decision-making processes, in emergencies, of vulnerable populations and individuals. In particular, there is a need to understand how observations and warning messages are interpreted by populations and individuals in the light of their prior knowledge and expectations to form the basis of decision-making and thus mitigative actions on the part of vulnerable populations.

Our choice of the NE Japan tsunami mitigation system and its performance in the 2011 disaster, as an example with which to illustrate the application of our concepts, raise the question of whether they can be applied to other mitigation systems. Certainly, some mitigation systems are so simple—for example the tradition-based self-warning and voluntary evacuation tsunami mitigation practiced in the southwest Pacific (McAdoo et al. 2009)—that their operation is largely or entirely dependent on a single mitigation strategy and so the problems of interaction between strategies may not arise. However, most mitigation systems, especially those that operate to protect developed societies against major hazards, are likely to involve multiple mitigation strategies. Detailed examination of a sufficient number of such systems to demonstrate the universal application of our approach is beyond the scope of the present paper, but we note as an example that the hurricane mitigation system that operated on the US Gulf Coast in 2005 included a range of mitigation strategies including permanent (most notably, the New Orleans flood defence levees), anticipatory (regional-scale evacuation) and responsive (local evacuation to high buildings and shelters) mitigation strategies that in both variety and complexity may be comparable to those that operated in NE Japan in 2011. Although the details of the technological, socio-economic and political environment in which the US hurricane mitigation system operated in 2005 are clearly different from, and arguably more complex than, the situation in Japan in 2011, we suggest that one way to resolve the many controversies that surround the Hurricane Katrina disaster may be to analyse the mitigation system that operated during that event using the conceptual tools and methods that we have outlined in this paper. We emphasise again that the primary aim of this paper is to outline a conceptual framework that may assist others to understand, investigate and analyse existing mitigation systems and ultimately help to devise and evaluate more effective mitigation systems in the future.

4.3 Implications of the classification and interactions framework for the disaster management cycle

In practice, the DM cycle is in often linearised (Coetzee and van Niekerk 2012) so that the stages are seen as entirely sequential with the overall effectiveness of actions within one circuit of the cycle being the linear sum of the actions taken in the parts, rather than a complex product of these parts and the interactions between them (Garcia and Fearnley 2012). In this paper, we have emphasised that although choices of mitigation strategies and of the policies designed to implement them are decided upon far in advance of hazard events, the actions involved in the actual operation of them may occur long before (permanent mitigation) in the mitigation phase of the DM cycle, shortly before (anticipatory mitigation) in the preparedness phase, or during (responsive mitigation) hazard events, in the responsive phase. Therefore, we have identified that not only do interferences occur between different mitigation strategies across the four phases, but that interferences also occur between mitigation strategies and strategies developed and implemented in other phases of the DM cycle. Thus, although the DM cycle remains a useful conceptual tool, it has important limitations as a framework within which to evaluate the successes and failures of disaster management measures. Our classification, as exemplified by the case study of Tohoku, highlights the need to recognise the changing social, political, technological and other contexts in which mitigation strategies operate, and the interactions they have with other strategies for preparedness, response and recovery. These interactions can be defined as a complex system; “a system in which large networks of components with no central control and simple rules of operation [that] give rise to complex collective behaviour, sophisticated information processing and adaptation via learning or evolution” (Mitchell 2009, p 13), and exhibit non-trivial emergent behaviours. Rather than critique the value of the DM cycle, we intend this research to support the applicability of nonlinear and holistic approaches to disaster management (Mileti 1999; Ramalingam et al. 2008) that enable decision-makers, at all levels, to understand the limitations involved and determine the risks in establishing effective mitigation strategies, rather than simply following normative or procedural protocols.

4.4 Potential application of the classification and interactions framework in the practice of mitigation system design and operation

The classification and interaction framework presented in this paper may have practical application to the work of different actors involved in hazard mitigation.

Emergency managers could use this framework in a process of prospective analysis of mitigation systems not yet tested by occurrence of the hazards that they are designed to mitigate. The aim of this would be to identify weaknesses in the mitigation systems in which they are responsible due to destructive interactions between mitigation strategies. Furthermore, they could design corrective actions that ensure non-interference between mitigation strategies or, even better, positive interaction between mitigation strategies.

In the light of the concepts presented here, hazard scientists need to examine, recognise and correct limitations of knowledge that are critical to both the operation of individual strategies as well as for negative interactions between mitigation strategies such as those resulting from unexpected brittle failure of permanent mitigation strategies.

Finally, the analysis presented here indicates that policy-makers should not choose and implement individual mitigations strategies in isolation, but should evaluate them within the framework of the overall mitigation systems.

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