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CAT 360

Catastrophe Risk from Every Perspective

The CAT 360 is a quarterly newsletter that features articles developed by our Research and Development Team and covers topics that relate to Catastrophe Modeling, Natural Perils and Information Technology on a global basis. Please feel free to contact the editors if you have any questions or comments regarding any of our publications.

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Making sense of earthquake clusters

Recent global events are a reminder of the destructiveness of earthquakes. The recent Mw 8.8 Chile earthquake and Mw 7.0 Haiti earthquake occurred within two months of each other. Both caused extensive property damage and human casualties (with death toll estimates rising to 230,000 in Haiti and approximately 800 in Chile at the time of writing). The Chilean quake, ranked in the top ten largest earthquakes ever recorded, is thought to have been so powerful it shifted the earth on its axis.

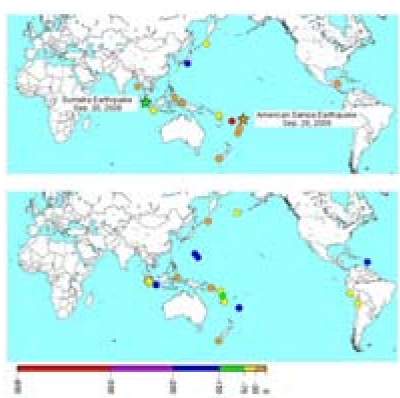

Figure 1 - Upper panel: Earthquakes ≥ Mw7.0 in 2009. Lower panel: Earthquakes ≥ Mw7.0 in 2007. Color codes represent the depth (in km).

Other earthquakes have also occurred closely in both time and space. Last year on the 29th of September, an Mw 8.1 earthquake took place in the Samoan Islands. It was followed just a day later by an Mw 7.6 earthquake that occurred off the southern coast of Sumatra (Figure 1). The short duration between these two events led to an important question: Were the two events related or independent? And if there is evidence that earthquakes are related, is it possible to know when and where the next quake will happen?

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Clustering defined

Imagine that you are walking on the street and bump into three friends in a short period of time. It may be purely random. Or all three friends could be heading to the same place (such as a rock concert, as friends often share similar interests). If the meetings are purely random they have no implication on your chance of meeting another music-loving friend. But if the latter is true, it suggests you will probably see another music-loving friend further down the street.

It may not be the perfect analogy, but earthquakes (and earthquake clusters) can happen randomly or inter-relatively. In this article we will discuss how earthquakes interact, causing clusters.

Growing evidence demonstrates that earthquakes are not completely random or independent. The upper and lower panels of Figure 1 are maps of earthquakes with magnitudes greater than 7.0 in 2009 and 2007 respectively. Earthquake "clusters" in the Pacific Rim are clearly evident in both years. So are these clusters random or linked?

In some cases, one earthquake reduces the probability of subsequent earthquakes; while in other cases, one earthquake might trigger other earthquakes, causing earthquake clusters. The difficulty for scientists, insurers and catastrophe modelers is in understanding the patterns.

It is known that a big earthquake releases stress on the fault segment where the rupture occurs. Therefore, on the same fault, the probability of another earthquake has reduced greatly. In contrast, if a fault has not ruptured for a long time, the stress will accumulate and thus increase the probability of a quake. This phenomenon is known as earthquake time dependency, which means that the probability of the next earthquake is dependent on the time and magnitude of the last earthquake on the same fault.

On the surface, earthquake clusters seem to be contrary to the theory of earthquake time dependency. If the stress is released, why would an earthquake trigger another? In fact, although the stress is released in the segment near the rupture, it can actually increase in other areas. In addition, if the precedent earthquake is small and unable to release the majority of stress on the fault, a subsequent earthquake can happen.

Scientists have found that in an earthquake cluster, quakes occur in a somewhat predictive manner. For property catastrophe insurance companies this can have a crucial bearing on their assessment of earthquake risk in a given location.

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Evidence of clustering

The clearest evidence of earthquake clustering is found in aftershock sequences following the main shock of an earthquake. But while patterns are more readily observed in the aftershock sequences of one event, separate earthquakes can also occur in clusters. For example, progressive quakes along the North Anatolia fault in Turkey triggered two large earthquakes (Mw. >7.0) within a three-month period in 1999 near Izmit (primary) and Duzce (secondary). The whole succession of quakes lasted several decades on a fault segment of more than 450 miles.

In the US, four earthquakes with a Mw. greater than 7.0 occurred within just a two month period in 1811-1812 in the

In 2008, a cluster of four earthquakes with a Mw. greater than 6.2 ruptured the Hellenic Arc and Trench within a six-month period in Greece. What is unusual about this cluster is that the four earthquakes occurred on faults that are spatially isolated.

These examples of clustering demonstrate that large earthquakes are able to trigger additional earthquakes, ranging from aftershocks in the immediate vicinity to remote earthquakes hundreds of miles away. Where the next earthquake in a chain occurs depends on the characteristics of the preceding events and the dynamics of the fault system on which they occur. In order to understand the behavior of an

New Madrid region. It was postulated that this sequence of large earthquakes was triggered on a linked strike-slip and thrust fault system (where the fault surface is nearly vertical and the footwall moves laterally with very little vertical motion). In addition to these four quakes, studies have suggested that the 1811-1812 sequence also triggered events well outside the New Madrid Seismic Zone.

earthquake cluster better, it is essential to understand these mechanisms.

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Trigger mechanisms

There are two main models for the earthquake triggering mechanism: static stress triggering and dynamic triggering. The static stress triggering theory was first put forward in the late 1960s but it took more than 20 years to gather the high-quality seismic and deformation data necessary to test the patterns predicted by the model. Put simply, the model states that an earthquake reduces the average shear stress on the fault that slipped, but increases shear stress in regions off the fault and the fault tips.

In 1992, a Mw. 7.3 earthquake occurred in Landers, California. Scientists calculated the stress changed immediately after the earthquake (Figure 2). They found that stress decreased in large areas shown in blue and purple. However, there was a significant increase in areas perpendicular to the fault and at the fault tips, shown in red. Around three and half hours later, another quake (Mw. 6.5) occurred in Big Bear where the model had predicted increased stress. In fact, 67% of the Landers-Big Bear aftershocks occurred in regions where calculations had showed increased stress.

Because static stress changes diminish relatively rapidly with time and distance, their triggering potential is confined in spatial scale. The model cannot therefore explain why earthquakes cluster over a greater distance and/or timescale. These more spread out clusters can instead be explained by propagating earthquake waves, otherwise known as dynamic triggering, which can nudge the stress fields in regions close by or at a further distance. As well as nudging stress fields, seismic waves

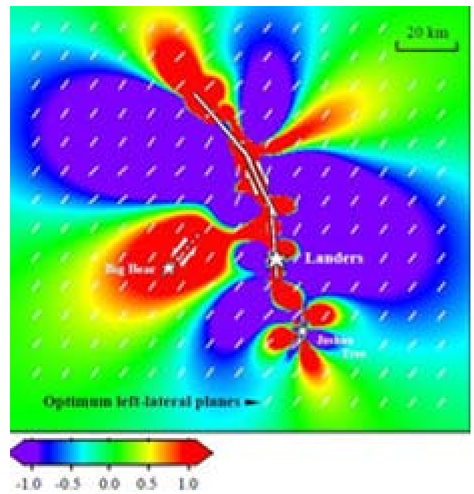

Figure 2 - Colomb stress change caused by the Landers and Joshua Tree Earthquakes before the occurrence of the Big Bear shock. The warm color shows stress increase and the cold color shows stress decrese. Source: King et al., Bull. Seismol. Soc. Am., 84, 935-953, 1994

The study of dynamic triggering was hampered by a lack of data until the 1980s and 1990s. The 1992 Landers Earthquake provided both rich observational data and evidence for dynamic triggering. Following the earthquake, seismic activity picked up across Western North America, at distances ranging from 200 km (125 miles) to 1,250 km (781 miles). However, most of these triggered events were low in magnitude.

Because dynamic triggering encompasses much larger heterogeneous areas, the triggering mechanism may differ from site to site. The conditions and physical processes that favor dynamic triggering are not yet fully understood but this will change as more complete datasets emerge.

are also associated with the fluid activation or creep that leads to earthquakes. While static stress triggers change the stress field permanently, dynamic stress triggers are oscillatory because they occur through wave interaction.

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Applying earthquake clustering

Earthquake clustering has several applications. It can be incorporated into earthquake hazard maps, with hazard increasing in regions where stress has increased and vice versa. And it can be applied to earthquake prediction. Clustering suggests there is some pattern to earthquake sequences - they are not fully random. Scientists can calculate where and how the stress has been changed after a mainshock and this information can be used to increase the predictability of the aftershock sequence and the next mainshock.

Earthquake hazard maps plot the probability of exceeding a certain ground shaking threshold. Scientists compute time-dependent probabilities to take into account the seismic cycle of a fault. Information on the seismic cycle is drawn from historical records. In contrast, the theory of earthquake triggering computes how stress is transferred to nearby faults, and uses the information to modify the earthquake probability in nearby faults.

For example, after the 1995 Kobe earthquake in Japan, Toda et al. calculated that the 30-year probability had dropped ten-fold near one section where stress had decreased. However, the 30-year probability had increased five-fold near Kyoto. Another study in the US suggested that the 30-year probability of a Mw. 6.8 earthquake along the Hayward fault is 15% to 20% lower if the effect of 1906 San Francisco Earthquake is included.

Scientists are already learning important lessons from studying the recent devastating earthquake in Haiti. They have computed the stress change brought about by the quake along the Enriquillo fault. Aftershocks are abundant on the western section of the fault where the stress has increased (Figure 3). But on the eastern section it is relatively quiet. The preliminary study suggests there could be another large earthquake in the eastern section of the fault that could potentially affect the Dominican Republic.

The recent Mw 8.8 Chile earthquake has increased the stress in the north and south end of the rupture. To the south, there was a giant earthquake in 1960, which released most of the stress. To the north, the events of Valparaiso (1906 and 1985), La Serena (1943) and Vallenar (1922) released only a fraction of the accumulated stress that built up following the last very large earthquake in 1730. After this latest event, the likelihood of having another earthquake on the southern end of the rupture is negligible, while it is still possible to have another earthquake at the northern end.

One might ask: if we can model the stress change, why can't we predict when and where the next earthquake will occur? It is also reasonable to question why earthquake clustering does not happen in each case. There are several reasons. To begin with, models of stress changes are fraught with uncertainty as it is not possible to actually measure the stress changes in the earth. Instead, these are modeled values based on assumptions and needing real-time data to validate and improve them.

While aftershocks are rich in data for verification purposes, main earthquake events that have been triggered by other earthquakes occur very rarely. There are only a handful of examples in the historical record. And earthquakes remain unpredictable. Just because the

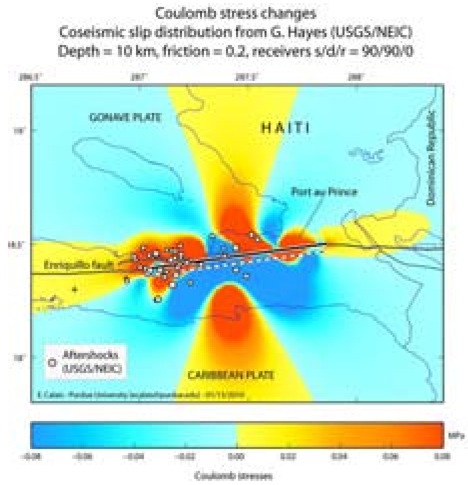

Figure 3 - Changes in Coulomb failure stressed caused by the M7.0 earthquake on 12th January 2010. Red are the areas that have been brought closer to rupture. Note that the aftershocks are concentrated at the western end of the rupture. This is the same area where the model predicts an increase in Coulomb failure stress. The calculation uses the following parameters: Friction of 0.2 on receiver faults with Strike = 90 degrees, Dip = 90 degrees, Rake = 0 (i.e. pure left-lateral strike-slip).
Source: http://web.ics.purdue.edu/~ecalais/haiti/

seismic stress inside a particular region has increased, it does not guarantee that a large earthquake will actually happen. It just means there is a higher probability of a large earthquake occurring.

Another big unknown is that we do not know how close a fault is to failure. A very small change in the stress can trigger another large earthquake along more vulnerable faults. This means that the absolute stress change is not a good indicator of the next big one. We need to know the initial condition on the fault and scientists have yet to understand when and why a loaded fault will erupt.

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Modeling clusters

Catastrophe models have incorporated time-dependency in their stochastic event sets. The event sets reflect the conditional probability given the last event that has occurred. Challenges in quantifying time-dependent probabilities are outside the scope of this article.

Earthquake clustering presents another challenge for the catastrophe model. There are several factors at play that can greatly influence the output of a model. The first factor is whether the events are defined as aftershocks or separate mainshocks. As described in the previous sections, both aftershocks and mainshocks can happen in a clustered manner. In an insurance or reinsurance contract, aftershocks are often included in the loss occurrence definition.

By definition, aftershocks are smaller than the mainshock and occur within 1-2 rupture lengths distance from the mainshock. However, the larger the mainshock (such as with the recent Chile quake), the longer they will continue. Aftershocks can continue for weeks, months or years. For example, on 11th March 2010, 12 days after the mainshock,

Another factor is the time and span of the events. A main event and aftershock could theoretically occur more than a year apart. This possibility (although very small) would not be taken into account in the commercial cat models available today, and not reflected in the financial component of the models.

In addition, the proximity and magnitude of the subsequent events is very important. Will the second event be strong enough to cause damage to a structure? If a structure is weakened by the first event, will additional shaking cause more damage? These questions are especially relevant in the case of aftershocks. Although damaging aftershocks are not explicitly modeled, the vulnerability curve is calibrated against real event claim data, which may include damages from aftershocks. Whether the adjustment is adequate requires further investigation.

The treatment of earthquake clustering also depends on regions. In the New Madrid Seismic Zone, catastrophe models have attempted to implement clustering based on historical records. But there

there were three strong aftershocks greater than Mw 6.0 occurring within a half hour in Chile, the strongest aftershock being Mw 6.9.

are two key difficulties in accurately modeling clustering. First, the underlying triggering mechanism is not fully understood and second, the historical record is scarce. It will take time to physically model the clustered events and to validate the model.

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Conclusion

There is growing evidence that earthquakes sometimes occur in clusters in both time and space. Scientists have built models to explain this clustering behavior. These models have been used to predict which regions are prone to aftershocks and other earthquakes after an event occurs. However, the behavior of earthquake clustering is not fully understood due to lack of data and a thorough knowledge on the dynamics of each fault line.

Earthquake triggering is an evolving field. With advances in science and access to more data (including crucial information gleaned from the recent Chile and Haiti earthquakes), scientists can hope to model earthquake clusters more accurately. Once scenarios of earthquake clusters become better understood, how one earthquake can alter future earthquake hazards will be more easily quantifiable and more accurately represented in the catastrophe models.

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Epilogue

Three major earthquakes have recently occurred in different parts of the world. The Chile Earthquake - Mw 8.8: Feb 27, 2010; the Taiwan Earthquake - Mw 6.3: Mar 4, 2010 and the East Turkey Earthquake - Mw 6.1: Mar 8, 2010. Including the Haiti Earthquake on 12 January 2010, there have been four major events in a two-month timeframe.

These events occurred in different tectonic plates and there is no scientific evidence that they are inter-related. What they do illustrate is the randomness and potential devastation of earthquakes.

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