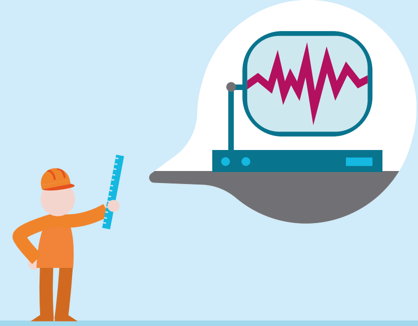
Technical Newsletter

#31 - March 2016



GUIDE TO EARTHQUAKES - PART II
Risk assessment: Earthquake forecasts, predictions and probabilistic analysis

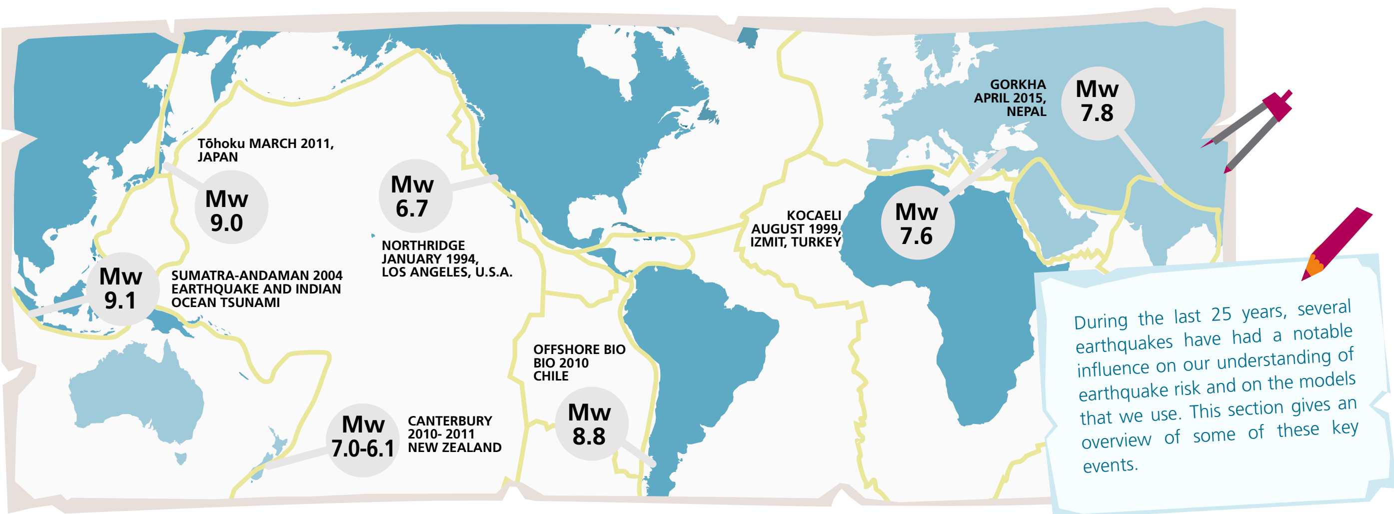
Overview

Compared to other perils, large and damaging earthquakes have long return periods. They are relatively infrequent, but when they do occur there is little warning and their impact is significant.

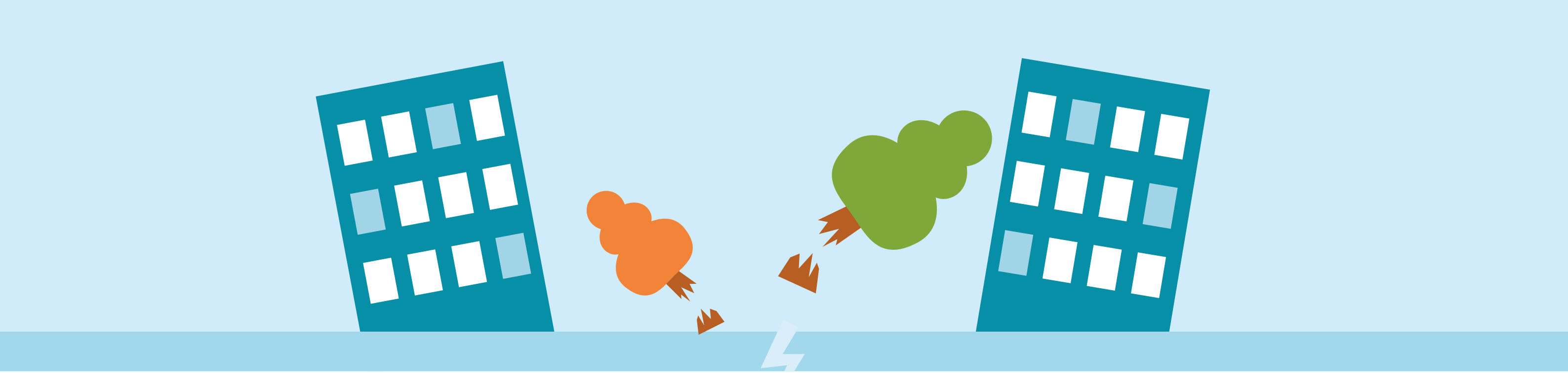
Earthquakes account for 60% of fatalities and 30% of insured losses from the top 10 natural disasters since 1980. In this second issue of our three-part series on earthquake risk modelling and management, we focus on earthquake risk assessment. We discuss key historical earthquake events of significance for catastrophe modelling and the (re)insurance industry along with how earthquakes are linked with each other. We also explore the debate over whether it's possible to predict where and when earthquakes will occur. We examine seismic hazard maps and probabilistic forecasts, and look at how these feed into risk management and mitigation strategies.

In Part III we will turn our attention to the probabilistic earthquake catastrophe models widely used by the (re)insurance industry to understand, manage and transfer risk.

Key earthquakes of importance for the industry and modelling



SCOR Global P&C



The tectonics of the earth are largely hidden from human observation until earthquakes occur, revealing what has been happening under the surface over the course of long time periods.

The magnitudes reported in this section are those reported by US Geological Survey (USGS) for consistency. Magnitudes reported by other seismological institutes may vary, due to different scales or instrumentation being used.

NORTHRIDGE Mw 6.7
JANUARY 1994
LOS ANGELES, USA

The Northridge earthquake had many significant consequences. It led to the overhaul and re-evaluation of structural engineering practices and design standards after the collapse of many bridges and supports for elevated freeways and certain types of buildings[1]. One of the key insights was the surprisingly high fragility of steel moment-resisting frame buildings: a construction type widely used in Los Angeles and elsewhere in the USA. The earthquake also prompted greater investment and deployment of GPS-based sensors for measuring ground motion, leading to improvements in our understanding of earthquakes. Also, coming shortly after Hurricane Andrew in 1992, this event cemented the demand for catastrophe models in the insurance industry.

KOCAELI Mw 7.6
AUGUST 1999
IZMIT, TURKEY

The 1999 Kocaeli earthquake in north-western Turkey, approximately 90 km east of Istanbul, caused extensive damage. The earthquake highlighted the phenomen of stress transfer and the importance of including it in risk modelling. It was the latest in a series of 11 major earthquakes since 1900 along the North Anatolian fault, moving progressively westwards towards Istanbul [2]. While failure on one part of a fault plane will reduce stress immediately surrounding the rupture, it can increase the stress on another part of the fault plane, or on nearby fault planes. The 1999 earthquake increased the stress on the segment just south of Istanbul, adding to the strain already building up since the last major earthquake on this segment in 1766.

"THERE IS A > 60% PROBABILITY OF AN EARTHQUAKE STRIKING ISTANBUL IN THE NEXT 30 YEARS[3]."

The earthquake also resulted in the introduction of a compulsory earthquake insurance scheme for residential properties, the Turkish Catastrophe Insurance Pool (TCIP), to address the low level of insurance penetration highlighted by the 1999 event.

SUMATRA–ANDAMAN Mw 9.1
DECEMBER 2004
(EARTHQUAKE AND INDIAN OCEAN TSUNAMI)

This Mw 9.1 earthquake was the third largest ever recorded at the time, and transpired to be the first of several great earthquakes over the course of the following decade. Tsunami waves were recorded as far afield as Nova Scotia and Peru, having been channelled along mid-ocean ridges. The event highlighted the destructive nature and far-field impacts of a massive tsunami, a risk which much of the world was uneducated about and unprepared for, and stimulated investment in tsunami warning systems in many countries. More than 10 years later, tsunami modelling is still an emerging science, given the computing power required to model both the large-scale ocean dynamics and high-resolution on-shore modelling of impacts; though some models are now available to the (re)insurance industry for limited countries.

OFFSHORE BIO BIO Mw 8.8
FEBRUARY 2010
CHILE

Despite the very significant destruction of houses, only 4 engineer-designed buildings were destroyed by this Mw 8.8 event, with another 50 requiring demolition. Chile has a strong set of building codes which are strongly enforced, including the enactment of a law that holds building owners liable for the first 10 years of a building's existence for any losses resulting from inadequate application of the building code during construction. Overall, the earthquake demonstrated that strict building codes and standards can greatly reduce losses in even the largest earthquakes, in direct contrast to the much lower magnitude Mw 7.0 Haiti earthquake which struck earlier in the year, resulting in the loss over 200,000 lives. Another notable feature of the Chile earthquake was the extensive business interruption losses from damaged industrial production facilities; accounting for up to two-thirds of the insured loss for some facilities.

[1] Naeim F. 2004. Impact of the 1994 Northridge Earthquake on the Art and Practice of Structural Engineering. Structural Design of Tall and Special Buildings 13: 373–389.
[2] Stein R.S., Barka A.A. & Dieterich J.H. 1997. Progressive Failure on the North Anatolian Fault Since 1939 by Earthquake Stress Triggering. Geophysical Journal International 128 (3): 594–604.
[3] Parsons T, Toda S, Stein R, Barka A, Dietrich J. 2000. Heightened Odds of Large Earthquakes Near Istanbul: An Interaction-Based Probability Calculation. Science 288(5466): 661-665.

Figure 1: Map of the main Himalayan fault line and seismic hazard levels: darker blue = higher seismic hazard, lighter blue = lower seismic hazard.

CANTERBURY EARTHQUAKE SEQUENCE 2010-2011 NEW ZEALAND

The Canterbury Earthquake Sequence of 2010 to 2011 included at least five significant events over a 16 month period, with many smaller aftershocks.

"THE SEQUENCE STARTED ON 4TH SEPTEMBER 2010, WHEN THE Mw 7.0 CANTERBURY (DARFIELD) EARTHQUAKE STRUCK 40 KM WEST OF CHRISTCHURCH NEAR THE TOWN OF DARFIELD."

The most damaging earthquake in the sequence occurred 6 months later – a Mw 6.1 event to the east, just 10 km south-east of the city of Christchurch (Lyttelton) on February 22nd.

Did you know?

Most people are familiar with the Richter scale. However, there are a number of magnitude scales, based on different measuring techniques, such as "moment magnitude" (denoted Mw).

In this case, the Mw 6.1 event caused more damage than the Mw 7.0 event because it was closer to Christchurch, and closer to the surface at a depth of just 5 km compared to 9 km. The ground acceleration was much greater than from the previous earthquake. Additionally, whilst both earthquakes caused liquefaction (when the soil loses all of its strength, to the point it behaves like a liquid), the severity of the liquefaction in Christchurch's eastern suburbs from the second earthquake was particularly extreme, and has been the focus of much research with modelling improvements expected in 2016.

TŌHOKU Mw 9.0 MARCH 2011 JAPAN

This Mw 9.0 undersea earthquake was above the maximum severity thought possible for the region. Based on known historical experience and the physical characteristics of the plate boundary, each of the fault segments that ruptured was assumed to have a maximum magnitude of less than 8.0, and it was assumed that they would not fail together. Both this and the 2004 Sumatra earthquake fell well outside the established relationship between maximum magnitude and tectonic and geological parameters, which had held true across other earthquakes on subduction zones in the past century.
These events have prompted new, ongoing, research to answer the question of where else might Mw 8.5 + earthquakes be possible, including the better integration of evidence from sedimentary deposits and rock movements about the location and extents of tsunamis dating back far beyond current historical earthquake databases.

GORKHA Mw 7.8 APRIL 2015 NEPAL

Nepal sits along the boundary of the Indian and Eurasian plates which are colliding. Records dating to 1255 indicate the region experiences a magnitude 8 earthquake approximately every 75 years[3], thus the earthquake was not a surprise.

Poor quality building stock resulted in a large amount of damage and fatalities - although the shaking in Kathmandu was not as severe as had been expected from an earthquake of this magnitude. Post-earthquake analysis has revealed that the Mw 7.8 earthquake did not release all the built-up strain along the fault system and the potential remains for a > Mw 8.0 in the future.
Research continues into understanding the impact of the earthquake on stress in other areas of the Himalayan zone and surrounding areas given the proximity of several major cities.

> "THERE IS CAUSE FOR CONCERN FOR DELHI WHICH LIES IN A HIGH SEISMIC ZONE WITH A POPULATION OF CLOSE TO 25 MILLION PEOPLE AND A VULNERABLE BUILDING STOCK."

[3] Nepal National Society for Earthquake Technology. 2012. Recorded Historical Earthquakes in Nepal (Earthquake Catalogue of Nepal 1255 - 2011 AD).

Are earthquakes linked?

Three big questions in the risk management world are: what triggers Great Earthquakes; is there a link between the series of Great Earthquakes experienced over the past decade; and can earthquakes be predicted?

Both theory and observation have shown that earthquakes are influenced by other earthquakes. Large events will be followed by many aftershocks within the fault rupture zone, the frequency and magnitude of which is related to the magnitude of the original earthquake.

> "SOMETIMES AN EARTHQUAKE MAY LATER BE RE-CLASSIFIED AS A FORESHOCK OF A SUBSEQUENT MAIN SHOCK IN A SEQUENCE."

Aftershocks can themselves be large enough to trigger further aftershocks in a new aftershock zone.

This is nicely illustrated by the pattern of earthquakes following the Mw 7.0 Canterbury EQ in New Zealand in Figure 2. One can see a clear shift in activity to the east following the Mw 6.1 event on February 22nd. Of course, not all of the aftershocks that occurred after February 22nd are related to the Mw 6.1 event, as aftershocks from the initial Mw 7.0 earthquake will have continued for months and years.

Typically there are ten times as many aftershocks for each integer (+1) increase in magnitude in the first shock. Earthquakes such as L'Emilia 2012 in Italy and Christchurch 2011 in New Zealand are two examples of how damaging aftershocks can be, where aftershocks caused more damage than the main shock due to their location. Alternatively an aftershock may cause less damage than otherwise to be expected from that magnitude if the building stock has already been damaged or destroyed. Aftershocks occur within days, weeks, months or even decades of the mainshock, diminishing in frequency over time as illustrated in Figure 3. Note that each aftershock sequence has its own unique pattern, making aftershock modelling and prediction extremely difficult.

Figure 2: Pattern of aftershocks following the Mw 7.0 Darfield (green) and Mw 6.1 Lyttelton (red) earthquakes.

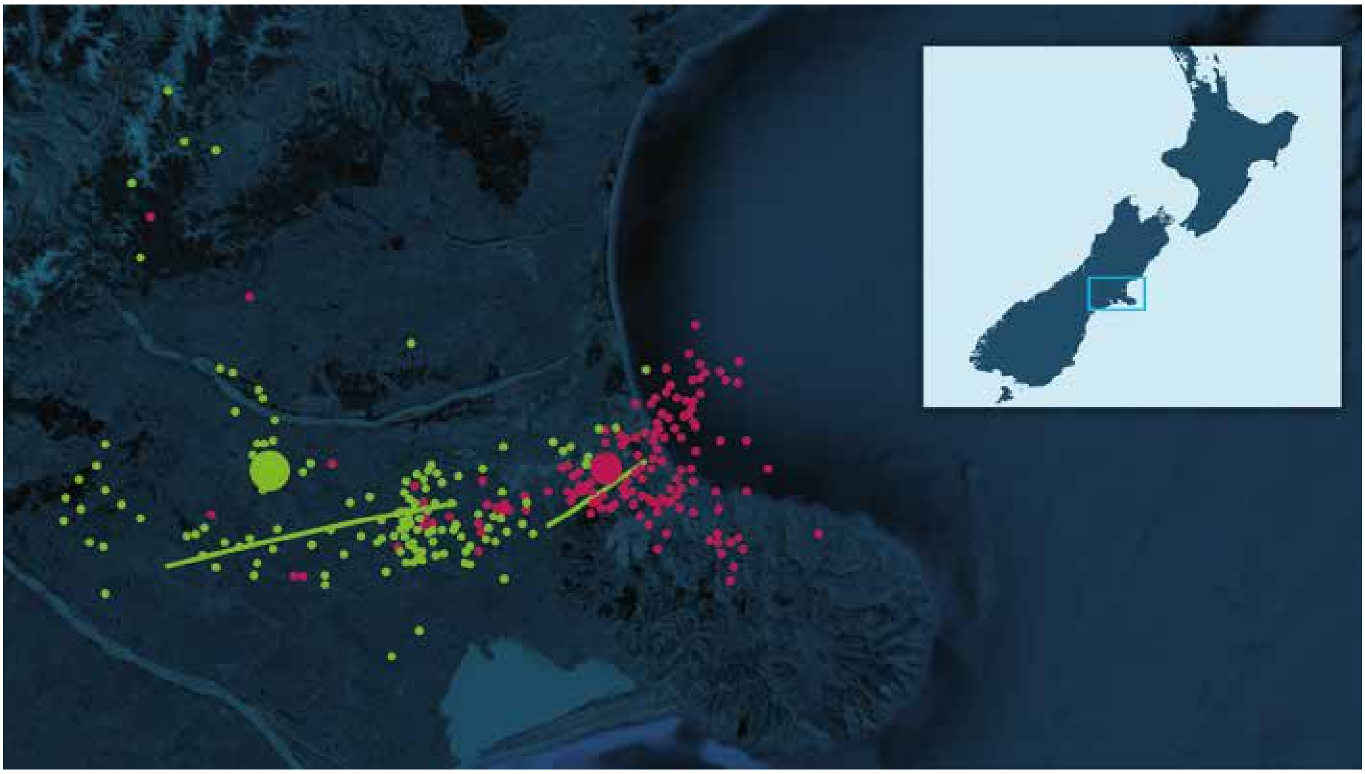
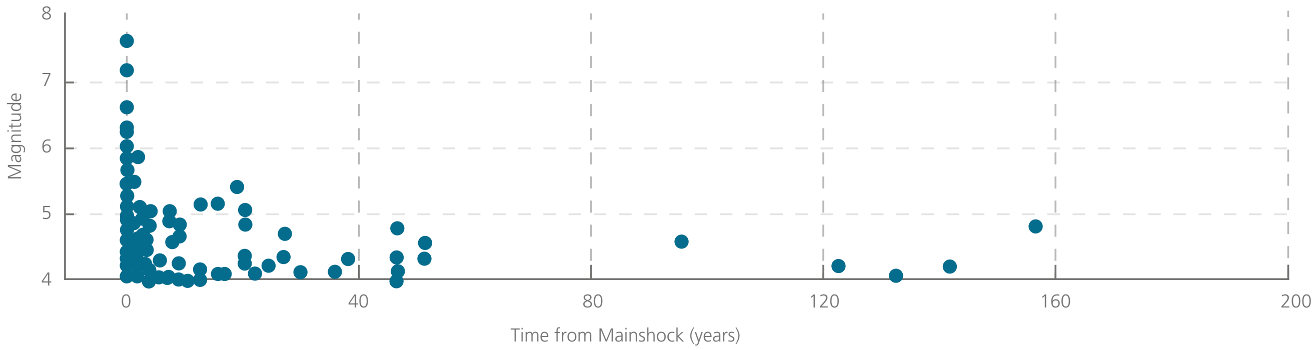


Figure 3: Typical aftershock sequence (Data source: CEUS-SSC catalogue/ USGS).

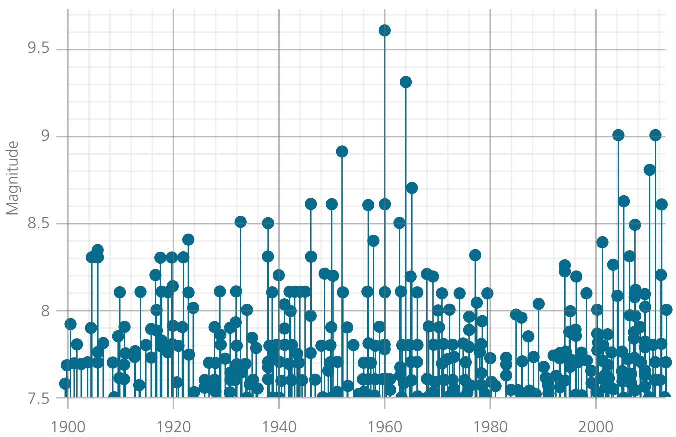


Data source: CEUS-SSC catalogue/ USGS.

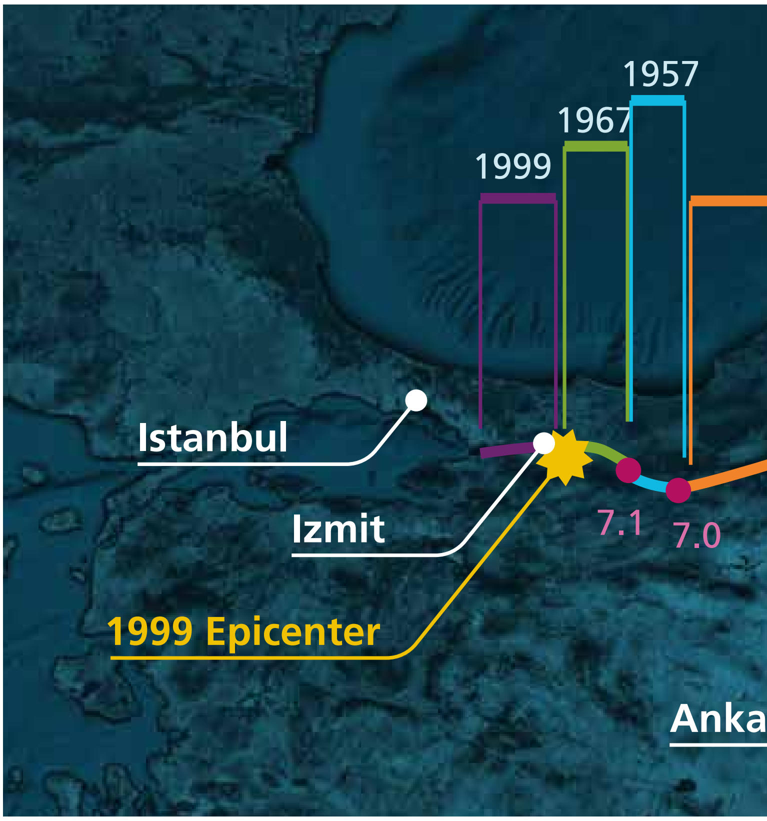
Further away from the aftershock zone, surface waves generated by large earthquakes have been observed to trigger small earthquakes at far distances[4]. The Landers, California 1992 and Izmit Turkey 1999 earthquakes are both known for their influence on the subsequent regional seismic activity, beyond the typical aftershock zone. The seismic waves from distant earthquakes in Japan, Sumatra and Chile triggered swarms of small earthquakes at sites in Oklahoma, Colorado and Texas.

It remains unclear, however, whether great earthquakes can trigger other great earthquakes at distances very far from the original event, heightening the global seismic hazard after every large earthquake. Looking at historical data (figure 4), we see two apparent clusters of very large events - one in the last decade, and another in the 1950's.

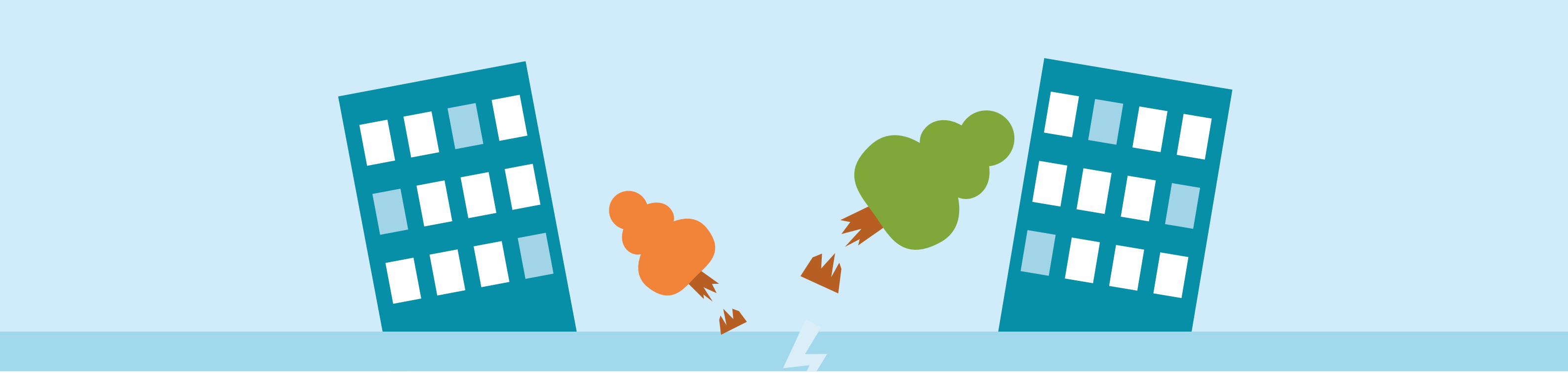
Figure 4: Worldwide seismicity since 1900 showing the number of earthquakes above Mw 7.5 per year



Source: GEM

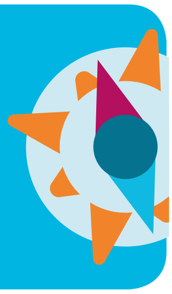


[4] Parsons T. & Velasco A.A. 2011. Absence of Remotely Triggered Large Earthquakes Beyond the Mainshock Region. Nature Geoscience 4: 312–316.



2002, Denali fault earthquake

In November 2002, the Mw 7.9 Denali Fault earthquake struck central Alaska, triggering hundreds of small earthquakes in Yellowstone Park over 4,000 km away.

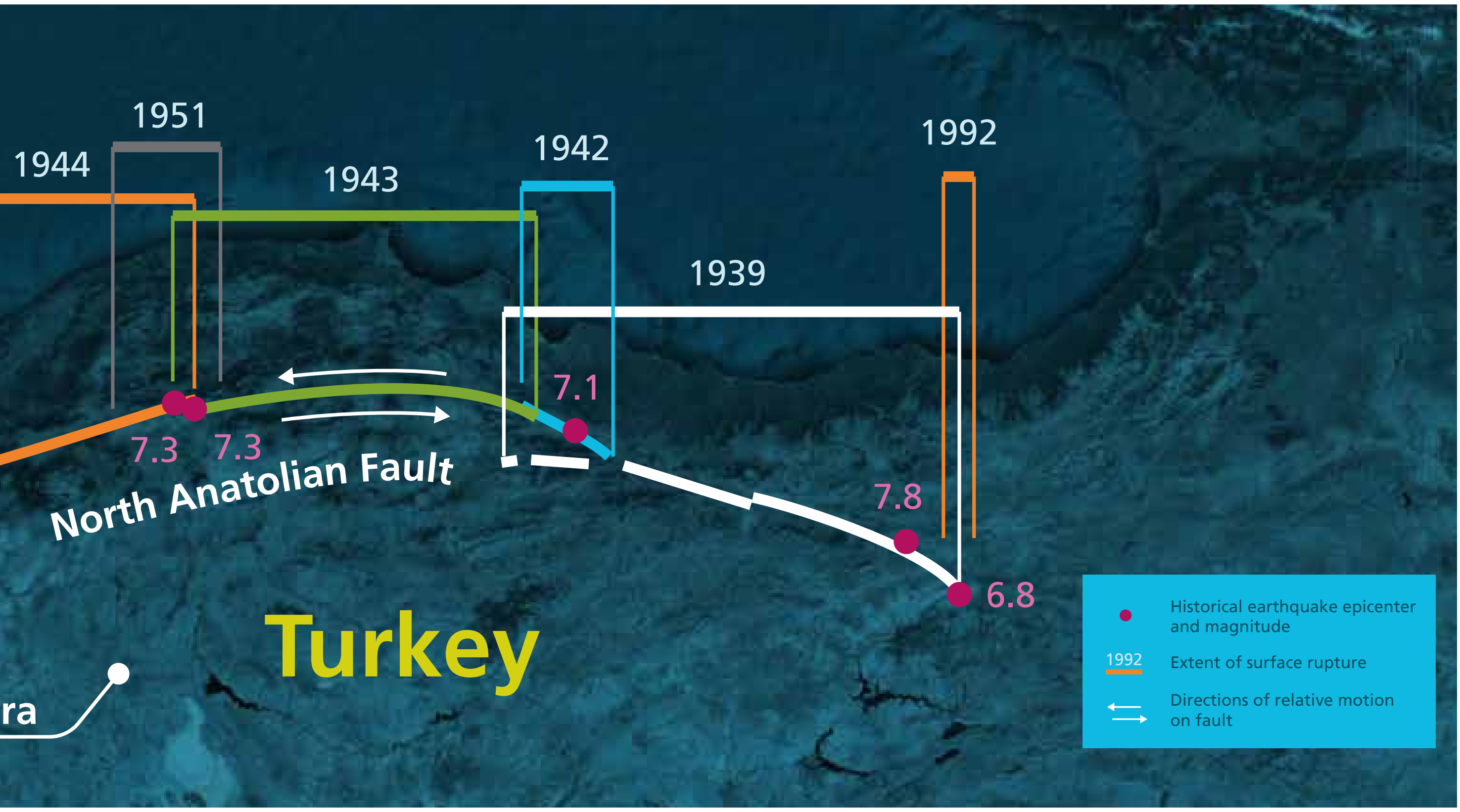


Statistically, however, these apparent clusters are indistinguishable from random bad luck.

No plausible physical mechanisms that would explain clustering of great earthquakes have yet been put forwards[5], although research continues into this topic. In a different phenomenon, the stress released on a fault during an earthquake may not completely dissipate but instead move along the fault, a process known as stress transfer.

This process can lead to another earthquake sooner in time than would otherwise occur in that region. As described previously in this paper, the progression of earthquakes from east to west along the North Anatolian Fault across northern Turkey is the result of stress transfer over the course of many decades, with more events likely in the future closer to Istanbul[6].

Figure 5: Location of successive earthquakes moving from east to west along the Northern Anatolian fault towards Istanbul.



Source: United States Geological Survey

[5] Shearer P. M. & Stark P. B. 2011. Global Risk of Big Earthquakes Has Not Recently Increased. PNAS 109 (3): 717–721.
[6] Stein R.S., Barka A.A. & Dieterich J.H. 1997. Progressive Failure on the North Anatolian Fault Since 1939 by Earthquake Stress Triggering. Geophysical Journal International 128 (3): 594–604.

Are humans increasing earthquake risk in unprepared areas?

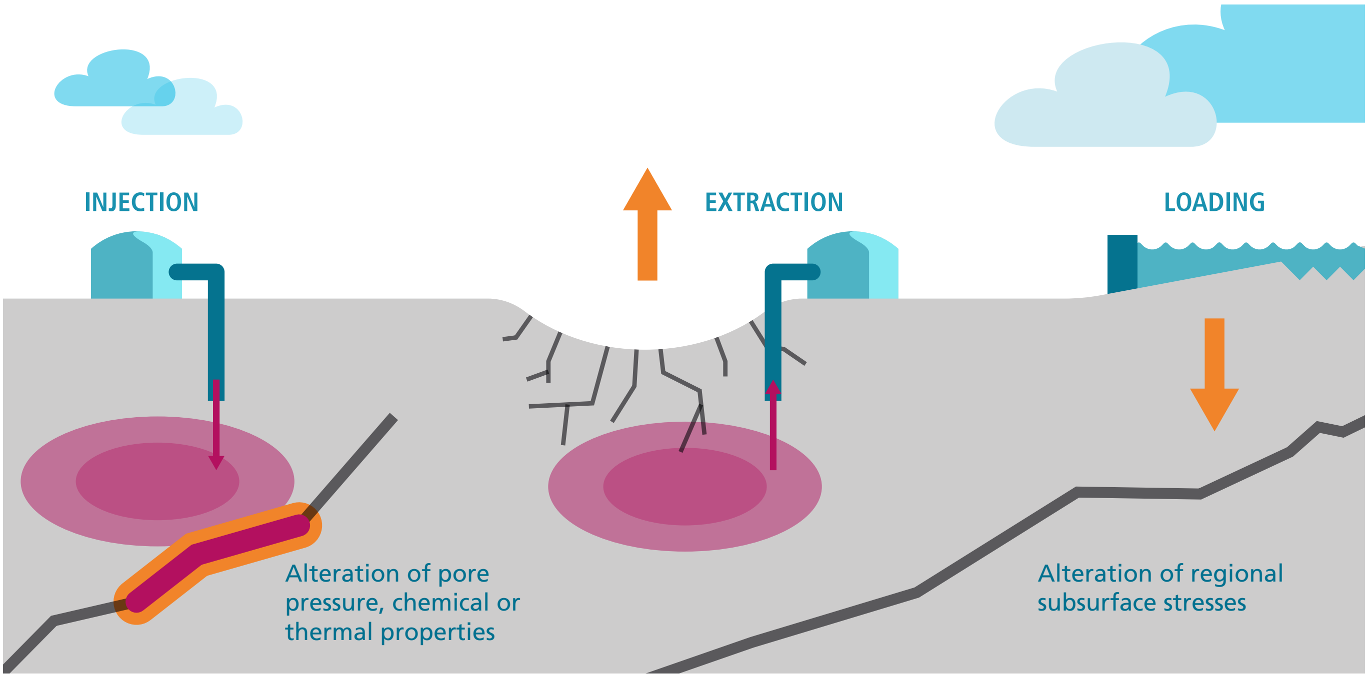
Human-induced earthquake activity has occurred around the world for many years, driven by various activities such as underground mining, big dam and reservoir construction and more recently hydraulic fracturing of rock for shale-gas extraction, also known as fracking.

Human-induced activity can lead to earthquakes in areas not used to, or prepared for, seismic activity. Reservoir induced activity was identified as early as the 1930s following the creation of Lake Mead on the Colorado River impounded by the Hoover Dam. Since then more than 70 examples have been identified around the world including the 1967 Mw 6.3 Koyna earthquake in India which claimed over 200 lives and caused significant damage to homes and the dam itself.

"SINCE 2010, THE UNITED STATES GEOLOGICAL SURVEY (USGS) HAS IDENTIFIED A DRAMATIC TENFOLD INCREASE IN SEISMICITY IN THE MID AND EASTERN USA, WITH EARTHQUAKES UP TO Mw 5.7 RECORDED IN OKLAHOMA."

The recent increase in seismicity in Oklahoma has been attributed to high-rate injection of wastewater from the oil and gas industry into deep disposal wells[7].

Figure 6: Illustration of three different ways in which seismicity can be induced or altered through injection, extraction or increased loading via big dam/reservoir.



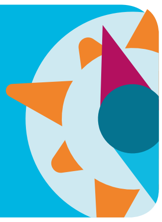
[7] Weingarten M., Ge S., Godt J.W., Bekins B. A. & Rubinstein J. L. 2015. High-rate Injection is Associated With the Increase in U.S. Mid-Continent Seismicity. Science 348 (6241): 1336 – 1340.

In response to the elevated activity in Oklahoma, the Insurance Commissioner John Doak advised residents to buy earthquake insurance and has asked insurers to clarify whether their policy covers damage from earthquakes resulting from human activities. In other regions, such as western Canada, fracking has been identified as driving increased seismic activity.

However, not all fluid-injection or fracking activities will trigger seismic activity. It depends on the combination of the rate of injection and other factors such as: the presence of faults that are large enough to produce discernible earthquakes, stresses that are large enough to produce earthquakes, and the presence of pathways for the fluid pressure to travel from the injection point to faults. A thorough geological survey should enable effective risk assessment and inappropriate sites to be rejected for such activities.

In the longer term, human-driven climate change may have an impact on seismic and volcanic activity patterns around the world. It is well known that the lifting or imposing of the weight of ice and ocean water at the surface affects the underlying structure of the Earth. Thinning and shrinking of ice caps and glaciers in the future will release pressure and could lead to an increase in activity from currently dormant volcanoes and fault lines, as well as increase landslide risk. However, while some geological responses to surface events could occur fast, others could take thousands of years to emerge.

In the first 6 weeks of 2016, Oklahoma has already seen 140 quakes 3.0 or larger: an average of 2.5 earthquakes per day. Before 2008, the average was one and a half per year.



Predicting and forecasting earthquakes: is it possible?

Debate continues in the scientific community as to whether it will ever be possible to accurately predict the exact time, location, and magnitude of earthquakes.

There have been many assertions relating the timing of earthquakes to some other natural force e.g. supermoons, solar activity and hurricanes. However, efforts to link the behaviour of faults located several kilometres underground with changes in humidity and temperature at the surface or to link the timing of earthquakes to tidal forces have so far not been successful.

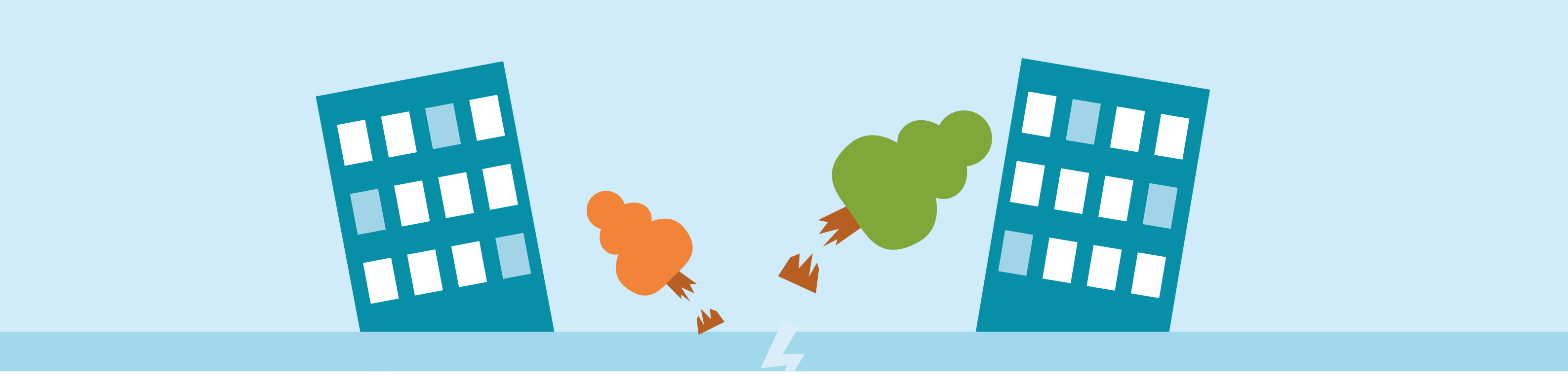
"PREDICTION REQUIRES FINDING A COMMON OBSERVABLE PRE-CURSOR, WHICH COULD BE USED AS A WARNING SYSTEM."

Foreshocks, changes in strain accumulation, ground deformation, changes in radon gas levels, animal behavior and other signals continue to be investigated, but no reliable pre-cursors[8] have been found yet.

However, the positive societal implications of being able to predict earthquakes means that research should, and does, continue. As one example, the SCOR Corporate Foundation for Science is supporting research and activities in the Global Earthquake Forecast System project run by ETH Zurich and the ETH Zurich Foundation. The Collaboratory for the Study of Earthquake Prediction (CSEP) is another organization which has ongoing investigations testing the quality of prediction methods against actual earthquake occurrences around the world.

However, probabilistic forecasts of the likelihood of earthquakes happening in a specified area over a specified period are possible where there is sufficient information on well-studied fault systems. For example, the latest Uniform California Earthquake Rupture Forecast (UCERF) released in 2014 estimates the likelihood that California will experience a magnitude 8 or larger earthquake in the next 30 years as 7%. This information feeds into seismic hazard assessment for use in engineering design of buildings and infrastructure, catastrophe models and emergency preparedness plans.

[8] International Commission on Earthquake Forecasting for Civil Protection. 2011. Operational Earthquake Forecasting: State of Knowledge and Guidelines for Utilization. Annals of Geophysics 54(4): 315–391.



The problems with predicting earthquakes and communicating uncertainties: L'Aquila

The problems surrounding earthquake prediction were highlighted by the L'Aquila trial of earthquake scientists in Italy.
The Mw 6.3 L'Aquila earthquake in April 2009 in the region of Abruzzo, in central Italy damaged 70% of the buildings in the medieval city of L'Aquila, and caused 306 fatalities.
The main damaging earthquake was preceded by two smaller earthquakes, and was part of a so-called swarm (frequent small tremors) of earthquakes that had started the previous January.
In October 2012, an Italian court sentenced six scientists and a government official, Bernardo De Bernardinis, to six years in prison for manslaughter, finding them guilty of failing to give adequate advance warning of the main damaging quake prior to the quake. The court accepted it was impossible to predict a quake, but ruled that the experts had "minimised" the threat and created a sense of complacency in local inhabitants by issuing reassuring statements.
A court of appeal in 2014 acquitted the 6 scientists of the charges, but upheld the verdict against Bernardo De Bernardinis for issuing misleading public statements about the risk, although with a reduced term.
Criticism against the original ruling was widespread in the scientific community, given the impossibility of predicting earthquakes. However, the case did raise valid points about the communication of risk – a topic as important as the science and models themselves.

Seismic hazard maps and risk assessment

Seismic hazard maps show where there is a probability of damaging shaking over a certain time period. Probabilistic seismic hazard analyses have been extensively utilized for design and construction decisions for almost half a century[9].

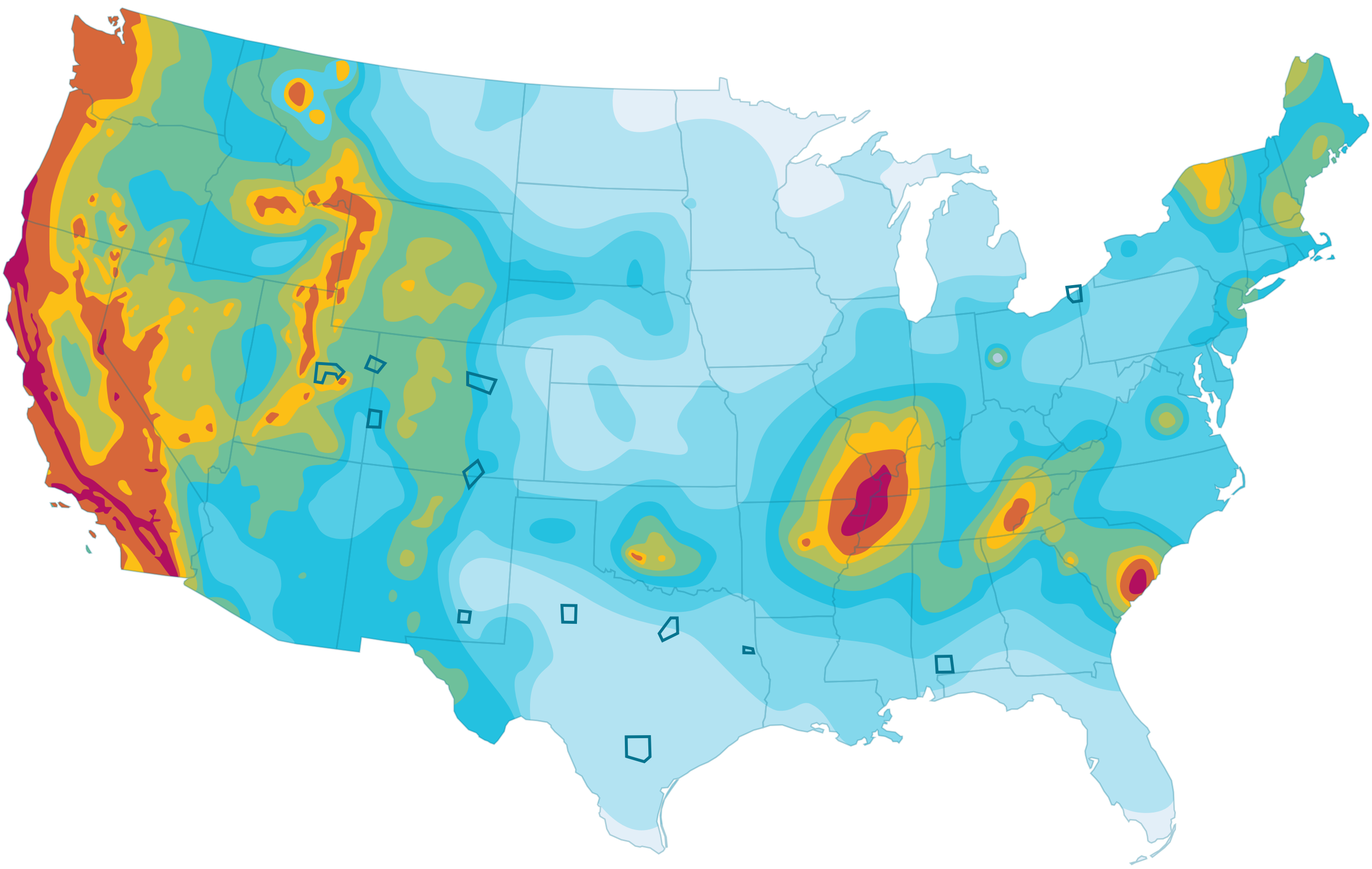
As noted by Beauval[10], new regulatory requirements in the 2000s that hazards be estimated in probabilistic terms such as the recommendations in Eurocode 8 for the European Union, have prompted an increase in the number of probabilistic hazard studies. These studies are often regarded as the definitive view of seismic hazard for a country and typically provide the basis or input for probabilistic catastrophe models used by the (re) insurance industry. For example, the United States Geological Survey (USGS) publishes updates to the USA seismic hazard maps every five years, prompting updates to the catastrophe models which utilize this input. Development of these seismic hazard maps utilizes much of the science, data and methodologies described in this paper, and also suffers from uncertainties and, at times, errors which only become apparent after major events such as the Tōhoku earthquake. This uncertainty is not immediately evident in seismic hazard maps, but must be borne in mind, as noted by *Geller et al.* in 2013[11] reflecting on the Fukushima nuclear power plant disaster. *Stein et al.* in 2012[12] recommend two specific actions in order to facilitate this. First, that the uncertainties in hazard map predictions should be assessed and clearly communicated to potential users. This will enable users to decide how much credence to place in the maps and make them more useful in formulating cost-effective hazard mitigation policies. They also recommended that hazard maps should undergo rigorous and objective testing to compare their predictions to those of null hypotheses, including ones based on uniform regional seismicity or hazard.

The evolution of catastrophe models beyond seismic hazard analysis has enabled the monetization and transfer of risk, complementing building-code orientated adaption and mitigation strategies. However, as with the seismic hazard maps, uncertainty in catastrophe models must also be borne in mind and should be made more transparent to users than is currently the case. We shall explore this topic further in part III of this series.

---

[9] Cornell C. A. 1968. Engineering Seismic Risk Analysis. Bulletin of the Seismological Society of America. 58(5): 1583-1606.
[10] Beauval C., Bard, P-Y., Hainzl S. & Guéguen P. 2007. Can Strong-Motion Observations Be Used To Constrain Probabilistic Seismic Hazard Estimates? Bulletin of the Seismological Society of America 98 (2): 509-520.
[11] Geller R. J., Epstein W. & Nöggerath J. 2013. Fukushima —Two Years Later, Opinion. Seismological Research Letters 84(1): 1-3.
[12] Stein S. Geller R. J. & Liu M. 2012. Why Earthquake Hazard Maps Often Fail and What to Do About It, Tectonophysics 562–563: 1–25.

Figure 7: 2014 U.S. Geological Survey National Seismic Hazard Map of probabilistic ground motions with a 2 percent probability of exceedance in 50 years: (is equivalent to 1 in 2475 years).



Explanation
Peak acceleration, express as a fraction of standard gravity (g)

0.8 | 0.4 | 0.3 | 0.2 | 0.14

0.1 | 0.06 | 0.04 | 0.02 | 0

Areas where suspected nontectonic* earthquakes have been deleted

*A region far from any tectonic plate boundaries which is tectonically stable.

SCOR Global P&C

Summary

There are several known mechanisms whereby earthquakes influence the occurrence of subsequent events through aftershocks, stress transfer and far-field triggering of smaller tremors and swarms by large earthquakes.

However, whilst there is speculation, there has been no proof to date that there is a physical connection between the series of Great Earthquakes occurring around the world on entirely separate fault systems far away from each other. We also know that human activity, such as mining, has influenced the occurrence of earthquakes historically, and continues to do so with new industrial processes such as high-rate wastewater injection and fracking under certain geological conditions. Research into understanding interrelationships between geology and these processes can enable risk assessment of potential sites and informed choices about where they should and should not be conducted to mitigate against increasing seismicity in areas not used to or prepared for it.

Yet, the actual prediction of exactly when and where earthquakes will occur remains out of reach, though research continues. Probabilistic forecasts of earthquakes along specific faults are possible, such as those in California and the North Anatolian fault in Turkey, and give planners and risk managers a time-dependent view of risk levels on those faults. Historically, seismic hazard maps have been relied on for risk protection and management decisions, but have been shown to be inaccurate following events outside previously accepted theories and methods for estimating earthquake size and recurrence rates. Even with an improved understanding of earthquake mechanisms through new research and post event analysis, new ways of understanding and communicating uncertainty need to be integrated into seismic risk assessment and decision making in the future. The importance of communicating risk and uncertainty appropriately was dramatically highlighted by the events following the L'Aquila earthquake in 2009.

In our next, and final, issue of this three-part series, we will examine the catastrophe models used by the industry for assessing earthquake risk, demonstrating how the concepts discussed so far together with new research and post event analysis feed into the models, and the outlook for the future of models and earthquake risk management.

Paul NUNN
Head of Risk Modelling
and Global Natural Hazards,
SCOR Global P&C

pnunn@scor.com

For more information, please contact our team

Dr. Kirsten MITCHELL-WALLACE, kmitchell-wallace@scor.com
Ismaël RIEDEL, iriedel@scor.com

Dr. Claire SOUCH
Dr. Guillaume POUSSE

PLEASE FEEL FREE TO VISIT US ON SCOR.COM

SCOR Global P&C
5, avenue Kléber
75795 Paris Cedex 16
France
scorglobalpc@scor.com

SCOR Global P&C

TO GET THE FULL RANGE OF TECHNICAL NEWSLETTERS, PLEASE CONTACT SCORGLOBALPC@SCOR.COM

Editor: SCOR Global P&C Strategy & Development
ISSN: 1967-2136