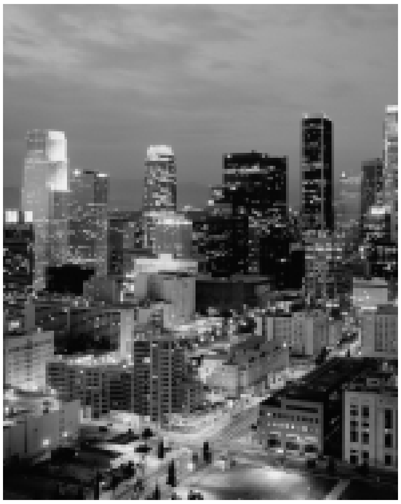
Swiss Re

Random occurrence or predictable disaster?

New models in earthquake probability assessment

Imagine your favourite newspaper one day supplementing the daily weather report with an earthquake forecast. Admittedly, this is still a far-fetched idea, but recent advancements in seismic research have helped to improve earthquake probability assessments by including the factors of time dependence and stress transfer from past events. Swiss Re maintains that the insurance industry should integrate these new findings in order to ensure that earthquake premiums remain commensurate with the risks concerned. This will ensure a fair global risk-sharing via the international reinsurance market. It will also help the insurance industry provide risk transfer products which manage the financial consequences of earthquakes in a sustainable and cost-effective way.



Many major metropolitan areas, such as Los Angeles, are exposed to earthquake risk and stand to benefit considerably from developments in earthquake forecasting.

Summary

The results of a recent research project[1] conducted by the United States Geological Survey (USGS) in co-operation with Swiss Re clearly indicates that the probability for a major earthquake hitting Istanbul in the near future is far greater than previously anticipated. These findings are supported by the delayed return cycles of important earthquake faults in the vicinity of this densely populated area and by last year's disastrous event in Izmit, which transferred additional stress to these faults. The research findings prompted the team, consisting of leading American, Turkish and Japanese scientists, to raise the probability value for strong ground shaking in Istanbul substantially against the long-term average statistics. Such developments could be expected to trigger significant premium hikes for earthquake insurance in Istanbul. Even so, overall premiums could be maintained at affordable levels by offsetting – to some extent – the premiums required for such peak risk areas with those of less exposed areas in Turkey.

Towards an improved evaluation of earthquake risk

The large earthquakes in 1999 again brought home the sudden, devastating force of this most feared of natural catastrophes. The actual extent of damage caused by earthquakes should not, however, come as a surprise, since their consequences can be assessed fairly accurately in advance. The uncertain factors regarding a quake – as catastrophic earthquakes in the past have confirmed without exception – are the exact time, location and intensity of its striking. Still, even after many decades of scientific research, short-term earthquake prediction appears to be well beyond our reach. Has earthquake research really made such little progress?

In fact, considerable progress has been achieved. The model of plate tectonics, improved knowledge of local geological conditions and detailed statistical methods have made it possible to determine the probability of a particular earthquake striking at any place on earth. Today, the degree of seismic hazard can be quantified on a global scale and differentiation can be made between areas of high and low seismic hazard (see Figure 1).

Of course, these earthquake probability assessments are still a far cry from any short-term prediction of earthquakes. One modest step towards a more precise short-term prediction was achieved in connection with the two devastating earthquakes in Turkey 1999 – in Izmit on 17 August and Dücze on 12 November. While nobody could forecast the exact moment when the two earthquakes would strike, an increased probability in the area for precisely these two events was indicated in several scientific studies.

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[1] published in Science, Vol. 288, 28 April 2000, by Tom Parson, Shinij Toda, Ross S. Stein, Aykut Barka & James H. Dietrich

Swiss Re is convinced that the insurance industry must take into account these new scientific findings and methods, as they facilitate both a more accurate assessment of insured earthquake risks and, ultimately, a fair global spread of risks, without which earthquake insurance would not be possible. The aim of the present study therefore is to make the latest advances in seismological research known to a wider, non-specialised audience and to examine its consequences for the insurance industry.

The origin of earthquakes

The tendency of earthquakes to occur along relatively narrow belts rather than in a homogeneous pattern throughout the world was one of the key lines of evidence leading to the theory of plate tectonics in the 1960s. This theory maintains that the earth's surface consists of a number of rigid plates, each of which is made up of continental or oceanic crust and the uppermost part of the earth's mantle. The rigid plates are underlain by a softer solid on which they "creep". The earth's entire crust is made up of several main plates, named after continents and oceans, and numerous small plates, named after regions, all of which are in motion with respect to one another. Although the relative movement of the earth's plates averages only a few centimetres per year, this is sufficient to build up earthquake-generating stress loads predominantly at – or in the vicinity of – the plate boundaries. The model below serves to illustrate this earthquake-generating process:

Take a stretch of elastic string tied to a stone lying on a smooth surface, and pull the elastic gently. The rock will not budge at first, owing to its resistance to motion, ie its friction with the underlying surface. As you pull harder, the elastic will stretch until the applied force exceeds the frictional force acting against it. The stone will then shift forward slightly on the surface and the process will start over again.

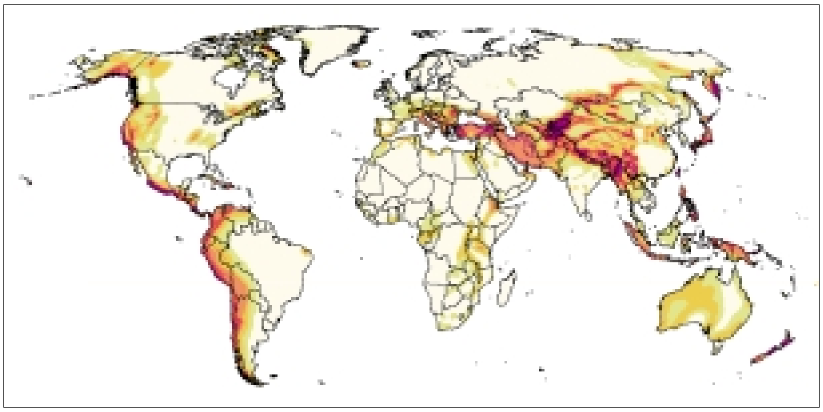

Figure 1: Worldwide seismic hazard[2] from Swiss Re's CatNet. High hazard areas are shown in red to purple, low to moderate hazard areas in white to yellow.

This simple model very roughly describes the so-called "stick-slip" process leading up to an earthquake: the quake occurs when the stress acting parallel to the plate boundaries exceeds the frictional forces of the plates. The two plates then shift into a new position and the "stick-slip" process starts anew.

This process was also responsible for the five disastrous earthquakes in 1999 (see Table 1). All five events hit on or in the vicinity of major plate boundaries. In most cases, the ruptured faults were well known, as they had already been subjected to this process in the past.

The probability of earthquakes

Earthquake prediction would be a straightforward matter if the interface between two moving crustal blocks were entirely smooth and homogeneous, because the interval between two slips would then remain constant. In reality, however, geophysical conditions, such as surface irregularities between the rocks and different rock properties, bear an influence on the interval between two individual events. This is why the traditional approach in seismology is to model earthquake recurrence as a random process in which the probability of a future event is influenced by neither location nor time of previous events, ie earthquakes are assumed to have no "memory". Known as the *Poisson* or *time-independent model* for earthquake recurrence, this approach has been fairly reliable for modelling earthquake activity, particularly for events of small to moderate magnitude. For a single fault system, however, the assumption of independent occurrence may not be correct. The seismic history of the North-Anatolian fault since 1939 serves as a striking example (see Figure 2), with large-magnitude earthquakes moving mostly westwards, like a row of falling dominoes, over the past 60 years.

In view of this pattern, it seems rather unlikely that earthquakes should be entirely unrelated to one another. This and other similar earthquake sequences in space and time have prompted scientists to develop an alternative model for estimating future seismic activity known as the *time-dependent model* of earthquake occurrence. In time-dependent models, the interval since the last earthquake occurrence on a given fault segment is explicitly recognised. The proba-

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[2] after GSHAP 1999, see http://seismo.ethz.ch/GSHAP

Event	Casualties and losses	Main observations
Armenia, Colombia 25 January 1999 M_w 6.2 (strong) 4.461N / 75.724W 17 km focal depth unnamed fault	1,900 casualties 4,750 injured 250,000 homeless USD 1.5 bn economic loss USD 0.1 bn insured loss	Large amplification of ground motion in soft soil areas, numerous earthquake-induced landslides. Emergency response hampered by large losses to critical emergency facilities, equipment and personnel. Same type of damage to be expected for other Colombian cities such as Bogotá, Medellin and Cali in a similar event. Low earthquake insurance penetration. Insured losses mainly from industrial and commercial risks.
Izmit, Turkey 17 August 1999 M_w 7.4 (major) 40.748N / 29.864E 17 km focal depth North Anatolian strike-slip fault	19,118 casualties 50,000 injured 600,000 homeless USD 20 bn economic loss USD 1 bn insured loss	Expected seismic gap event. Warning sign for Istanbul. Enormous death toll (largely avoidable through appropriate building design and construction). Large ground faulting losses (avoidable through appropriate land use planning). Large amplification of ground motion, soil liquefaction and soil settlement in soft soil areas. Critical lifeline facilities intersected by fault movement. Low earthquake insurance penetration. Insured losses mainly from industrial and commercial risks, important business interruption losses.
Athens, Greece 7 September 1999 M_w 5.9 (moderate) 38.119N / 30.045E 10 km focal depth unnamed fault	145 casualties 2,000 injured 50,000 homeless USD 0.6 bn economic loss very low insured loss	Event location rather surprising, unknown fault. Warning sign for Athens. Well-organised emergency response.
Chi-Chi, Taiwan 20 September 1999 M_w 7.6 (major) 23.772N / 120.982E 7 km focal depth Chelungpu thrust fault	3,400 casualties 8,700 injured 600,000 homeless USD 14 bn economic loss USD 1 bn insured loss	Unexpectedly high magnitude, numerous strong aftershocks. Extensive surface rupture, many earthquake-induced landslides, rock falls and large debris flows. Damage concentrated on un-inspected buildings with ground floor arcades. Critical lifeline facilities interrupted by fault movement. Water and electric power outage leading to extensive business interruption. Low earthquake insurance penetration. Insured losses mainly from industrial and commercial risks, substantial business interruption losses.
Dücze, Turkey 12 November 1999 M_w 7.1 (major) 40.758N / 31.161E 10 km focal depth North Anatolian strike-slip fault	834 casualties 4,950 injured USD 0.7 bn economic loss very low insured loss	Event seismically inter-connected with Izmit event. Very low earthquake insurance penetration.

Table 1: Overview of catastrophic earthquakes of 1999

bility of an event occurring in the future grows with the interval since the last event. These time-dependent models facilitate a more accurate assessment of the occurrence probability for a future earthquake than the time-independent models – provided that there is sufficient data available both on the seismic history and on the geophysical properties of a given fault. In fact, it is even possible in some cases to clearly identify certain segments of a seismic fault where a major earthquake is due or even overdue. These critical situations, also known as seismic gaps, have been identified in various parts of the world, eg in the regions of Tokai (Japan), Guerrero (Mexico) and in Izmit (Turkey), where the forecast proved tragically correct.

In recent years, the time-dependent models have been further improved with the inclusion not only of the time elapsed since the last event on a particular fault segment, but also of the effects of the seismic activity among neighbouring faults on that particular fault segment. This new area in time-dependent seismic hazard assessment has become known as *stress-interaction* or *fault-interaction* modelling and is lead by geophysicist Ross Stein and his colleagues from the United States Geological Survey. Swiss Re is convinced that, taken together, time-dependent probability models and the stress-interaction theory mark an important advancement in seismic hazard assessment, particularly for areas exposed to large-magnitude earthquakes. This is why Swiss Re has co-sponsored an extensive research project in the Marmara Sea near Istanbul, Turkey,

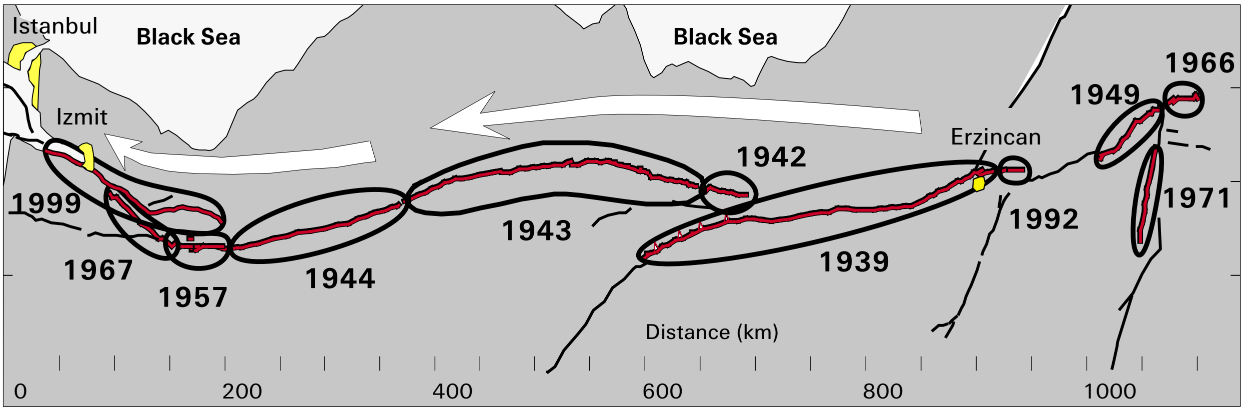

Figure 2: Seismic activity along the North-Anatolian fault since 1939. Major cities a shown in yellow, ruptured faults in red, unruptured faults in black. Note the steady westward progression of large-magnitude earthquakes (large arrows).

which is headed by Dr Ross Stein, his colleagues and local seismologist Dr Aykut Barka. The following section outlines the most important results of their study.

Increased odds of large earthquakes near Istanbul: study outline and results

The Izmit earthquake of 17 August 1999 is only the most recent event in a largely westward progression of seven large earthquakes along the North Anatolian fault zone occurring since 1939 (Fig. 2). Istanbul lies roughly 100 km north-west of the region that was so badly shaken in 1999. Istanbul has sustained severe damage at least a dozen times over the past 15 centuries, namely in the years 447, 478, 542, 557, 740, 869, 989, 1323, 1509, 1719, 1766, and 1894. Assuming that the earthquakes occurred entirely independent of one another (following the time-independent model of earthquake recurrence), Stein's team of seismologists calculated the probability of severe earthquakes (producing an MMI of VIII or more[3]) for this region to be approximately 20% during the next 30 years. According to this method, the chances of a severe earthquake striking Istanbul within the next 30 years would thus be one out of five. Still, this probability estimate does not include the time elapsed since the last large earthquake which severely affected Istanbul (1894). The argument supported in time-dependent seismic hazard assessment is that because 106 years have already elapsed since the last major earthquake in the Istanbul area, the probability of another major occurrence is increasing. Accordingly, the 30-year probability estimate of 20% obtained using the time-independent model might be too optimistic. Ideally, the time-dependent renewal probability for Istanbul is calculated on the basis of an earthquake catalogue covering many years and listing all large historic events for each earthquake source threatening to affect Istanbul.

While such catalogues are difficult to come by for most parts of the world, an extensive seismic history can be reconstructed for the Istanbul area: there is a compilation of earthquake damage descriptions in the Marmara Sea region reaching back to medieval times. This reconstructed earthquake catalogue comprises eight earthquakes since 1500 AD with a magnitude of M7[4] or greater. These are believed to have occurred on four fault segments of the North Anatolian fault system, which is capable of generating severe damage in the Istanbul area (see Table 2). The time elapsed since the last large event and the average displacement rates observed by global positioning system (GPS) measurements along each fault segment suggest that at least two out of the four fault segments – the Prince's Island and the Central Marmara fault segments – are late in the earthquake renewal process.

These two fault segments obviously have an increased probability to rupture in the near future and therefore raise the probability of Istanbul being affected by strong ground shaking. The study team thus found that the probability of an M7 or larger earthquake occurring in the Istanbul area during the next 30 years is raised from 20% in the time-independent assessment to approximately 50% in the time-dependent assessment. In other words, using the new assessment model, the probability for a damaging earthquake in Istanbul during the next 30 years is assumed to be more than twice the level originally assumed.

[3] MMI = Modified Mercalli Intensity scale, a numerical index describing the physical effects of an earthquake on man and man-built structures. MMI classes range from I to XII.

[4] M = Magnitude, a numerical quantity to characterise earthquakes in terms of the total energy released. Moderate and strong magnitude earthquakes are in a range of M5.0 to M6.9; major magnitude earthquakes reach M7.0 and above.

Until this stage, the research team had followed the current practice of seismic hazard assessment, which includes the time-independent Poisson probability and the time-dependent renewal probability. Dr Stein's team decided to go one step further to determine the 30-year probability for a damaging earthquake in Istanbul: they examined the effects of stress transferred from the two 1999 events in Izmit and Dücze to the fault segments threatening the capital city.

The theory of stress interaction among adjacent faults has been successfully applied to explain the 60-year sequence of earthquakes, in which all but one event spurred the next in the direction of Istanbul (see Figure 2). This theory maintains that when a fault breaks and produces a large earthquake, the stress level on the fault that slipped suddenly drops. The stress released by this earthquake changes the stress pattern in the surrounding area and could theoretically bring an adjacent fault closer to failure, thus raising the occurrence probability for the next earthquake on this fault. The interaction among faults may thus contribute significantly to the overall probability for a large, devastating earthquake to strike near Istanbul.

This proposition was thoroughly tested in the wake of the Izmit earthquake. Ross Stein and his colleagues first calculated the changes in the stress pattern in the Marmara Sea area which were triggered by the Izmit earthquake on 17 August. Figure 3 shows the resulting stress map. Areas marked yellow to red indicate regions with an increased stress load, while green to purple areas show regions with decreased stress. The overlay of this map showing the aftershock activity of the Izmit event reveals that the aftershock patterns and the areas with raised stress loads correlate significantly. Tragically, the calculated stress field also proved accurate concerning the M7.1 event in Dücze on 12 November 1999, which occurred precisely within an area showing a substantial stress increase. The stress interaction theory thus appears to be plausible.

Fault segment	**Earthquake events**	**Estimated inter-event time**	**Estimated time elapsed since last event**
Yalova	M7.6 (1509), M7.6 (1719), M7.0 (1894)	190 years	106 years
Prince's Island	M7.2 (1766)	210 years	234 years (late)
Central Marmara	M7.6 (1509)	540 years	491 years (late)
Izmit	M7.6 (1719), M7.4 (1999)	280 years	1 year

Table 2: Reconstructed seismic history of the four fault segments of the North-Anatolian fault system capable of generating severe damage in the Istanbul area. Seven events with a magnitude of M7 or greater have occurred since AD 1500. The inter-event times are determined on the basis of the seismic history and global positioning (GPS) measurements in cases where only one historic event on a fault segment is known. The table shows that at least the Prince's Island and the Central Marmara fault segments are probably late in their earthquake cycles.

These findings prompted Stein's team to take the stress transfer analysis a step further: they attempted to quantify the probability increase of an earthquake occurring in the Istanbul area as a result of the greater stress regime in the Marmara sea region. Their study revealed an additional probability increase of strong ground shaking (MMI≧VIII) in greater Istanbul from 50% to 62% over the next 30 years.

In summary, the study[5] sponsored jointly by the USGS and Swiss Re on the seismic hazard in Istanbul shows that the 30-year time-independent probability for strong ground shaking in Istanbul is 20%. The earthquake probability climbs to 50% when the time elapsed since the last major event in 1894 is considered, and rises even higher – to 62% – when the effect of the stress interaction induced by the 1999 Izmit event is included (see also Table 3).

Implications of time-dependent earthquake activity for the insurance industry

Since the unpredictability of loss events is a precondition for insurability, the question may well arise whether the new seismic hazard assessment methods will in fact jeopardise the insurability of earthquake losses. The answer must clearly be negative, as even the most advanced methods do not actually provide earthquake predictions, but merely facilitate a more accurate estimate for the probability of future earthquakes. Hence the exact time, location and magnitude of an earthquake remain entirely unpredictable.

Another precondition for insurability is the balance of premiums and losses across a portfolio of individual risks. For catastrophe perils, this diversification obviously cannot be established within a single given region, owing to the accumulation of losses from single large events. The only option in this case is to spread the risk over a larger area, ideally throughout the world. The international reinsurance market is the most suitable platform for enabling the global community of policyholders to share catastrophic risks. For example, policyholders in the US, Japan, Italy, Chile and many other countries actually paid for the damage resulting from the earthquakes in Turkey and Taiwan in 1999 via the global reinsurance market. In another year, the roles are just as likely to be reversed.

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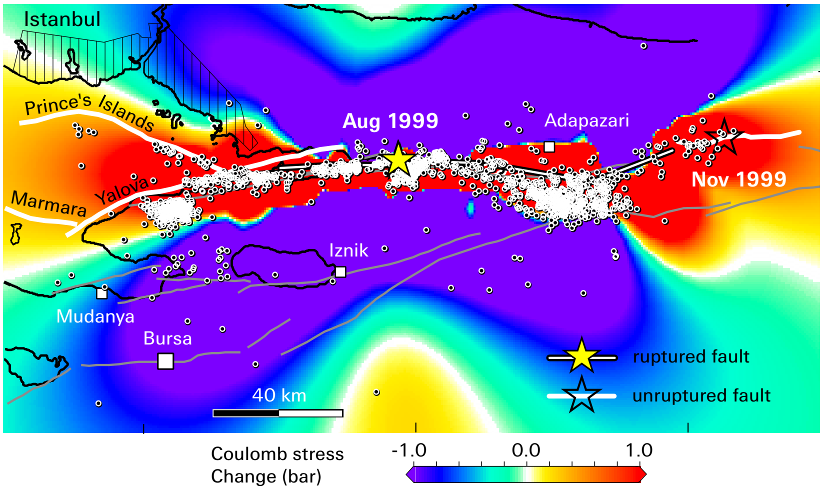

Figure 3: Change in stress patterns triggered by the Izmit earthquake on 17 August 1999. Yellow to red colours indicate the area where stress increased, while green to purple colours show the area where the stress decreased in the wake of the Izmit event. The Düzce earthquake of 12 November 1999 occurred in an area where stress was significantly raised by the stress release of the Izmit event. Together with clusters of aftershocks, it supports the theory of increased probability of fault failure prompted by stress transfer. The red area of the Marmara Sea contains faults which may significantly affect the Istanbul area.

To ensure a fair distribution of costs within the global community of policyholders, the premiums must be commensurate to the risk in the individual regions. It follows that the recent advancements achieved in earthquake research must be included in estimates of the insured earthquake risk. What are the practical implications?

In areas with an increasing probability of strong earthquake activity, the earthquake risk assessment obviously needs to be periodically revised and adjusted, and an increased risk will be reflected by higher premiums. Of course, the same principle holds true for areas with a decreased earthquake probability, with the effect that earthquake premiums need to be revised downwards. Let us take a hypothetical risk location in an earthquake-prone area to illustrate this point. Assuming that the long-term, time-independent seismic hazard is known, the average annual loss burden (ie the earthquake risk premium to cover the insured risk) can be calculated by dividing the risk-specific mean damage ratios per MMI shaking degree by the corresponding MMI return periods and summing up the results (see Table 4). The earthquake risk rate in our example would then amount to approximately 1.1 per mille.

Let us assume further that the time-dependent hazard assessment, including the effects of stress interaction, prompts a significant upward or downward adjustment of the seismic hazard estimate. This in turn would necessitate an adjustment of the return periods for the shaking intensities and thus for the calculated earthquake risk rate. This simplified example of an earthquake risk premium calculation shows how the new seismic hazard assessment methods can be integrated directly into the field of insurance.

In order to keep the necessary adjustments at affordable levels also in highly exposed areas, such as Istanbul, the risk can be spread over a larger region, eg the whole of Turkey. Insured parties in less exposed areas should then be willing to pay more than the premium reflecting their local exposure in order to provide some relief for those in heavily earthquake-prone areas. This principle of solidarity has been successful in many insurance markets. The extent to which it can be applied depends on political rather than on insurance-related considerations and is subject to the social environment in a country with catastrophe exposure. The principle is at its most effective if the given insurance penetration is as high and homogenous as possible. However, this often can only be achieved by introducing some degree of compulsory insurance.

Seismic hazard assessment model	**Probability of strong ground shaking in Istanbul during the next 30 years (including the probabilities calculated in the above process)**
Time-independent (also known as time-averaged or Poisson) model: earthquake occurrence is entirely random.	20% (chance of 1 in 5)
Time-dependent (also known as renewal probability) model: time elapsed since last event increases the probability of a future event.	50% (chance of 1 in 2)
Stress transfer (also known as stress or fault interaction) model: stress released by an earthquake increases the probability of a future event on neighbouring faults.	62% (chance of 1 in 1.6)

Table 3: Steps from a time-independent to a time-dependent seismic hazard assessment including stress transfer. The table shows the 30-year probability for strong ground shaking in the greater Istanbul area using three different seismic hazard assessment models. The highest probability of 62% includes the effects of seismic stress transfer and represents the most accurate seismic hazard assessment.

	MMI VI	**MMI VII**	**MMI VIII**	**MMI IX**	**MMI X**	**Total EQ risk rate**
Mean damage in % of replacement value	0.5%	3.5%	15%	35%	60%	
MMI return periods in years (seismic hazard)	25	100	500	2000	10000	
Average annual loss burden in % of replacement value	0.5%/25 = 0.02%	3.5%/100= 0.035%	15%/500 = 0.03%	35%/2000 = 0.018%	60%/10000 = 0.006%	1.1 per mille

Table 4: Simplified calculation of an earthquake risk rate for a hypothetical risk in an area exposed to earthquakes. Assuming that a time-dependent hazard assessment, including the effects of stress-interaction, results in a significant adjustment of the seismic hazard estimate (ie the return periods for the MMI shaking intensities), the resulting earthquake risk rates will also change.

In this sense, Swiss Re welcomes the current efforts of the Turkish Government and the World Bank to set up a Turkish Catastrophe Insurance Pool (TCIP). The TCIP's purpose will be to offer compulsory residential earthquake insurance. While the actual product will be distributed by the local insurance industry, the corresponding risk will be pooled in the TCIP which in turn will transfer most of the risk to the reinsurance and possibly to capital markets. Swiss Re is providing active support for the project by sharing its international expertise in catastrophe insurance in order to help establish a lasting and technically sound insurance scheme.

Insurance can be an efficient and affordable tool to manage the financial consequences of earthquakes, provided that it is based on scientific risk assessment, on an acceptable degree of solidarity within a region, and on fair global risk sharing via reinsurance to balance premium and losses. However, insurance cannot save any lives in case of an earthquake. This is why no effort must be spared at any time in promoting scientific advancements and appropriate implementation of earthquake preparedness measures, since this alone will reduce the tragic loss of lives associated with earthquakes.

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