



Scenario Earthquakes in Development Decision Making

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The use of scenarios to anticipate the outcome of future earthquakes is critical in a range of earthquake science applications including for example, developing building codes, pricing insurance and planning emergency response. The approach risk in Tomorrow's Cities, leading to our risk concept note, 'Risk-based, pro-poor urban design and planning for Tomorrow's Cities', has also highlighted the importance of scenarios in the collaborative consideration of the consequences of planning decisions on future risk. The choice of scenario earthquakes can have important implications in many circumstances, but how well can we constrain likely future events and how is the variability in possible futures represented in scenario choices?

On 28 March 2005, the magnitude 8.7 Nias earthquake ruptured the Sunday megathrust fault where the Indo-Australian plate is being forced under the Eurasian plate. The earthquake produced strong shaking and more than 1000 deathsⁱ. This earthquake was unique in that its approximate location and energy release had been forecast in a paper published in Nature only 11 days previouslyⁱⁱ.

Earthquakes communicate by stress transfer. A large earthquake deforms the earth's crust around it changing the so-called Coulomb stress field on neighbouring earthquake faults^{iii, iv}, bringing some closer to failure and triggering aftershocks, some of which are very large. Estimation of the Coulomb stress from the great Sumatra-Andaman earthquake, which produced the Indian Ocean tsunami, resolved onto neighbouring active fault segments, combined with considerations of their seismic history, allowed researchers to suggest an increased risk that was confirmed by the Nias event. Remarkably, the calculated Coulomb stress change was less than 0.1 MPa^v, which is less than the stress caused by a handshake. The precise mechanism whereby this geologically tiny perturbation broke the grip holding some small part of the opposing sides of the fault together is not properly understood, but the resulting non-linear amplification of the rupture process eventually broke an area of 50,000 km², displacing the fault by as much as 15 m and releasing 1000 Hiroshima energy equivalents. This avalanche of energy release was probably initiated 30 km below the seafloor.

The accurate, if imprecise, forecast of the location and approximate size of such a large earthquake might be considered a success of physical science, but this success comes at a very high price. Firstly, it demonstrates that large earthquakes can be triggered by almost infinitesimal stress changes and that the precision with which the initial conditions are required to be known 30 km below the ocean floor, make general prediction of rupture initiation a practical impossibility. Secondly, the non-linear amplification of the initial rupture required to produce a massive failure is controlled by the detailed interplay of (probably unknowable) local

stress and strength on the rupturing fault. Observations expose the fractal complexity of earthquake slip (e.g. Ref ^{vi}) resulting from this process and suggest that the amount of slip, even after rupture initiation, is also inherently unpredictable. Any earthquake is simply one possible outcome of a game of tectonic bagatelle.

The variability in the characteristics of repeated rupture is consistent with observations of successive events on the same fault that are completely different (e.g. Refs ^{vii viii ix}). In general the hypothesis of 'characteristic' events repeating in seismic 'gaps', with a historical record of previous large events with no recent occurrence at that location, does not hold. In particular, these concepts failed to show any skill in explaining any of the four killer earthquakes west of Sumatra since the Nias earthquake. These events suggest that, even if it were possible to identify faults with high likelihood of rupture, we would still be unlikely to select scenario events with high confidence. The details of the final earthquake slip are only determined during the rupture process itself, and the eventual earthquake could take an infinity of forms generating a wide range of possible outcomes. Worse still, these details, even for earthquakes of similar magnitude, are likely to be important in defining impact, particularly where cascading hazards are involved.

Consider, for example, how tsunamis are generated by megathrust earthquakes. Strain, accumulated over hundreds of years, depresses the near-shore sea floor by metres and large earthquakes rupture the plate interface allowing this centurial strain energy to be released in seconds, forcing the seafloor upward over a vast area and producing a 10 billion tonne bulge in the sea surface. The collapse of this bulge generates a tsunami, whose impact might be expected to be related simply to the earthquake magnitude. However, several studies have shown that this is not the case (e.g. Refs ^{x xi}). Again, non-linear amplification, this time of small differences in the relationship between water depth and earthquake slip, result in very different impacts when viewed, for example, from the coastal city of Padang in western Sumatra. Almost identical earthquakes on the same segment of the off-shore fault might produce a <50 cm wave for the city or a >5 m wave, killing no one or possibly hundreds of thousands (cf. Ref ^{xii}). Recent numerical estimates for the shaking produced by a number of possible scenario earthquakes for Istanbul show analogous divergence in ground motion intensity measures leading to a wide range of estimated building and lifeline damage, casualties and economic losses^{xiii}.

These observations have important philosophical as well as practical implications for the use of scenario events in earthquake risk management. Despite undeniable advances in the understanding of the physical processes underlying large earthquakes, several seismic butterfly

effects ensure that the outcome will arguably always be a surprise (cf. Ref ^{xiv}). Imagine a world in which earthquake physics was completely known and where the notion of determinism introduced by Laplace^{xv} would only require precise assessment of the initial conditions fully to constrain the future (and the past). However, the hope that these initial conditions might be estimated by the techniques of geology and geophysics with sufficient accuracy and precision to yield definitive scenario earthquakes are dashed by the exponential (or even super-exponential) divergence of dynamical trajectories in these non-linear earthquake processes. This divergence, and the inherent unpredictability in such systems, was first noted by Ed Lorenz^{xvi}, and is a key element of modern 'chaos' theory. The immutable uncertainty in our observations, no matter how good our physical understanding, forbids the identification of a meaningful scenario event. Conservative scenarios might wildly underestimate the consequences of particular decisions and unfulfilled forecasts of the worst impacts will leave physical scientists exposed to accusations of crying wolf, fundamentally undermining their collective credibility.

What are the implications of this perspective for physical science in earthquake risk management? Many physical scientists now recoil from traditional pronouncements made with certainty and clarity that often made scientists and engineers effective decision-makers in many development environments. For some the demolition of this technocracy is a cause for celebration but, spurious as scientific over-confidence might have been, the potential vacuum created by its demise is unlikely to be filled by better assessments of earthquake risk. Consequently, the challenge becomes a reassessment of what can be learned by scientific risk estimation and finding a more nuanced, and perhaps a more modest, role for its insights, including the realities of the uncertainties involved.

In Tomorrow's Cities, we are trying a different approach to assessing the role of uncertainty in forecasting, and communicating risk to decision-makers. In this approach, we attempt to use the convening power of physical science simulation with full consideration of the uncertainties rather than promoting the, frequently unspoken, implication of scientific certainty. Here, scenarios cover a wide range of possible impacts from the high-magnitude design earthquakes through to small every-day shakes, connecting intensive earthquake risk to extensive multi-hazards like floods and landslides. Multi-hazard scenarios are then integrated into complex assessments of risk used as a basis for engaging multi-disciplinary teams of decision-makers who provide multiple perspectives to illuminate complex development decisions, including consideration of the consequences of particular choices. Rather than usurping local decision authority, science now becomes a tool for decision support in a collaborative environment, where decision makers and local partners are involved early in framing the research questions

using co-produced assessment of risk which at least attempt to include the perceptions of marginalised communities. Rather than scientists providing definitive forecasts, they provide a critical, but supporting, role in a multi-disciplinary process.

Time will tell if this is a more effective, sustainable role for physical earthquake science in making tomorrow's cities safer in the developing world.

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