Simulation-based Seismic Hazard Assessment for Queensland: progress and directions

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1 Introduction

Assessment of the seismic hazard for regional areas of Australia is severely hampered by sparse and incomplete seismic records. Three key inputs for probabilistic hazard assessment (recurrence statistics, source zones and attenuation relations) are poorly constrained by available data. To compound matters, international research has demonstrated that regional seismicity varies spatially and temporally due to nonlinear interactions between faults. Estimates of recurrence statistics and source zones based upon a relatively short seismic catalogue, may deviate considerably from the longer-term averages thus biasing seismic hazard estimates. On the bright side, numerical modelling of earthquake sources has demonstrable predictive value, offering the possibility to accurately forecast the location and size of damaging earthquakes. Wave propagation models may be used to delineate regions prone to local site amplification and quantify the site response.

In recent years, there has been considerable advancement in technology for the simulation of the entire seismic cycle including tectonic loading, earthquake nucleation and rupture, wave propagation, and crustal relaxation. Pilot projects have demonstrated the feasibility of performing simulations to better constrain the earthquake statistics for a given region. For simulation-based seismic hazard assessment to be effective, a multilateral approach is required that encompasses geologically constrained model construction, both static and dynamic stress transfer simulations, and comprehensive parameter sensitivity studies.

A project has commenced to construct a computational model for South-East Queensland with the initial aim of studying the intermediate- to long-term recurrence statistics of earthquakes occuring along major faults in the region. This paper outlines current progress towards construction of the computational model and highlights some of the technical challenges encountered thus far. Utilizing Mohr-Coulomb Failure Analysis, we relate the fault orientations, friction coefficients and principal stresses, providing constraints upon the permissible boundary conditions for the fault system simulations.

2 Computational model construction

A computational fault model for a given region may take different forms depending upon the numerical method used to simulate the fault system dynamics. The simplest method (Rundle, 1988 [4]; Ward, 2000 [6]) is a Green's Function approach in which the interactions between faults are computed using analytic Green's Functions for the stress change due to slip of rectangular fault patches (Okada, 1992 [3]). This method requires a fault model in which faults are subdivided into a number of rectangular segments, each of which is assigned a strike, dip and segment dimensions. Such a model will be termed

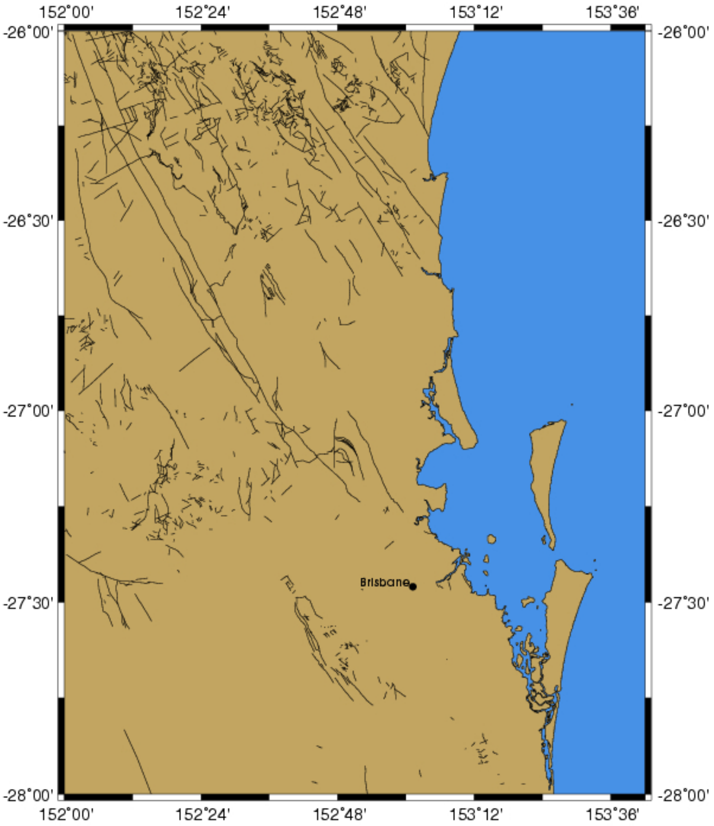

Figure 1: The complete South-East Queensland Fault Database recently updated from geological, geophysical, gravity and magnetic survey data by Humphries (2003).

a 'fault plane model'. Quasi-dynamic (Xing et al., 2003 [7]) and dynamic (Saez et al., 2004 [5]) Finite Element methods that solve the continuum equations for elasticity, require a computational mesh for the entire region of interest. The fault plane model provides the necessary input to existing mesh generation software to construct these computational fault meshes.

To construct a fault plane model for South-East Queensland, we commenced with the recently updated fault database (Humphries, 2003 [2]) available digitally as a GIS dataset. The database contains over 1400 faults with 75 larger than 10km in length. A map of the complete fault database is shown in Figure 1. The density of faults smaller than 10km length is markedly lower in the central and southern regions, largely due to insufficient geophysical data (the northern region is a mining area where considerably more exploration data is available). For this reason, the small faults will not be included in the fault plane model.

A subset of the GIS dataset containing only the larger faults is shown in Figure 2. The density of points varies considerably from fault to fault and along the largest faults. Construction of a fault mesh using this data would result in great variability in element sizes, which is a well-known source of numerical instability in Finite Element simulations.

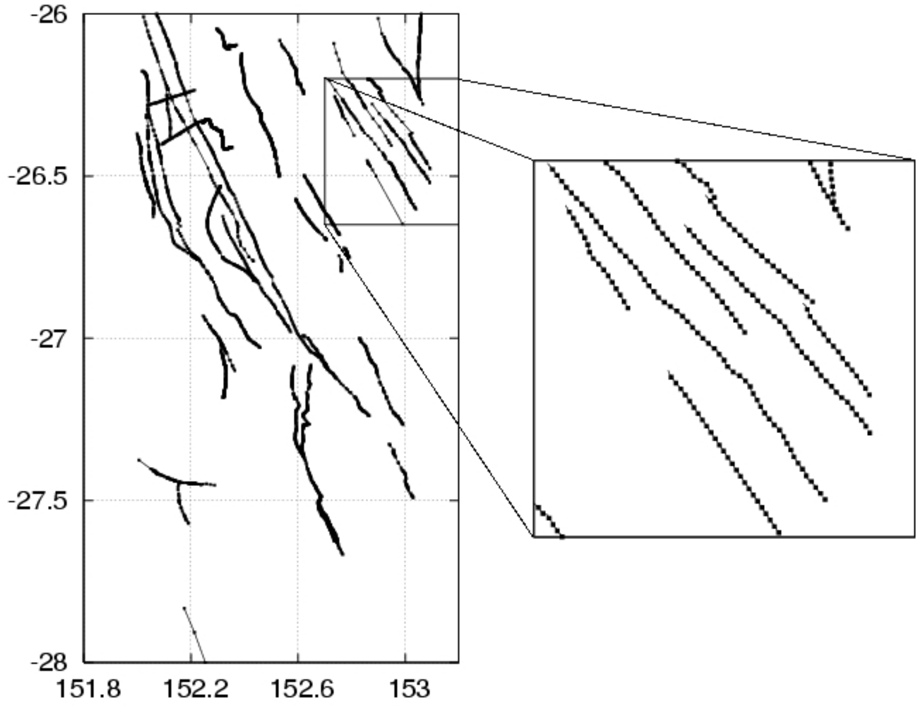

Figure 2: The fault database with all faults smaller than 15km removed showing the variable density of points along faults. To remove this, a smoothing algorithm (described in the text) is used to produce a fault plane model (see the INSET) suitable for mesh generation.

It is preferable to commence with a fault plane model in which individual segments are of approximately equal size, ΔL.

We have developed a method to construct a new dataset with equally spaced points along each fault. For each fault a list of the points along that fault is extracted from the GIS dataset. The first point in this list is selected as a reference point and a line is fitted to all subsequent points within a distance ΔL of that point. The fit line is then extrapolated a distance ΔL to compute the second point in the new dataset. This second point is then taken as the reference point and the procedure is repeated. For segments where there are no original points within ΔL of the reference point, the next point in the original dataset is used to construct a line from the reference point and additional points are added at intervals of ΔL. A portion of the resultant fault plane model obtained for $\Delta L = 5$km is shown in the inset of Figure 2.

3 Analysis of the relationship between friction coefficients and tectonic stress

In seismically active regions such as California, inversion of seismic data permits estimation of the frictional properties of faults and focal mechanisms provide indication of the tectonic stress directions. Augmented with historical, paleoseismic and geodetic measurements, estimates of the long-term rate of offset of each fault segment may be made.

Friction coefficients and offset rates are the only additional geophysical data required for the Green's Function method however Finite Element simulations also require the orientations and relative amplitudes of the horizontal principal stresses. The Australian Stress Map (Hillis and Reynolds, 2003 [1]) does not contain any stress orientation datapoints in South-East Queensland, although the inferred stress trajectories indicate that the maximum horizontal stress direction is $N14°E$. There is also little geodetic data to constrain tectonic rates for the region.

Despite this lack of knowledge, significant insight can be gained from Mohr-Coulomb failure analysis. Since we intend initially only to model earthquakes in 2D, we may assume all faults are strike-slip; normal and reverse faulting be modelled in 2D. For strike-slip faults, the well-known Mohr-Coulomb Circle relates the two principal stresses (σ_I and σ_{II}) to the shear stress (τ) and normal stress (σ_N) on a fault plane oriented at an angle (θ) to the maximum principal stress direction:

$$\begin{aligned} \sigma_N &= \frac{(\sigma_I + \sigma_{II})}{2} + \frac{(\sigma_I - \sigma_{II})}{2} \cos(2\theta) \\ \tau &= \frac{(\sigma_I - \sigma_{II})}{2} \sin(2\theta) \quad . \end{aligned}$$

N.B. positive principal stresses are compressive in this formula.

To simplify the analysis that follows, we introduce a parameter defined as the ratio of the two principal stresses, $\alpha = \sigma_I/\sigma_{II} > 1$ and compute an *effective friction coefficient* ($\hat{\mu}$) for each fault segment, where:

$$\hat{\mu} = \frac{\tau}{\sigma_N} = \frac{(\alpha - 1)\sin(2\theta)}{(1+\alpha) + (\alpha - 1)\cos(2\theta)} \tag{1}$$

The effective friction coefficient has a straightforward interpretation: The principal stresses will induce slip along any fault segment with a friction coefficient $\mu_f < \hat{\mu}$. Suppose we assume that all faults have a nominal friction coefficient of $\mu_f \sim 0.5$. By varying the ratio of the maximum principal stresses and their directions, the faults that will slip may be identified (e.g. Figure 3). A rose diagram (Figure 3) illustrates the sensitivity of fault activity to principal stress ratio and direction. For all choices of α, the highest percentage of slipping faults occurs for either $N - S$ compression or for $N60°W$ i.e. ±30° of the predominant strike direction ($N30°W$).

This static analysis would suggest that the most appropriate stress direction is $N - S$ compression, which is consistent with the tectonic motion of the Australian continent relative to the Pacific plate. The static analysis is a useful starting point for identifying the principal stress directions and amplitude ratios, for regions where independant estimates of such are unavailable. For the purposes of numerical simulations, it provides a starting point for specifying boundary conditions that will ensure rupture of the modelled faults. This analysis does not take account for stress interactions between faults, resulting in stress shadows, particularly in subregions containing numerous semi-parallel faults. The effect of stress interactions is considered in the numerical simulations, allowing the interplay of frictional properties and stress conditions to be studied.

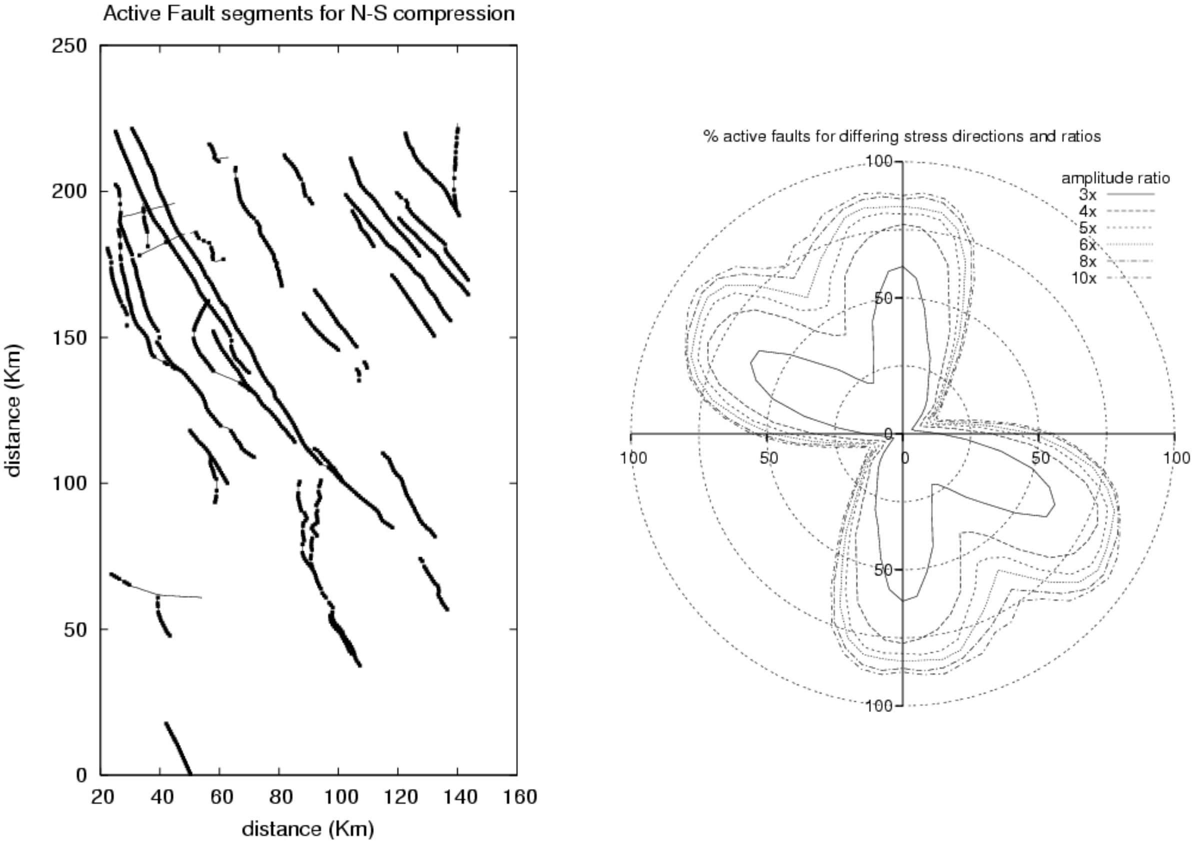

Figure 3: LEFT: Map of the fault segments that will slip under N-S compression with the maximum principal stress 4 times the minimum principal stress. Active segments are shown as bold squares. Unactive segments are shown as a thin line. RIGHT: A rose diagram showing the percentage of active faults for differing principal stress orientations and amplitude ratios (α).

4 Concluding remarks

The South-East Queensland fault modelling project is still in its early stages but attempts to model this region have already yielded valuable insight into the tectonics of the region. Mohr-Coulomb failure analysis provides an effective way to determine the appropriate amplitude ratios of principal stresses given only the orientations of faults and the direction of the maximum horizontal stress. In the next stage of the project, simulations of long-term seismicity will commence, providing the first synthetic seismicity catalogues with which to study the sensitivity of recurrence statistics to tectonic loading rates, frictional properties and the limitations of the various numerical methods employed.

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