FAST TRACK PAPER

A gravity gradient method for characterizing the post-seismic deformation field for a finite fault

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SUMMARY
Gravity gradients are an effective method for delineating the extent of subsurface density anomalies. The change in subsurface density contrasts due to the seismic deformation gives rise to detectable gravity changes via the dilatational gravity signal or Bouguer anomaly. Solutions for the corresponding gravity gradients of these signals are developed for a vertical strike-slip fault. Gravity gradient solutions exhibit similar spatial distributions as those calculated for Coulomb stress changes, reflecting their physical relationship to the stress changes. The signals’ magnitudes, of the order of $10^{-4}$ E, are beyond the resolution of typical exploration instruments. Improvements to Superconducting Gravity Gradiometers are necessary for gravity gradients to be used as a viable method for the observation of the stress field changes over large spatial scales.

Key words: Numerical solutions; Seismic cycle; Time variable gravity; Earthquake interaction, forecasting, and prediction.

1 INTRODUCTION
The analytic solutions of the deformation field from seismic events are well established in the literature for elastic half-spaces (Chinnery 1963; Mansinha & Smylie 1971; Okada 1985) and further developed for the corresponding stress and strain fields (Okada 1992). Seismic triggering studies that interpret the Coulomb stress changes arising from the resultant deformation field after a seismic event, have demonstrated the potential for identifying regions of future seismic activity (King et al. 1994; Stein et al. 1994; Freed & Lin 2001). However, the Coulomb stress changes are inherently unobservable by direct measurement and are typically restricted to surface observations; their values at focal depths must be inferred.

By contrast with stress and strain measurements, gravity observations record changes from all depths and their acquisition over large spatial scales is common due, in large part, to their extensive use in exploration geophysics. The analytic solutions for the gravity changes from an earthquake were first numerically solved for by Rundle (1978), and analytically solved for a thrust fault and dilatational point source by Walsh & Rice (1979). Okubo (1991, 1992) developed the general solutions for a finite fault within an elastic half-space. In Section 2, we outline our method and solutions. Section 3 shows the results for several of the gradient solutions followed by a discussion of the results in Section 4.

2 THE GRAVITY GRADIENT SOLUTIONS
To calculate the gravity gradient changes for an earthquake, we first use the potential Green’s functions developed by Okubo (1992). In general, the expressions used for the dilatational gravity potential changes are given by

$$
\Delta P^{\ast}(x_1, x_2, x_3) = \{\rho G[U_1S^\ast(\xi, \eta) + U_2D^\ast(\xi, \eta) + U_3T^\ast(\xi, \eta)] + \Delta \rho G U_3 C^\ast(\xi, \eta)\}.
$$

(1)

where $\rho$ is the density of the medium, $G$ is Newton’s Universal gravitational constant, $\xi$ and $\eta$ are coordinates on the fault length and width, respectively and $U_i$ is the slip vector. We have used the double vertical notation of Chinnery (1961). For our analysis, we need only focus on the strike-slip component, where $S^\ast(\xi, \eta)$ is
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3 RESULTS

Using the Green’s functions (5)–(7) in (1), we can calculate the gravity gradient solutions for a vertical strike-slip fault. In Fig. 1, we plot the vertical gravity gradient using eq. (5) for a right-lateral strike-slip fault. The vertical gravity gradient exhibits a similar antisymmetric butterfly pattern as that for the dilatational gravity (See Okubo 1992, fig. 4).

For the horizontal gradients, we make note of the fact that they are coordinate dependent, and thus their derivatives are dependent upon the direction in which their derivatives are found. The consequence of this is that derivatives in either the positive or the negative direction will produce similar spatial patterns but with opposite signs. As such, we plot only the magnitude of the horizontal components. We further note that we have employed the use of the more common unit for gravity gradients in exploration geophysics, that is, the Eötvös (E), which is equivalent to 0.1 μGal m⁻¹ or 10⁻⁹ s⁻². The thick black line is the location of the fault.

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Figure 2. (a) The $x$-horizontal gravity gradient magnitude for a vertical right-lateral strike-slip fault and (b) the $y$-horizontal gravity gradient magnitude. Parameters used in (a) and (b) are the same as those used in Fig. 1. Note that the scales are different in (a) and (b).

Figure 3. The gravity gradient solution given by eq. (8) with (a) $\epsilon = 0.15$ and (b) $\epsilon = 0.4$. Parameters are the same as those used in Fig. 1. Note that the scales are different in (a) and (b).

The Coulomb 3.0 software (Lin & Stein 2004; Toda et al. 2005). It should be noted that, to have a more consistent comparison with Fig. 4, Fig. 5 does not include the regional stress component, as it is currently not included in the gradient solutions.

We observe similarities in the spatial distribution for the gravity gradient plot of Fig. 4 and the Coulomb stress change plot of Fig. 5. Moreover, we note that by using eq. (4) we solve for the expected gravity gradient solution at the surface, whereas the Coulomb stress changes are calculated at depth.

4 DISCUSSION

Using the gravity gradients to delineate the edges of subsurface density anomalies, we have provided the gravity gradient Green’s function solutions for the subsurface density anomalies in the post-seismic regime for a vertical strike-slip fault. The physical relationship between the gravity gradients and the corresponding Coulomb stress changes for the deformation field of a finite, strike-slip fault is clearly evident in the similar spatial distributions of Figs 3 and 4, respectively. Moreover, Walsh & Rice (1979) have shown explicitly that the gravity solutions for a dilatational point source and dip-slip fault can be found in terms of the stress changes following seismic events.

As such, the use of gravity gradients may offer researchers the ability to map the actual Coulomb stress changes by using the
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