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

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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 seismicity (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.

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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.

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

$$
\Delta P(x_1, x_2, x_3) = \{\rho G(U_1 S^*(\xi, \eta) + U_2 D^*(\xi, \eta) + U_3 T^*(\xi, \eta)] + \Delta \rho GU_3 C^*(\xi, \eta))\}
$$

(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 $S^*(\xi, \eta)$ is...
Gravity gradients of deformation fields

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).

Figure 1. The vertical gravity gradient for a vertical right-lateral strike-slip fault. $L = 10$ km, $W = 10$ km, depth to the top of the fault is 1 km, and the dislocation is 5 m. The units are in Eötvös (E), which is equivalent to $0.1 \mu$Gal m$^{-1}$ or $10^{-9}$ s$^{-2}$. The thick black line is the location of the fault.
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).

Figure 4. The gravity gradient solution of eq. (8) for the 1992 April Joshua Tree earthquake. The parameters are $L = 8 \text{ km}$, $W = 10 \text{ km}$, with a right-lateral dislocation of 0.8 m and an $\epsilon$ value of 0.35. To avoid singularities, the depth to the top of the fault is 500 m. The thick black line indicates the approximate location of the Joshua Tree Fault.

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
gradients as a proxy for the stress changes in the system. Furthermore, we suggest this may offer a practical complement to the traditional suite of seismic hazard assessment tools such as combined InSAR and GPS methods (Samsonov & Tiamo 2006) and statistical seismicity methods (Bowman & King 2001; Tiamo et al. 2002), in addition to traditional Coulomb stress change solutions (King et al. 1994; Freed & Lin 2001).

Exploration techniques of the 1930s commonly yielded gravity gradient resolutions of the order of magnitude of \( \pm 1 \) E (Bell 1997), and recent developments in quantum-based instruments promise improved sensitivity in the near future. Moody et al. (2003) are developing an instrument for use in an aircraft or ship with an accuracy of <1 E Hz\(^{-1/2}\). Superconducting Gravity Gradiometer (SGG) designs for space-borne missions, which require \( 10^{-4} \) E Hz\(^{-1/2}\) sensitivity, have been demonstrated to achieve 0.02 E Hz\(^{-1/2}\) in the lab. Enhancements to the SGG, for example, by employing magnetically suspended test masses (versus the current mechanical suspension), may provide improved sensitivity by several orders of magnitude yielding resolutions of \( 10^{-5} \) E Hz\(^{-1/2}\) (Moody et al. 2002).

We suggest that highly sensitive SGGs, designed for constant terrestrial observation, may allow for the measurement of the post-seismic gravity gradient changes arising from large events such as the Joshua Tree–Landers–Hector Mine sequence. Plans to incorporate the underlying regional stress, as well as more complex fault geometries, are underway. Moreover, extension of the method to include thrusting fault solutions, which contain larger gravity signals than strike-slip faults, may produce more readily observed signals.

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