Computing Scheme of Co-seismic Change of Deflection of the Vertical and Applied in the 2010 Chile Earthquake

Wenke Sun and Xin Zhou

Abstract

This paper introduces a scheme to compute co-seismic change of deflection of the vertical. To compare the theoretical deflection changes with the GRACE-observed ones, the dislocation Love numbers are truncated and the Green's functions are computed with application of a Gaussian filter. This study further examines the problem of seawater correction to modeled geoid and deflection changes. As an application of the dislocation theory and the computing scheme, we consider the 2010 Chile earthquake (Mw8.8) using two fault slip models, to compute the co-seismic geoid and deflection changes considering seawater corrections. Results indicate that the co-seismic geoid and deflection changes can be detected clearly by GRACE observation, and the co-seismic geoid change is not sensitive to the fault slip models; whereas the co-seismic deflection changes are sensitive. These behaviors provide us a new and useful approach to invert seismic faults using GRACE-observed deflection changes as constraints.

Keywords

2010 Chile earthquake • Co-seismic deformation • Deflection of the vertical • Geoid

1 Introduction

Many scientists have presented dislocation theories to interpret observed co-seismic deformations such as displacement, strain, tilt, and gravity change, such as theories for half-space media by Okada (1985), Okubo (1992) and Wang et al. (2006) among others. These theories are mathematically simple and are widely used in practical applications in modeling co-seismic deformation even today.

Scientists also developed dislocations theories for a more realistic Earth model, such as Pollitz (1992), Sun and Okubo (1993), Sun et al. (1996, 2006, 2009), Piersanti et al. (1995), Sabadini et al. (1995), Soldati et al. (1998) and Tanaka et al. (2006). Previous results indicated that co-seismic deformation accompanying a large earthquake occurs not only near the epicenter, but over the whole earth. For that reason, we are compelled to investigate global co-seismic deformations using both a theoretical model and practical observation. A spherical dislocation theory is considered to be necessary to model/invert the fracture fault and to calculate the co-seismic deformations over the earth surface.

The coseismic gravity field changes are similarly detectable by gravity measurement. For example, coseismic gravity changes generated by the Tokachi-Oki earthquake in 2003 were detected using superconducting gravimeters (Imanishi et al. 2004). Furthermore, according to Gross and Chao (2001) and Sun and Okubo (2004), the satellite gravity mission GRACE is theoretically able to detect the coseismic gravity changes caused by earthquakes with magnitude of 8 or greater. Subsequently, the co-seismic and post-seismic gravity changes caused by 2004 Sumatra–Andaman Earthquake (Mw9.3) and the 2010 Chile earthquake (Mw8.8) were detected by GRACE (Han et al. 2006; Panet et al. 2007; Ogawa and Heki 2007; Chen et al. 2007; Linage et al. 2009;

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Heki and Matsuo 2010; Zhou et al. 2011b). Therefore, to interpret the observed deformation and to reflect the effects of the earth curvature and vertical structure, the dislocation for a spherical earth model is important and necessary (Sun et al. 2009).

Sun and Zhou (2012) presented a new scheme to compute the change of deflection of the vertical, expending the current dislocation theory for a spherical earth model (Sun and Okubo 1993). Then, as an application, the Green's functions are used to calculate co-seismic deflection changes caused by the 2011 Tohoku-Oki earthquake. Results show that this earthquake generated considerable co-seismic deflection changes, and detected by GRACE.

GRACE provides us with a global potential model for each month; it is not only useful to compute gravity and geoid changes, but also to compute change of deflection of the vertical. The deflection of vertical is defined as derivative of the geoid and it is expected to be more sensitive to co-seismic deformation than geoid. It has the potential to open a new approach to study co-seismic deformation with GRACE data.

In this paper, we briefly introduce the computing scheme to compute the change of deflection of the vertical. Then we apply the scheme to compute the co-seismic deformation caused by the 2010 Chile earthquake (Mw8.8), to see whether the co-seismic change of deflection of the vertical is detectable or not, and assess the sensitivity of this quantity to co-seismic slip models.

2 Co-seismic Geoid and Deflection Changes for a Point Dislocation

We define the dislocation model at radial distance r_s on an infinitesimal fault dS by slip vector $\mathbf{\nu}$, normal $\mathbf{n}$, slip angle λ, and dip angle δ in the coordinate system $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$; unit vectors $\mathbf{e}_1$ and $\mathbf{e}_2$ are taken, respectively, in the equatorial plane in the directions of longitude $\phi = 0$ and $\frac{\pi}{2}$, and $\mathbf{e}_3$ along polar axis $\mathbf{r}$. Relative movement (displacement) of the two fault sides is defined as U. In the following, we present the Green's functions of co-seismic change of deflection of the vertical by following the scheme of Sun et al. (2009).

If a dislocation occurs in a spherical medium, such as a spherically symmetric, non-rotating, pure elastic and isostatic earth, the excited geo-potential change $\psi(r, \theta, \phi)$ is given by:

$$\psi = \sum_{n,m,i,j} k_{5,m}^{n,ij}(r) Y_n^m(\theta,\phi) \cdot \nu_i n_j \frac{g_0 U dS}{a^2} \tag{1}$$

where, $Y_n^m = P_n^m(\cos\theta)e^{im\phi}$, $P_n^m(\cos\theta)$ is the associated Legendre's function, a is the earth radius, g_0 is the gravity on earth surface. $k_{5,m}^{n,ij}(a)$ is the dislocation Love number of co-seismic potential change, defined as $k_{5,m}^{n,ij}(a) = y_{5,m}^{n,ij}(a) \cdot a^2/g_0$ (Sun and Okubo 1993), where $y_{5,m}^{n,ij}(a)$ are obtainable by solving the linearized first order equations of equilibrium, stress–strain relation, and Poisson's equation for excited deformation (Takeuchi and Saito 1972) $\dot{\mathbf{Y}} = \mathbf{AY}$, where $\mathbf{Y} = (y_{1,m}^{n,ij}, \cdots, y_{6,m}^{n,ij})^T$, and dot "ÎĞ" represents the derivative with respect to r. $\mathbf{A}$ is a coefficient matrix depending on the earth model. Solutions $\mathbf{Y}$ satisfy the discontinuity condition across the radius of the source (Saito 1967) and the free boundary conditions.

Since $i = 1, 2, 3$; $j = 1, 2, 3$, there are 9 possible combinations of i and j, correspondingly, the total solutions of all y should be nine. However, the number of independent solutions of $y_{k,m}^{n,ij}(a)$ is four. In this study, we choose ($y_{k,m}^{n,12}$, $y_{k,m}^{n,32}$, $y_{k,m}^{n,22}$, $y_{k,m}^{n,33}$) as four independent solutions. They are excited by vertical strike-slip, vertical dip-slip, horizontal opening along a vertical fault, and vertical opening along a horizontal fault, respectively. After solutions of $y_{5,m}^{n,ij}$ are obtained for source functions, the dislocation Love number $k_{5,m}^{n,ij}(a)$ can be determined, so that the corresponding co-seismic geoid and deflection changes of vertical can be derived as the following (Sun and Okubo 1993; Sun et al. 2009).

$$N(a,\theta,\phi) = \frac{\psi(a,\theta,\phi)}{g_0} \tag{2}$$

$$\xi(a,\theta,\phi) = \frac{1}{a}\frac{\partial N(a,\theta,\phi)}{\partial\theta} \tag{3}$$

$$\eta(a,\theta,\phi) = -\frac{1}{a\sin\theta}\frac{\partial N(a,\theta,\phi)}{\partial\phi} \tag{4}$$

Considering the definition of potential change $\psi(a, \theta, \phi)$ in (1), the above deflection changes can be further written as

$$\xi = \sum_{n,m,i,j} k_{5,m}^{n,ij}(a)\frac{\partial Y_n^m(\theta,\phi)}{\partial\theta} \cdot \frac{\nu_i n_j U dS}{a^3} \tag{5}$$

$$\eta = -\sum_{n,m,i,j} k_{5,m}^{n,ij}(a)\frac{\partial Y_n^m(\theta,\phi)}{\sin\theta\,\partial\phi} \cdot \frac{\nu_i n_j U dS}{a^3} \tag{6}$$

If we define Green's functions of the co-seismic deflection changes (take the vertical strike-slip component as example) as

$$\hat{\xi}^{12}(a,\theta) = -2\sum_{n=2}^{\infty} k_{5,2}^{n,12}(a)\frac{\partial P_n^2(\cos\theta)}{\partial\theta} \tag{7}$$

$$\hat{\eta}^{12}(a,\theta) = 2\sum_{n=2}^{\infty} 2k_{5,2}^{n,12}(a)\frac{P_n^2(\cos\theta)}{\sin\theta} \tag{8}$$

the corresponding change of deflection of the vertical become

$$\xi^{12}(a,\theta,\phi) = \hat{\xi}^{12}(a,\theta)\sin 2\phi \tag{9}$$

$$\eta^{12}(a,\theta,\phi) = \hat{\eta}^{12}(a,\theta)\cos 2\phi \tag{10}$$

The above Green's functions are useful to calculate co-seismic deflection of the vertical changes excited by four types of independent sources. In combination, these components allow calculation of a displacement field that is excited by an arbitrary seismic source.

3 The Green's Functions with a Gaussian Filter

The present theoretical expressions can be used to interpret the GRACE observed data. Due to the limited spatial resolution of the GRACE measurements, usually a Gaussian filter is used to smooth the GRACE data. To compare them with the observed co-seismic deformation, the modeled co-seismic deformations must be filtered in the same way. Usually, one first computes the co-seismic deformations according to a dislocation theory and a seismic slip model, and then applies a filter to the modeled results (e.g., Sun et al. 2009; Zhou et al. 2011a). In this computing scheme, all the dislocation Love numbers of $k_{k,m}^{n,ij}(a)$ are involved in the computation, where the harmonic degree n must be large enough to guarantee convergence; for a very shallow source, a truncation of the Love numbers $k_{5,m}^{n,ij}(a)$ goes to a large number N. For example, when the source depth $d = 20$ km, the truncation number is $N = 3,185$. Figure 1 shows the normalized dislocation Love numbers $k_{5,m}^{n,ij}(a)$ with truncation at $N = 3,185$. The Green's functions are calculated by summing up these dislocation Love numbers. It means that a large amount of numerical computation should be made. The problem is that the high frequency part of the dislocation solutions has no contribution after the filter is applied.

To reduce the unnecessary computation time, we may consider applying the Gaussian filter to the dislocation Love numbers, so that the Green's functions of co-seismic deflection change become

$$\xi_w^{ij}(a,\theta,\phi) = \sum_{n,m} k_{5,m}^{n,ij}(a) w_n \frac{\partial Y_n^m(\theta,\phi)}{\partial\theta} \tag{11}$$

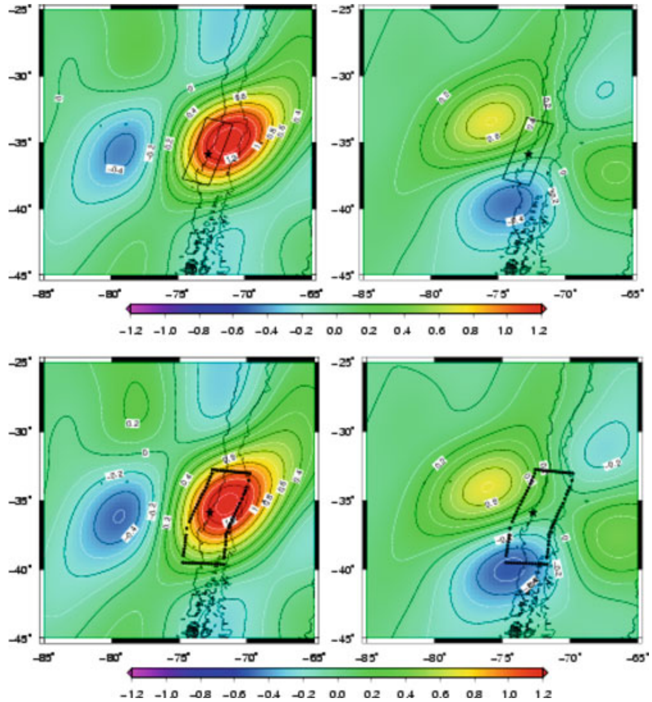

Fig. 1 Sea-water corrections to the change of deflection of the vertical (*left*: N–S; *right*: E–W) with 300 km Gaussian filter. The upper panel shows the result for the USGS (2010) slip model, while the lower panel gives the results for the Vigny et al. (2011) model. Unit: mas

$$\eta_w^{ij}(a,\theta,\phi) = -\sum_{n,m} \frac{k_{5,m}^{n,ij}(a)}{\sin\theta} w_n \frac{\partial Y_n^m(\theta,\phi)}{\partial\phi} \tag{12}$$

where w_n is a spectral form of the Gaussian filter (Wahr et al. 1998). The coefficients decrease quickly as harmonic degree n increases. When $n = 140$, w_n already drops to seven order of magnitude smaller. Due to the fast convergence behavior, the filtered dislocation Love number $\bar{k}_{5,m}^{n,ij}(a)$ drop to almost zero at $n = 140$. This property implies that we may only compute dislocation Love numbers for $n \leq 140$, no matter how deep the source depth is. Even for 1 km source depth, we need only consider the dislocation Love numbers for $n \leq 140$, instead of $n = 63{,}700$.

To verify the validity of the computing scheme, we compare the coseismic geoid changes caused by the 2010 Chile earthquake, calculated by: (a) using conventional Green's functions to integrate over the fault surface, and then filter the modeled geoid change with Gaussian filter ($r = 300$ km); (b) using the filtered Green's functions and then integration finally. The comparison shows that the geoid changes calculated by the two schemes are almost identical, with the maximum difference of about 0.1 mm, which is considered caused by the numerical error. It implies that the above computing scheme is valid and efficient.

It should be pointed out that the Gaussian filter concept is important not only for the deflection of the vertical but also for the changes of gravity and geoid height in order to reduce the computing time. It should also be mentioned that the discussions in the paper are valid only for satellite gravimetry. For terrestrial gravity/deflection measurements and comparisons, the filter is unnecessary.

4 Seawater Corrections to Modeled Co-seismic Deflection Changes

The above theory is valid for the solid earth, so that the surface uplift on earth surface is replaced with air. However, large earthquakes often occur in ocean areas, and the deformation in the ocean bottom is replaced by seawater, which causes additional potential and gravity changes.

We use here an approximate approach in computing the seawater effects. We should consider seawater change caused by the vertical displacement at the sea bottom, because the solid part of the Earth model has already been taken into account in the conventional dislocation theory. To compute the seawater contribution to co-seismic gravity change, we may consider the vertical displacement beneath the computing point as a Bouguer layer, so that the seawater correction can be simply estimated as

$$\delta g^{w.c.}(a,\theta,\phi) = -2\pi G \rho_w u_r(a,\theta,\phi) \tag{13}$$

where the super-script "$w.c.$" stands for seawater correction, G is the Newton's gravitational constant, $\rho_w = 1.03 g/cm^3$ is the seawater density, $u_r(a,\theta,\phi)$ is the co-seismic vertical displacement. To make the seawater correction to the geoid change, the seawater change cannot be treated as a Bouguer layer. In this case, the spatial distribution of the seawater change can be computed by performing numerical integration, i.e.,

$$\delta N^{w.c.}(a,\theta,\phi) = -\frac{G}{g}\int_S \frac{\rho_w u_r(a,\theta',\phi')}{l(\theta,\phi;\theta',\phi')} ds \tag{14}$$

where $l(\theta,\phi;\theta',\phi')$ is the distance between the computing point and displacement point, S stands for the ocean surface. Similarly the sea water corrections to the coseismic deflection change are

$$\delta\xi^{w.c.} = \frac{1}{a}\frac{\partial \delta N^{w.c.}(a,\theta,\phi)}{\partial\theta} \tag{15}$$

$$\delta\eta^{w.c.} = -\frac{1}{a\sin\theta}\frac{\partial \delta N^{w.c.}(a,\theta,\phi)}{\partial\phi} \tag{16}$$

We consider a computing area bounded by longitude from −63° to −85°, and latitude from −45° to −20°. Using the USGS (2010) and Vigny et al. (2011) fault slip models for the Chile earthquake (Mw8.8), we compute the seawater corrections to co-seismic deflection change using (15) and (16). Integration is limited in the ocean area. The computed seawater corrections with the 300 km Gaussian filter are plotted in Fig. 1. Figure 1 shows a large seawater effect to the deflection change, reaching −0.4 to +1.3 mas for the $\delta\xi^{w.c.}$ component, and −0.4 to +0.6 mas for the $\delta\eta^{w.c.}$ component, respectively. In addition, Fig. 1 shows that the seawater correction is large over the continent. The phenomenon is considered due to the seawater distribution near the coast, and the deflection change (derivative of the geoid) appears roughly around the edge of the seawater.

5 Co-seismic Deflection Changes by the 2010 Chile Earthquake

The 2010 February 27 Chile earthquake (*M*w8.8) ruptured the boundary between the Nazca and the South American Plates known as the Constitución–Concepción seismic gap (Madariaga et al. 2010). This was the second largest earthquake (after the 2011 Tohoku-Oki one) to occur since the 2004 Sumatra–Andaman earthquake, and has a good chance of showing coseismic change of deflection of the vertical detectable with GRACE.

We first process the GRACE data to obtain co-seismic deflection changes caused by the 2010 Chile earthquake. We use the GRACE Level2 data sets composed of Stokes' coefficients up to degree 60, released by the Center for Space Research, Univ. of Texas. To reduce the significant longitudinal "stripes", we apply the scheme with decorrelation filtering P3M6 (Swenson and Wahr 2006) and 300 km Gaussian smoothing. To extract the coseismic jumps, we first remove the seasonal and long term trend signals by least squares. Co-seismic geoid and deflection changes are plotted in the first panel in Figs. 2 and 3, respectively. The result shows that the coseismic geoid and change of deflection are clearly detectable by GRACE and displays as dominantly negative changes. However, the main blue-violet negative lobe in the E–W component is probably noisy in GRACE data due to the orbit and stripes.

We then compute the theoretical co-seismic deflection changes using the above computing scheme. To compare the modeled co-seismic deformation with the GRACE observed ones, the dislocation Love numbers are truncated at degree 60 in computing Green's functions, and the P3M6 and 300 km smoothing Gaussian filter are applied. The modeled geoid and deflection changes for the two slip models are basically the same in magnitude.

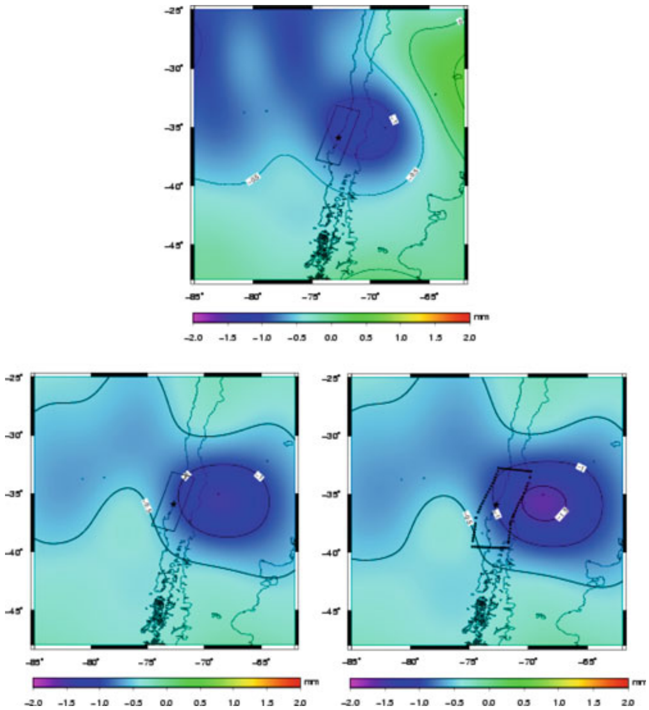

Fig. 2 Coseismic geoid changes measured by GRACE (*upper panel*) and modeled by USGS (2010) (*lower left*) and Vigny et al. (2011) (*lower right*) fault slip models. The P3M6 and 300 km Gaussian filter are applied. Unit: mas

We then add the sea water corrections to the theoretically computed the co-seismic deformations, to obtain the final co-seismic geoid and changes of deflection (Fig. 3). The modeled geoid changes for the two slip models are identical in both magnitude and distribution pattern. The N–S deflection changes for the two models are almost the same as the GRACE observed one in distribution pattern, but larger in magnitude and a difference in orientation with the GRACE one, which might be generated by the leakage of soil moisture signature. It is expected to be removed if the GLDAS model is introduced. Note that the N–S component of the deflection of vertical is intrinsically immune of longitudinal stripes, which is a great benefit to use deflection of vertical for various studies with GRACE. The E–W component shows big differences in the distribution pattern and the model predictions are smaller in magnitude. This difference might be caused by two reasons. One reason is that because the GRACE orbit flies in nearly the N–S direction, the E–W component of the observed deflection change contains larger error than that of the N–S component. Another reason is considered from the error of the fault slip model. It should be pointed out that even if the deflection change for the two models it is not very large, it becomes even more striking for larger earthquakes. A similar comparison for the 2011 Tohoku-Oki earthquake shows even larger difference in the E–W component of three slip models (Sun and Zhou 2012).

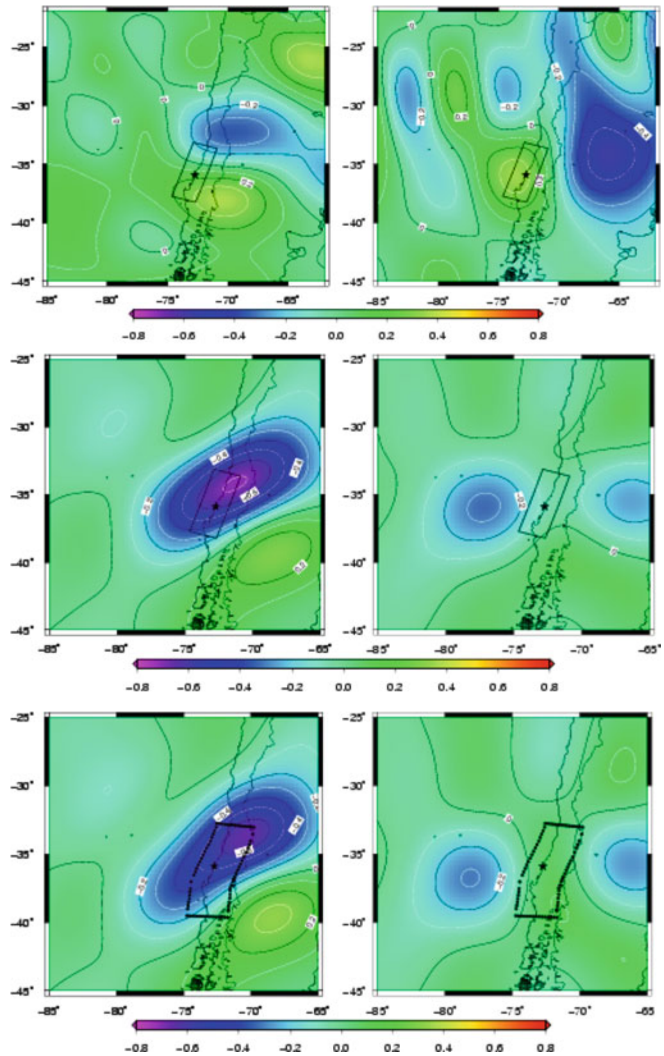

Fig. 3 Coseismic changes of deflection of the vertical (*left*: N–S; *right*: E–W) measured by GRACE and modeled by USGS (*middle panel*) and Vigny (*lower panel*) fault slip models. The P3M6 and 300 km Gaussian filter are applied. Unit: mas

This phenomenon indicates that the deflection change is sensitive to the fault slip model. It can be considered due to the fact that the deflection is a mathematical differential of geoid, and is naturally sensitive to high frequency part.

In summary, we presented a scheme to compute co-seismic deflection change of the vertical. As an application of the computing scheme, we considered the 2010 Chile earthquake using two fault slip models. The modeled co-seismic geoid and deflection changes indicate that the co-seismic geoid change is not sensitive to the fault slip models; the co-seismic deflection changes are sensitive to the fault slip models. These behaviors provide a new and useful approach to invert the seismic fault using GRACE-observed deflection changes as a constraint.

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