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Effects of Earth’s layered structure, gravity and curvature on coseismic deformation

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SUMMARY
The effects of Earth’s layered structure, gravity and curvature on coseismic deformation are systematically quantified for all fundamental point sources and some finite-fault sources, respectively. The point-source simulations show that the layering effect (about ≤25 per cent) is significantly higher than the gravity effect (about ≤11 per cent) and the curvature effect (about ≤5 per cent). A case study on the 2011 Mw 9.0 Tohoku earthquake is made to quantify the uncertainties of the dislocation models of large earthquakes, in which the three different effects are neglected. Finally, it is investigated how geodetic finite-fault slip inversions are affected by neglecting the layering effect.

Key words: Gravity anomalies and Earth structure; Seismicity and tectonics; Computational seismology.

1 INTRODUCTION
An earthquake is always accompanied with mass redistribution and may cause coseismic and post-seismic deformation, geoid and gravity changes at various scales, which can be accurately mapped using modern geodetic techniques such as global positioning system (GPS), gravity satellite or other geodetic observations. Typically, a dislocation theory is applied to interpret the geodetic observed data.

The dislocation theory was first introduced into seismology by Stekete (1958). Since then, the dislocation theory has been improved as the models representing the Earth medium improved. Okada (1985, 1992) summarized the previous works and compiled a list of analytical formulae for computing the coseismic deformation based on a homogeneous elastic half-space earth model, which are widely used currently. Sato (1971) and Sato & Mats’ura (1973) investigated deformations in a multilayered medium. Rundle (1982) developed the viscoelastic-gravitational dislocation model. Ma & Kusznir (1994) researched the effects of layering and gravity based on a 3-D subsurface fault displacement fields. Han & Wahr (1995) studied the viscoelastic relaxation of the stratified Earth. Piersanti et al. (1995, 1997) focused on the post-seismic relaxation of a spherical, incompressible, self-gravitating, stratified viscoelastic Earth by point dislocations and finite dislocations based on the normal model technique. Sabadini & Vermeersen (1997) showed, within the limitation of an incompressible viscoelastic model, the effects of density layering over global post-seismic deformation. Soldati et al. (1998) also studied the gravitational perturbation for a layered incompressible Earth based on the normal model technique. Nostro et al. (1999) discussed the coseismic and post-seismic response by comparing flat models with spherical ones, based on an incompressible, self-gravitating Maxwell body. They found the self-gravitation has a minor role with respect to the coseismic deformations while the effects increase for the post-seismic regime. Pollitz (1996) presented a method to illustrate the effects of Earth’s sphericity and layering on the calculated deformation field. Okubo (1993) presented a reciprocity theorem between the dislocations and the conventional external forces in a SNREI (spherically symmetric, non-rotating, elastic and isotropic) earth model. Sun & Okubo (1993, 1998) and Sun et al. (2009) introduced the dislocation Love numbers for calculating Green’s functions for coseismic deformation, geoid and gravity changes based on the SNREI earth model. By comparing a layered spherical earth model (1066A) with a homogeneous half-space, Sun & Okubo (2002) found that the layering and curvature effects on the coseismic surface deformation (vertical displacement) can reach together the order of 20 per cent. Savage (1998) made a detailed discussion about the edge dislocation field in a layered half-space in the form of Fourier integral. Cattin et al. (1999) also verified the layers effects using a 2-D finite element model based on a dip-slip dislocation. Wang et al. (2003) provided an efficient scheme to compute the coseismic deformation based on a multilayered elastic model. Wang (2005) and Wang et al. (2006) further extended this scheme to include the viscoelastic-gravitational effect and published their code PSGRN/PSCMP, which can be used to calculate Green’s functions for all fundamental point sources and any generalized finite-fault source. For a spherical, layered, incompressible viscoelastic Earth, Melini et al. (2008) made some new insights from the Post-Widder Laplace inversion formula to the problem of post-seismic relaxation. Fu et al. (2010) studied the curvature and radial heterogeneity effects in the cases of the 2008 Wenchuan earthquake and the 2004 Sumatra earthquake.

Because of the mathematical simplicity, the dislocation model based on a homogeneous half-space model (Okada 1985) is widely
used to compute the coseismic deformation or to invert geodetic data for the fault slip distribution. However, this simple dislocation model neglects the effects of the gravity, curvature and the layered structure of Earth. The uncertainties caused thereby need to be investigated. The results of Pollitz (1996) showed the effect of sphericity is generally less than 2 per cent within 100 km of the earthquake source at crustal depths. Also, the error will be up to 20 per cent if the layered structure was ignored. Sun & Okubo (2002) found that both the layering and curvature effects on the coseismic surface deformation (displacement) are very large. The layered structure effect reaches a discrepancy of more than 25 per cent. Fu et al. (2010) studied the total effects of curvature and radial heterogeneity in the cases of the 2008 Wenchuan earthquake and the 2004 Sumatra earthquake. Wang et al. (2010) found that the total effects of the curvature and layer structure are great, without separating the two effects. There also been other sporadic discussions about the limitation of the Okada dislocation model due to neglecting these effects (Li et al. 2005, Yuan et al. 2007), but there is a lack of a systematical investigation of them, and some issues discussed in the previous studies are still open.

The main goal of this paper is to systematically quantify the uncertainties of the Okada dislocation model due to neglecting the effects of the layered structure, gravity and curvature of the Earth. For this purpose, the surface displacements caused by some independent point dislocations are calculated and compared for different earth models, in which the three effects can be included separately and jointly. Then, a case study is made on the 2011 Tohoku-Oki earthquake (Ms 9.0) using a finite-fault slip distribution to estimate the uncertainties caused by the three different effects jointly. Finally, it is investigated how geodetic finite-fault slip inversions are affected by neglecting the layering effect.

2 THE EFFECT OF EARTH’S LAYERED STRUCTURE ON COSEISMIC DEFORMATION

To estimate the layering effect, we compare the surface displacements caused by point dislocation sources in a homogeneous and a layered elastic half-space. Three independent point sources, i.e., strike-slip, dip-slip and compensated linear vertical dipole (clvd), are considered, respectively, all located uniformly at the depth of 20 km. The resulting 3-D coseismic displacement ($U_z$, $U_\lambda$, and $U_\theta$) are computed using the Okada (1985) formulae for the homogeneous model and the code EDGRN/EDCMP for the layered model. Spada & Boschi (2006) pointed out that a uniformly layered structure with ~40 layers approximates the results obtained using a layered PREM discretization to within 1 per cent. In our work, two layered structures are considered, which are adopted from the seismic reference models PREM (Dziewonski & Anderson 1981) and AK135 (Kennett et al. 1995), respectively. We consider the discrete layers which is different with that of Pollitz (1996). Note that PREM has a top water layer of 3 km thickness (ocean). In this study, this water layer is replaced by solid with the same parameters of the upper crust beneath the ocean bottom. In each case, the homogeneous model takes the same parameters of the top layer of the corresponding layered model. The comparison between the results of the homogeneous and layered models is shown in Fig. 1.

For the PREM model, the layering effects for all three displacement components and for all fundamental point sources are between 10 and 20 per cent of the peak displacement amplitude. Relatively, the vertical displacement of a clvd source is more affected by the layered structure than that of the strike-slip and dip-slip sources. Furthermore, the layering effect can change the sign of displacement ($U_z$, $U_\lambda$, and $U_\theta$) at epicentral distances $\geq 30$ km. These results are consistent with those obtained by Sun & Okubo (2002) who used the spherical geometry instead of the half-space. For the AK135 model, Montagner & Kennett (1995) introduced a density and Q model to the velocity distribution from the travel time to fit the observations of free oscillation frequencies, which makes big difference with the PREM model. The effects are larger than 20 per cent in most cases and the maximum reaches about 50 per cent, indicating that the differences between different seismic reference models are significant, too.

To study how the layering effect depends on the source depth, we also calculate the surface displacements for the sources at the depth of 100 km, but only for the PREM model. The results are shown in Fig. 2. The coseismic deformation reveals clearly that the layering effect increases with the source depth. The maximum of the relative layering effect is about 25 per cent for the vertical displacement caused by a clvd source at 100 km depth.

Melini et al. (2008) investigated the layer effect in the post-seismic relaxation, as a function of number of stratification layers, comparing with PREM. It is noted that the layer effect in Melini et al. (2008) means the effect of layer numbers on seismic deformation; while the layer effect in the current study implies the layer structure of the Earth on seismic deformation with respect to that of a homogeneous Earth. Melini et al. (2008) found that the convergence of some layered models to the discretized PREM for a fixed source–observer distance is a function of time. On the other hand, they compared the time-dependent displacement and incremental gravitational potential obtained with different $N$ values with results obtained with the reference model, and they found that different layer numbers are needed for different seismic models to reproduce well (to reach convergence) the PREM results, both in the coseismic and post-seismic limit.

3 THE EFFECT OF EARTH’S GRAVITY ON COSEISMIC DEFORMATION

In principle, coseismic deformation of large earthquakes can also be affected by the gravity field. After the gravity effect was first investigated by Rundle (1980), it was further studied by some researchers (Rundle 1982, Pollitz 1997; Wang 2005). Rundle (1982) claimed that the self-gravitating effect can be neglected. However, Wang’s (2005) results indicate that the gravity effect on the coseismic deformation and post-seismic is different. Such as the 1960 $M_w$ 9.5 Chilean earthquake, the gravity effect is 4 per cent for coseismic deformation, but for a long timescale, it can reach 20 per cent. Generally, the gravity effect is of second order and can negligible in computing coseismic deformation. Here we compare two classes of dislocation models based on the spherical earth model PREM with and without the gravity effect. To switch off the gravity effect, we set the gravitational constant to a vanishing small value when calculating the dislocation Love numbers. Three surface displacement components ($U_z$, $U_\lambda$, and $U_\theta$) in the spherical coordinate system are calculated for four independent dislocation sources (strike-slip, dip-slip, horizontal and vertical tensile) located at the depth of 100 km, respectively. Fig. 3 shows the differences between the displacement components with and without the gravity. The gravity effect for the horizontal tensile source is very large, reaches about 11 per cent, but smaller other sources, no more than 1 per cent. We also investigated the gravity effect for the source depth at 20 km (not show here). The
Figure 1. Comparison between the surface displacements caused by point dislocation sources in the homogeneous (solid lines) and layered (dashed lines) elastic half-spaces. The left-hand column (a, b, c) are results based on the elastic parameters adopted from the PREM model, and the right-hand column (d, e, f) based on the AK135 model. From top to bottom, the displacements are caused by the strike-slip (a, d), dip-slip (b, e) and clvd (c, f) sources, respectively, all of which have the unit seismic moment. The source depth is 20 km. The displacement unit is metre.
effect on horizontal tensile is less than 2.5 percent. For the other sources, it is less than 0.2 percent. It means that the gravity effects dependent on the source types. Results also show that the gravity effect is relative small for sallow source, but larger for deeper source. This fact confirms the conclusion of Soldati et al. (1998), that is, the magnitude of the coseismic gravitational perturbation is larger in the deep source. They performed a systematic study of space and time evolution of gravity changes associated with a wide selection of seismic sources investigating the effects of several different mantle viscosity profiles. Their results show that the gravitational
Figure 3. Relative differences between surface displacements with and without the gravity effect for four independent point dislocation sources at the depth of 100 km. The subfigures (a, b, c, d) stand for the results of strike-slip, dip-slip, horizontal tensile and vertical tensile, respectively. The red, blue and green lines are the displacement components $U_r$, $U_\theta$ and $U_\lambda$, respectively.

4 THE EFFECT OF EARTH'S CURVATURE ON COSEISMIC DEFORMATION

To investigate the curvature effect, we compare surface displacements caused by dislocation sources in two homogeneous elastic spheres. One has the same radius as the Earth and the other has the radius 10 times larger, both based on a compressible model. For source depths less than 100 km, the larger sphere is nearly equivalent with a half-space. Again, four independent point sources, that is, strike-slip, dip-slip, horizontal tensile and vertical tensile (Sun et al. 2009), are considered for this investigation, which are located at depth of 20 and 100 km, respectively.

Fig. 4 shows a comparison between the displacements caused by point sources at the depth of 100 km in the two spheres. The differences are invisible. To give a quantitative estimation, the relative curvature effects are plotted in Fig. 5. The results show that the curvature effect is small, coincides with the conclusion of Pollitz (1996). For the shallow source at depth of 20 km, the curvature effect is below 1 per cent (not shown here). For sources at the depth of 100 km, the maximum curvature effect can reach about 4.5 per cent. In general, the curvature effect increases with the source depth.

The curvature effect was also investigated by other scientists, for example, Nostro et al. (1999), who performed exhaustive study of coseismic and post-seismic surface deformations induced by shear dislocations using flat and spherical earth models. The differences between predictions based on flat and spherical models are due both to their global geometry and the effect of the gravity forces. Self-gravitation has a minor role with respect to that of sphericity for surface coseismic deformations, while in the post-seismic regime its effects increase considerably. These rates obtained in case of the 1960 Chilean earthquake are found to be also sensitive to the rheological properties of the mantle beneath the asthenosphere.

5 CASE STUDY OF 2011 Mw 9.0 TOHOKU EARTHQUAKE

The 2011 Mw 9.0 Tohoku earthquake occurred near the east coast of Honshu in Japan on 2011 March 11, with the hypocentre located at (38.322° N, 142.369° E) at the depth of 24.4 km. The ruptured area extended about 400 km long and 200 km wide on the subduction fault. It is the most devastating earthquake in the modern seismic record of Japan, causing a huge tsunami, destructive fires and destruction of nuclear power facilities. Here we are interested in the collective effect of Earth’s layered structure, gravity and curvature on the coseismic deformation on this earthquake.

The finite-fault model (Hayes 2011) provided by the United State Geological Survey (USGS) is used to compute the coseismic deformation. The coseismic deformation of a very large area is computed using a homogeneous elastic half-space without the gravity and a layered spherical elastic earth model with the gravity effect, respectively. The differences between these two models represent the collective effect of Earth’s layered structure, gravity and curvature. We calculate the near-field coseismic gravity change of this earthquake with different models. The results presented in Fig. 6 indicate the effects of layer structure; self-gravity and curvature are...
Figure 4. Comparison between surface displacements caused by point dislocation sources of magnitude $M_w 9.0$ in two homogenous elastic spheres (the solid line for the same radius as the Earth and the dot–dashed line for the 10 times larger radius). The subfigures (a, b, c, d) stand for the result of strike-slip, dip-slip, horizontal tensile and vertical tensile sources, respectively. $X$-axis is the logarithm of the epicentre distance.

Figure 5. Relative curvature effects on surface displacements caused by point sources (in percentage). The subfigures (a, b, c, d) stand for the results of strike-slip, dip-slip, horizontal tensile and vertical tensile sources, respectively. $X$-axis is the epicentre distance. The red, blue and green lines are the curvature effects of displacement component $U_r$, $U_\theta$ and $U_\lambda$, respectively.
obvious. Different with the theoretical study by Sun & Okubo (2002) and Pollitz (1996), the current investigation is based on a realistic earthquake and is an integrated and comprehensive result. We can see the total effect is 23 per cent on gravity change.

The results are shown in Fig. 7 for the far-field surface displacement. It can be seen that in the present case, the simplified dislocation model can overestimate the far-field displacement by factor of up to 2 and 5 for the horizontal and vertical components, respectively. Fig. 7(a) show that the maximum horizontal displacement is about 4.5 cm for Model 1 and 3.0 cm for Model 2. In Fig. 7(b), the maximum vertical displacement is 5.0 cm for Model 1 and 1.1 cm for Model 2. The results based on Model 2 are more consistent with the results observed by Wang et al. (2011). The results computed based on the layered spherical model with self-gravity are consistent with the GPS results. Based on the results presented in the previous sections, the overestimate is dominantly caused by neglecting the layering effect. In the following section, we will present the layering effect on the near-field displacement and discuss their impact for the geodetic fault-slip inversion.

6 IMPACT OF THE LAYERING EFFECT ON THE GEODEUTIC FAULT-SLIP INVERSION

So far, geodetic fault-slip inversions are typically performed by using Green’s functions of a homogeneous elastic half-space because of their analytical closed form (Okada 1985). In most cases, the observed surface deformation data can be reproduced satisfactorily by the derived fault-slip distribution. The artefact caused by neglecting the effect of Earth’s layered structure is often hidden within the ambiguity of the inversion solutions and is therefore less noticed. To quantify this artefact, we invert the GPS data for the
fault slip distribution of the 2011 $M_w$ 9.0 Tohoku earthquake based on a homogenous and a layered Earth’s structure, respectively. The fault inversion work has been done by many scientists (e.g. Iinuma et al. 2011; Lay et al. 2011; Pollitz et al. 2011). Such as, Pollitz et al. (2011) inverted the slip model using on-land GPS and offshore GPS data based on spherical model. He found the maximum slip is 33 m. In this study, the layered structure effect is studied based on the on-land GPS data only.

The complete GPS data set from the GeoNet covering whole Japan (Fig. 8) is used for this analysis. A rectangular fault is selected for this earthquake and has the size of 600 km long and 240 km wide. The fault strike is 193° along the trench and the dip angle is 14°, adopted from the NEIC W-phase solution. We use preliminary GPS displacement data (version 0.3) for the 2011 March 11, earthquake provided by the ARIA team at JPL and Caltech (The Advanced Rapid Imaging and Analysis 2011). The layered structure is adopted from the seismic reference model PREM, and the homogeneous structure takes the same parameters of the upper crust of PREM. The inversions are carried out using the same code based on the constrained least-squares method. To minimize the ambiguity of the results, a strong smoothing constraint is used uniformly. The derived slip distributions based on the two structure models are shown in Figs 9(a) and (b), respectively, and their difference is shown in Fig. 9(c). It can be observed that the layering effect can modify the inferred slip distribution significantly. In particular, the homogenous structure leads to a shallower and more compact slip area with a smaller moment magnitude ($M_w$ 8.8) than the layered structure ($M_w$ 9.0).

7 DISCUSSION AND CONCLUSIONS

The effects of Earth’s layered structure, gravity, and curvature on dislocation models are analysed separately. The results are summarized in Table 1. In comparison, the layering effect dominates over the other two. The Earth stratification plays a more important role, coincides with Pollitz (1996), Nostro et al. (1999), Sun & Okubo (2002). With the rapid technical development in the space geodesy, coseismic surface displacement can be measured nowadays with mm accuracy at epicentral distances of up to 5000 km (Petrov et al. 2009). For large earthquakes, all the three effects can be observed. If they are neglected, as done in most current geodetic modelling, artefacts in the earthquake source estimations may be significant.

Although the analytical half-space dislocation model is widely used, its limitation for analysing geodetic observations for large earthquakes needs to be noticed. In fact, there have been several open access codes based on layered half-space models, such as EDGRN/EDCMP (Wang et al. 2003) or PSGRN/PSCMP (Wang et al. 2006), which can be used to generate Green’s functions very fast and with sufficient numerical accuracy. In view of the Earth geophysical characteristics, our research has been carried on using different models, which are based on half-space and SNREI, compressible earth model. It shows that the effects of layer structure, spherical geometry and gravity are significative to model large-scale
deformation. In this case, the methods by Okubo (1991, 1992), Sun et al. (2009), Pollitz (1996, 1997), Wang (1999), etc. are useful.

Note that the inversion study in Section 6 is just to investigate the effect of different earth models and theoretical frame, not for a real fault inversion. Indeed, the case study is not particularly innovative since it presents an inversion of static GPS offsets focusing on a layered direct model. Many previous works introduced this complexity when inverting for the source seismic moment release (e.g. Chlieh et al. 2007; Hoechner et al. 2008). Especially, for an event such the great earthquake, inverting the source exploiting only GPS data, is not sounding. For a more reasonable inversion, more data sources are necessary, based on a reasonable dislocation theory and media model.

Finally, another important effect must be mentioned although it is not discussed in this paper since it has been specially discussed by several papers. That is, the ocean response to coseismic ocean bottom deformation should be carefully considered in computing coseismic deformations or fault inversions (Melini & Piersanti 2006; Linage et al. 2009; Heki & Matsuo 2010; Melini et al. 2010; Broerse et al. 2011; Cambiotti et al. 2011; Sun & Zhou 2012). The dislocation theories above are valid for a solid elastic Earth, and the corresponding computing program assumed dry Earth, so that the surface subsidence on the Earth surface is replaced with air. However, in practice, a large earthquake often occurs in an ocean or subduction area, as was true of the 2004 Sumatra earthquake ($M_\text{w}$ 9.3) and the 2011 Tohoku-Oki earthquake ($M_\text{w}$ 9.0). In this case, the deformation that occurred in the ocean bottom is replaced by seawater, and the seawater change caused by the sea bottom displacement causes additional potential and gravity changes. This seawater effect is essential and must be dealt with specially, so that the modelled coseismic deformation can be reasonably compared with GRACE data, since the seismic gravitational signal is dominated by the seawater correction that completely obscure the pure dislocation contribution. There are several methods to deal with the seawater correction.

The most simplified computing method was given by Heki & Matsuo (2010) who assumed a density contrast as the vertical seawater correction.

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