Topography effect on the seismogenic deformation of the earth’s surface

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Abstract. A comparison of the displacements of the earth’s surface after an earthquake was made, calculating with the analytical expressions coming from an infinite flat slab approximation and compared with these numerically considering the topography of the Earth. One conclusion of this work is that the flat Earth approximation, has a greater error in the lateral displacement than in the vertical one. It can also be noted that the error in the magnitude of the displacement is less or of the order of ten percent of the maximum displacement of the earth’s surface.

1. Introduction
In some fields of Geophysics it is necessary to know the deformation of the surface of the Earth due to the slip in geological faults. It’s known the analytical solutions [1, 2], but where the Earth is considered an infinite flat slab. Currently the effect of introducing real topography approximations has been considered in the literature. General solutions to this problem are numerical. There are examples of these studies [3, 4, 5]. In this contribution, we develop a numerical method based on the boundary element method, which is applied to a homogenous, isotropic Earth and with the real topography of its surface.

2. Model for the Earth
The Earth is considered to be a linear, homogeneous, isotropic elastic solid of ellipsoidal geometry described by WGS 84. The geological fault is represented by a cutting surface, $\Sigma$, where the abrupt dislocation of one face with respect to the other, tangent to the fault plane, gives rise to the earthquake and the deformation of the external terrestrial surface, $S$.

From the equations that describe this type of solid we can deduce the displacement, $u$, of any point $x$ on the external surface $S$, only knowing the displacements in the points $y$ of the entire surface

$$u(x) = \int_{\Sigma} \frac{a}{r^2} \left\{ -3 \hat{r} \cdot (\hat{r} \cdot U)(\hat{r} \cdot d\Sigma) - b \left[ U \cdot (\hat{r} \cdot d\Sigma) + (\hat{r} \cdot U) \cdot d\Sigma \right] \right\}$$

$$- \mathcal{P} \int_{S} \frac{a}{r^2} \left\{ \hat{r} \left[ -3 (\hat{r} \cdot u)(\hat{r} \cdot dS) + b u \cdot dS \right] - b \left[ u \cdot (\hat{r} \cdot dS) + (\hat{r} \cdot u) \cdot dS \right] \right\}$$

(1)
where \( r = y - x = r \hat{r} \), \( a = 1 / [4\pi(1 - \nu)] \), \( b = 1 - 2\nu \) and \( \nu \) is the Poisson’s coefficient.

This integral equation is solved self-consistently using an irregular triangular network (TIN) to represent the elements of the earth’s surface. For the creation of this TIN, we used the real topography of the Earth provided by Gebco [10].

The direction and magnitude of the dislocations in the fault, \( U \), are considered as input parameters and are obtained from slip models for the fault. There is usually more than one slip model for each earthquake, however, here we use a model for each of the cases with the propose of revealing the effect of the topography and without questioning the accuracy of the slip model.

For each of the earthquakes above considered we choose a model of slip among those published in the literature. We do not take into account the level of accuracy of those models, since at present, we just want to compare the effect of the real topography of the Earth in comparison of the flatness of the Earth assumption.

3. Results

The infinite flat slab model and the real topography of the Earth are compared, for four earthquakes of great magnitude. The information that characterizes these earthquakes is shown in Table 1, where the maximum values of the difference between the two methods are also shown, compared to the absolute value. These comparative values are made for the full displacement vector \( u \), to its vertical component, \( u_z \), and to its lateral component \( u_L \).

| Year | 2008 | 2010 | 2011 | 2014 |
|------|------|------|------|------|
| Location | Wenchuan China | Maule Chile | Tohoku-Oki Japan | Iquique Chile |
| Moment magnitude | 7.9 Mw | 8.8 Mw | 9.1 Mw | 8.1 Mw |
| Slip model | Fielding 2013 [6] | Delouis 2010 [7] | Hayes 2011 [8] | Wei 2014 [9] |
| \( \|\Delta u\|_{\text{max}} / \|u\|_{\text{max}} \) | 0.58/5.07 | 0.72/6.69 | 1.68/21.6 | 0.13/1.57 |
| \( |\Delta u_z|_{\text{max}} / |u_z|_{\text{max}} \) | 0.22/4.73 | 0.17/5.34 | 1.15/9.73 | 0.097/0.87 |
| \( |\Delta u_L|_{\text{max}} / |u_L|_{\text{max}} \) | 0.58/3.05 | 0.71/4.90 | 1.67/21.1 | 0.12/1.49 |

From the values in Table 1 it can be seen that the Wenchuan and Maule earthquakes have greater displacement magnitudes in vertical direction than in lateral direction, however, the relative difference between the methods is greater in the lateral direction than in the vertical direction.

For the earthquakes of Tohoku and Iquique it is just the opposite, they have magnitudes of displacement greater in lateral direction more that in vertical direction, and the relative difference between the methods, is greater in vertical direction that in lateral direction.

Figures 1 to 4 correspond to a color maps for each of these earthquakes, which represents the magnitude of the difference between the displacement considering the real topography of the Earth and the displacement considering an infinite flat slab. Additionally, height level curves (blue lines) are included that allow visualization of the areas with height gradients (curves closer to each other). The green lines represent the level curves of the absolute displacement of the
earth’s surface allowing visualizing that the biggest differences are not on the regions with the greatest displacements.

**Figure 1.** Differences in displacements for earthquake 2008 Mw 7.9 Wenchuan (China). The blue lines correspond to height level curves. The green lines correspond to the displacement level curves.

**Figure 2.** Differences in displacements for earthquake 2010 Mw 8.8 Maule (Chile). The blue lines correspond to height level curves. The green lines correspond to the displacement level curves.

**Figure 3.** Differences in displacements for earthquake 2011 Mw 9.1 Tohoku-Oki (Japan). The blue lines correspond to height level curves. The green lines correspond to the displacement level curves.

**Figure 4.** Differences in displacements for earthquake 2014 Mw 8.1 Iquique (Chile). The blue lines correspond to height level curves. The green lines correspond to the displacement level curves.

4. Conclusions

(i) This boundary element method allows to calculate of the deformation on the external surface regardless of how irregular it is, using known dislocations in a plane of failure. It’s also allows the calculations regardless of how irregular it is the plane of failure.

(ii) The difference in the displacements is mostly lateral rather than vertical.

(iii) The magnitude of the difference in the displacements of these methods is less or of the order of 10% of the maximum displacement over the entire surface.

(iv) The regions where there are greater differences between the methods are also regions that show high gradients of height in their topography.
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