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Influence of fault asymmetric dislocation on the gravity changes

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Abstract: A fault is a planar fracture or discontinuity in a volume of rock, across which there has been significant displacement along the fractures as a result of earth movement. Large faults within the Earth's crust result from the action of plate tectonic forces, with the largest forming the boundaries between the plates, energy release associated with rapid movement on active faults is the cause of most earthquakes. The relationship between unevenness dislocation and gravity changes was studied on the theoretical thought of differential fault. Simulated observation values were adopted to deduce the gravity changes with the model of asymmetric fault and the model of Okada, respectively. The characteristic of unevenness fault momentum distribution is from two end points to middle by 0 according to a certain continuous functional increase. However, the fault momentum distribution in the fault length range is a constant when the Okada model is adopted. Numerical simulation experiments for the activities of the strike-slip fault, dip-slip fault and extension fault were carried out, respectively, to find that both the gravity contours and the gravity variation values are consistent when either of the two models is adopted. The apparent difference lies in that the values at the end points are 17.97% for the strike-slip fault, 25.58% for the dip-slip fault, and 24.73% for the extension fault.

Key words: fault; asymmetric; gravity changes; numerical simulation

1 Introduction

One of the greatest discovery of seismology in 20th century is that the earthquake happened in the fault[1]. Steketee[2] is the earliest one to introduce the dislocation theory into the geodetic deformation field. He supposed there was a dislocation discontinuity (fault) in the evenly Earth medium, and deduced Green's function of strike-slip faults' displacement. Iwasaki and Sato[3] studied strain field in a semi-infinite medium due to an inclined rectangular fault. Okubo[4] did a research of potential and gravity changes raised by point dislocation. Okada and Ben-Menahem A[5,6] supposed that the Earth model was a homogeneous elastic half-space sphere, and deduced the analytic formulas between the displacement field and strain field in Earth's interior caused by point dislocation and rectangular dislocation under the situation of strike-slip, dip-slip, tensile and expansion. These formulas are the classic expression of the theory about the semi-infinite space Earth model. Considering earth viscosity is another progress to perfect the dislocation theory. Sato[7] studied the viscoelastic deformation of the rectangular thrust fault in layered Earth. Pollitz[8] solved the viscoelastic weightless Earth model's problems between displacement and strain fields caused by the dislocation in epicenter area. Considering the curvature and layered structure of the Earth, Sun and Okubo[9,10], with the help of the more realistic Earth model and the SNREI

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Earth model, evolved the new the potential and gravity change's dislocation theory. There are many successful research results of the dislocation theory model all over the world. Heki et al[11] found that the coseismal deformation conformed to the GPS observations. By calculating the deformation of the seismic fault sliding of Umatra-Andauan, Banerjee[12] achieved that the largest sliding displacement was 15 meter.

Usually, it is reasonable to explain the fault movement by the rectangular dislocation model. However, there are varieties of faults in reality and there are fixed endpoints in all faults. The unevenness of faults is more prevalent. Surface gravity and deformation effects caused by all kinds of fault movement have attracted a great attention in the past few years. Sun[13] calculated the terrestrial gravity field changes by the asymptotic distribution model, which are caused by the coseismic dislocation deformation. Fu and Sun[14] studied the coseismic dislocation deformation on the basis of the spatial distribution inhomogeneity, but he did not suggest any models. Zhang et al[15] established a distribution function model along the strike-slip direction and the direction of dip-slip sliding displacement according to the dislocation single pileup group and the double pileup group theory, and studied the displacement caused by the uneven model.

In the present work, gravity changes on the earth surface caused by uneven fault dislocation were studied. The variations caused by the Okada model and the uneven model, respectively, were compared. A theory of differential fault was applied to calculate the gravity changes by the uneven fault.

2 Fault uneven distribution function

Suppose a plane consists of x and y. X-axis is parallel to the fault trend and y-axis perpendicular to it as shown in figure 1. Z-axis is perpendicular down to the plane. The fault length is $2L$, the width is W, the bottom depth is d, and the angle of dip is δ. The pileup group is calculated between A and B. The group is adjusted to stress equilibrium by discrete dislocation, at which an equation can be written as

$$\frac{\mu b^2}{2\pi(1-\nu)}\sum_{j=i}\frac{1}{x_{(j)}-x_{(i)}}+\tau b=0 \tag{1}$$

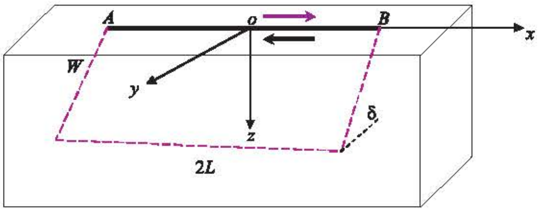


Figure 1 Rectangle dislocation model

To a continuous distributed dislocation group, a density function of continuous dislocation distribution is introduced as

$$D(x)=\frac{1}{b}\frac{\mathrm{d}b}{\mathrm{d}x_1} \tag{2}$$

In the equations (1) and (2), b is Burgers vector, μ and ν are Lame constants of medium, and τ is the average shear stress in the medium. Thus, the continuous pileup group equilibrium equation can be achieved as

$$\tau b=\frac{\mu b^2}{2\pi(1-\nu)}\int_{-L}^{L}\frac{D(x')\mathrm{d}x'}{x'-x} \tag{3}$$

Since x is contained in the interval $[-L,L]$, formula (3) is Cauchy singular integral equation. In order to solve the equation, Hilbert transform is used. A function $f(y)$'s Hilbert transform is defined as

$$H_x[f(y)]=\frac{1}{\pi}\int_{-1}^{1}\frac{f(y)\mathrm{d}y}{y-x} \tag{4}$$

The function of y can be changed into the function of x. Chebyshev polynomial's Hilbert transform can be realized by the first class and the second class of (5).

$$\begin{cases}T_n(\cos\theta)=\cos n\theta\\ U_n(\cos\theta)=\sin(n+1)\theta/\sin\theta\end{cases} \tag{5}$$

The varied result is written as (6):

$$H_x\left[\frac{T_n(y)}{(1-y^2)^{\frac{1}{2}}}\right]=U_{n-1}(x) \tag{6}$$

A variable η as shown in (7) is introduced into formula (3).

$$\eta = \frac{x}{L} \qquad -1 < \eta < 1 \tag{7}$$

Then a function $f(\eta) = D(\eta L) = D(x)$ is defined. Thus formula (8) can be obtained:

$$\frac{2(1-\nu)\tau}{\mu b} = \frac{1}{\pi}\int_{-1}^{1}\frac{f(\eta')}{\eta' - \eta}\mathrm{d}\eta' \tag{8}$$

The right hand of the formula (8) is Hilbert transform of function $f(\eta)$, and the left hand is $\frac{2(1-\nu)\tau}{\mu b} = \frac{2(1-\nu)\tau}{\mu b}U_0$, in which $U_0 = 1$. Together with formula (6), formula (9) is achieved as follow:

$$H_\eta\left[\frac{T_1(\eta')}{(1-\eta'^2)^{\frac{1}{2}}}\right] = U_0(\eta) \tag{9}$$

Formula (10) is further concluded by comparing formulas (9) and (8):

$$f(\eta) = \frac{2(1-\nu)\tau}{\mu b}\frac{T_1(\eta)}{(1-\eta^2)^{\frac{1}{2}}} \tag{10}$$

Considering $T_1(\eta) = \eta$, bring $\eta = x/L$ back to formula (10) to obtain formula (11):

$$f(\eta) = D(x) = \frac{2(1-\nu)\tau}{\mu b}\frac{x}{(L^2 - x^2)^{\frac{1}{2}}} \tag{11}$$

This formula is a dislocation density distribution function on the fault plane in elastic crust. The relationship between the displacement field and the dislocation density distribution can be expressed by formula (12).

$$-\mathrm{d}u = bD(x)\mathrm{d}x \tag{12}$$

After integration of both sides of formula (12), formula (13) can be got:

$$u = -\int\frac{2(1-\nu)\tau}{\mu}\frac{x}{(L^2 - x^2)^{\frac{1}{2}}}\mathrm{d}x$$

$$= \frac{(1-\nu)\tau}{\mu}(L^2 - x^2)^{\frac{1}{2}} \tag{13}$$

Formula (13) shows that on the two end points of the fault $x = -L$, $x = L$, the displacement on the fault plane is 0, and in the middle of the fault plane, the displacement on the location $x = 0$ is the maximum. And the value of the displacement field under evenly stress of the fault is proportional to the value of the shear stress and the length of fault. In order to compare it with Okada rectangular dislocation model, formula (13) is conducted with the Taylor series expansion to achieve formula (14).

$$u = \frac{L(1-\nu)\tau}{\mu}\left[1 - \frac{(x/L)^2}{2!} - \frac{3(x/L)^4}{4!} - \frac{45(x/L)^6}{6!} + \cdots\right] \tag{14}$$

Formula (14) is an expansion and perfection of the Okada rectangular dislocation model. When it is 0 order, it is similar to the Okada model.

3 Calculation of the gravity changes by the two models

3.1 Selection of the design parameters

A single fault was taken for study. The fault endpoint coordinates are ($X_0 = 0, Y_0 = 0$), the fault length $2L = 5$ km, the fault width $W = 5$ km, the vertical distance from the surface to the top of the fault $d = 1$ km, the azimuth of the fault $a = 0$, and the angel of tip $\delta = 90°$. For the pure strike-slip fault movement parameters, $U_1 = 5$ m, $U_2 = 0$ m, and $U_3 = 0$ m. For the pure dip-slip fault movement parameters $U_1 = 0$ m, $U_2 = 5$ m, and $U_3 = 0$ m. For the pure extensional fault movement parameters $U_1 = 0$ m, $U_2 = 0$ m, and $U_3 = 5$ m. For the above three kinds of faults, the medium density is $\rho = 2.67 \mathrm{g/cm^3}$, media Poisson's ratio is $\mu = 0.25$, and free-air gravity gradient is $\beta = 0.309\times10^{-5}\mathrm{ms^{-2}}$. There are 441 calculation points, the points' range lies in between (-10 km $\leqslant X \leqslant 10$ km, -10 km $\leqslant Y \leqslant 10$ km), and the interval is 1 km×1 km. Now, the Okada model can be employed to study the numerical simulation of the strike-slip faults, dip-slip faults, tensional faults etc. and the surface gravity changes caused by dislocation.

The black thick line in figure 2 stands for the fault (Hereinafter the same). A coordinate system is built with the middle point of the fault as the center. The abscissa is defined as X axis, the right direction of which signifies positive. The ordinate is defined as Y axis, the upward direction is positive. Small "crosses" indicate the distribution of the observation points.

According to formula (13), the fault dislocation was shown in figure 3. The red line stands for the uneven fault and the black line for the even fault. Clearly, much difference appears in the end points, whereas in the middle point the displacement coincides. As for the uneven fault, the displacement changes continuously according to formula (13). But for the even fault, it is a constant.

3.2 Comparison of the gravity changes by the two models

The distribution of ground gravity changes caused by strike-slip motion field has the property of negative symmetrical in four quadrants, in the first and the three quadrant gravity changes is positive, but in the second and the four quadrants the gravity changes is negative. The gravity change is positive in the direction of fault movement, but it is negative in the opposite direction.

The distribution of ground gravity changes caused by dip-slip motion field has the property of negative symmetrical as the fault is the axis line. In the $Y[-10,0]$ region, the gravity changes caused by the reverse thrust fault is negative, but in the $Y[0,10]$ region, the gravity changes is positive.

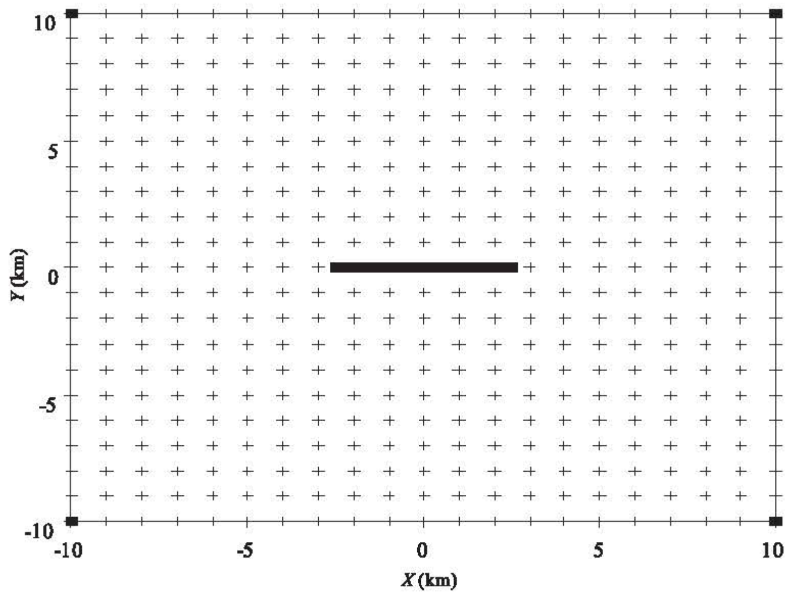


Figure 2 Distribution of fault and observation points

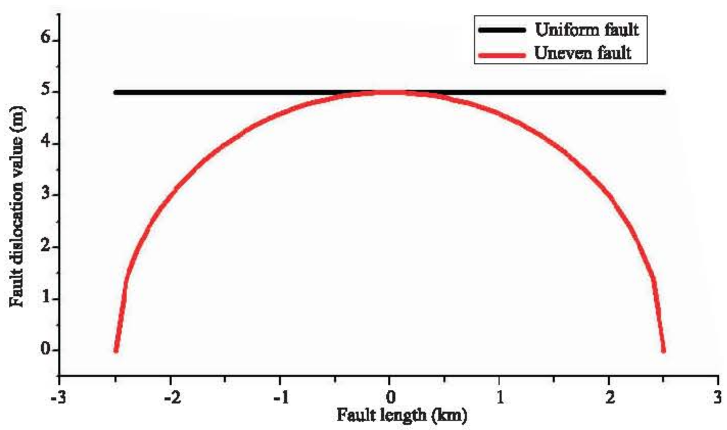
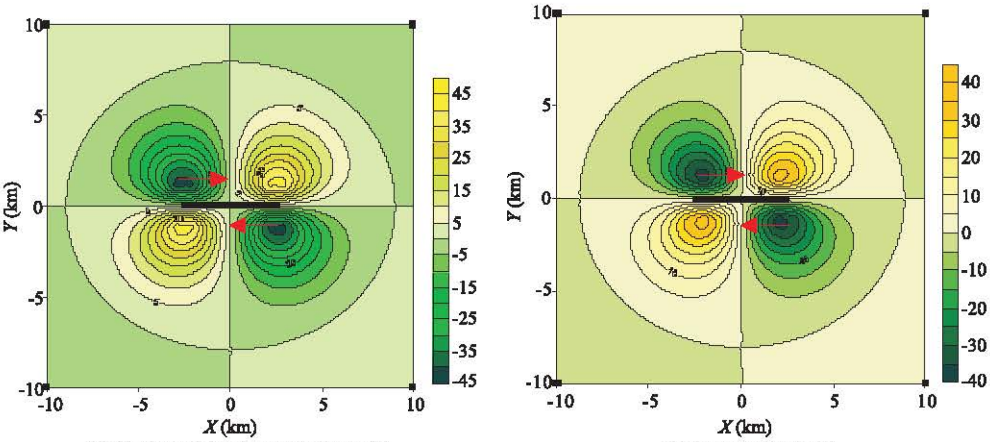


Figure 3 Distribution of asymmetric fault

The distribution of gravity changes caused by extension motion field has the property of symmetrical as the fault is the axis line. Ground gravity changes in the whole study area is negative.

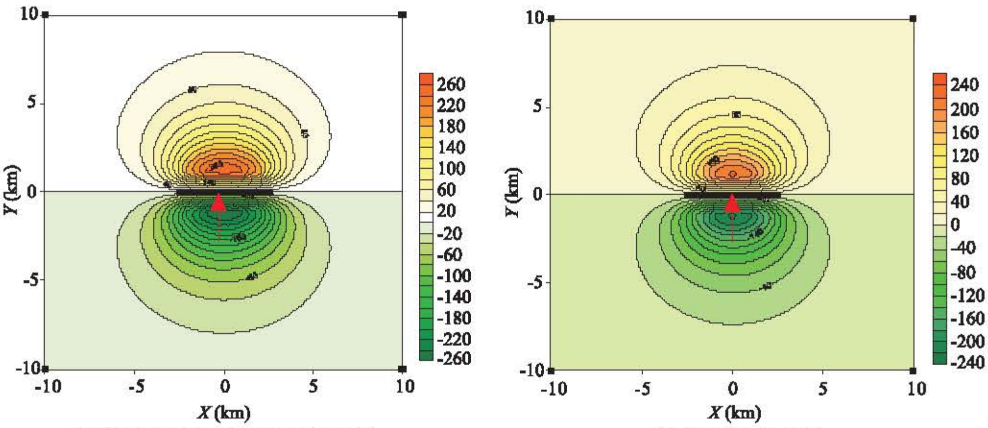
The calculated gravity changes by the two models are almost the same as shown in figures 4, 5, and 6. The calculated values by the uneven model are slightly less than those by the Okada model. This is because the displacement by the uneven model is below that by the even model. The gravity changes of the feature points by the two models are shown in table 1.

In table 1, the first column stands for the type of the fault movement, the second column is the location of the ground calculation point, the third column shows the gravity changes calculated by the Okada model, the fourth column indicates the gravity changes calculated by the asymmetric model, and the last column signifies the difference between the calculated results by the two models. It can be seen from table 1 that to the strike-slip faults, the dip-slip fault, and the tensile fault, the ground gravity change values calculated by the Okada model are over than those by the asymmetric model. The maximum difference lies near the end point of the fault, and the minimum difference is in the middle point of the fault. To the tensile fault, the maximum difference is 24.73%. To the dip-slip fault, the maximum difference is 25.58%. And to the strike-slip fault, the maximum difference is 17.97%. The main reason for such differences is that according to formula (13) the asymmetric model becomes gradually bigger from the end point to the middle point, namely from 0 m to 5 m. However, according to the Okada model, the displacement jumps directly from 0 m to 5 m without any functional changes.



(a) Okada model and asymmetric model (b) Asymmetric model

Figure 4 Gravity changes of strike-slip fault comparison between Okada model and asymmetric mode (Unit: 10^{-8} ms^{-2})



(a) Okada model and asymmetric model (b) Asymmetric model

Figure 5 Gravity changes of dip-slip fault comparison between Okada model and asymmetric mode (Unit: 10^{-8} ms^{-2})

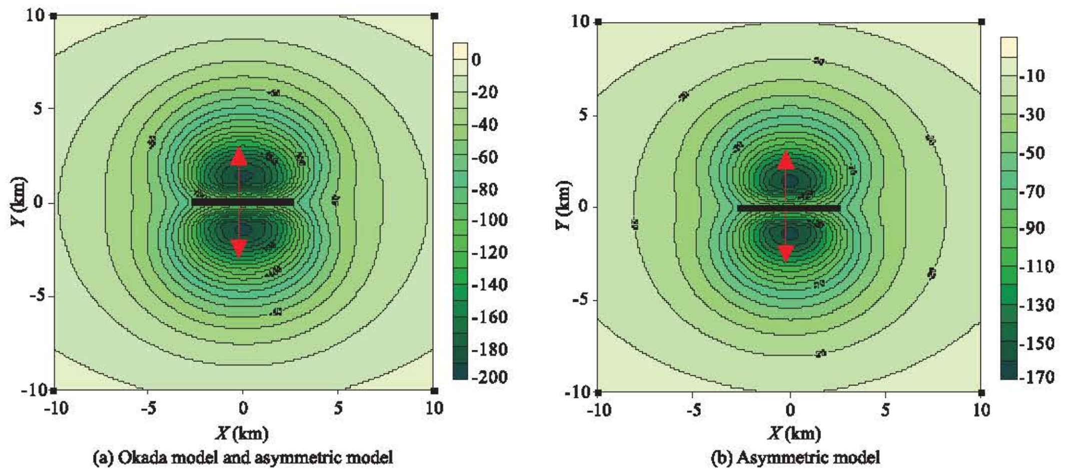


Figure 6 Gravity changes of extension fault comparison between Okada model and asymmetric mode (Unit: 10^{-8} ms^{-2})

Table 1 The gravity changes by the asymmetric model and the Okada model

Fault movement type	Calculated point(X,Y) (km)	Okada model (10^{-8} ms^{-2})	Asymmetric model (10^{-8} ms^{-2})	Difference (%)
	(−3,3)	−23.367	−19.168	17.97
Strike-slip faults	(0,3)	−14.744	−13.319	9.67
	(3,3)	23.3678	19.483	16.63
	(−3,3)	80.839	60.156	25.58
Dip-slip fault	(0,3)	141.819	117.254	17.32
	(3,3)	80.839	62.665	22.48
	(−3,3)	−90.162	−67.865	24.73
Tensile fault	(0,3)	−141.948	−116.585	17.87
	(3,3)	−90.162	−69.994	22.36

4 Conclusions

The dislocation on the fault plane was deduced. The farther the distance from the center position of the fault, the less the displacement. To all kinds of faults, the gravity changes calculated by the Okada model are greater than those calculated by the uneven model. To the strike-slip fault, the dip-slip fault and the tensile fault, the maximum differences in the gravity variations by the two models are 17.97%, 24.73%, 25.58%, respectively, the major reason of which is that the displacement by the asymmetric model is a variable, whereas that by the Okada model is a constant.

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