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Gravity anomaly from satellite gravity gradiometry data by GOCE in Japan Ms9.0 strong earthquake region

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Abstract

The great tsunami and secondary disasters caused by Ms9.0 strong earthquake occurred in northeastern Japan on March 11, 2011 has attracted widely public attention from all over the world. In this paper, gravity anomaly is calculated in the region between east longitude 132ºand 145º, north latitude 35ºand 50º by using satellite gravity gradiometry data observed by GOCE(Gravity field and steady-state Ocean Circulation Explorer). The computed gravity anomaly is compared with the topographical data and location of seismic activity in this region. The results show that gravity anomaly has great consistency with the regional tectonic distribution and Ms9.0 strong earthquake occurred in the steep gravity gradient zone. The spatial distribution of the gravity anomaly has obviously correspondence with extrusion action from the Pacific plate.

Keywords：Ms9.0 earthquake, satellite gravity gradiometry, gravity anomaly, Pacific plate, extrusion action

1 Introduction

Having wide coverage, high precision, high spatial resolution and high temporal repeat rate, as well as not restricted by topography and transportation, satellite gravity measurement is a new effective method to measure gravity anomaly and temporal gravity variation in earthquake area, volcano area and tsunami area. This new technology can measure the area that the traditional terrestrial gravity methods are unable to measure. It can also measure the temporal variable gravity field in high precision and become a hot spot quickly in geodesy and geophysics investigation. The principle of satellite gravity is that the satellite orbit perturbation caused by the earth gravity field is measured by using gravity sensors such as accelerometer, precise distance measurement and gravity gradiometer. The generalized satellite gravity measurement means a method to determine the earth gravity field based on the satellite gravity technique. It includes the ground photoelectric satellite tracking technology developed in twenty century sixties, Dopper ground satellite tracking technology, satellite laser ranging technology, satellite altimetry technology, satellite to satellite tracking (SST) technology and satellite gravity gradiometer technology. The satellite gravity data contain the density distribution information of the atmosphere, hydrosphere, earth-crust, mantle, centrosphere under the satellite orbit. The effect of atmosphere on the satellite gravity measuring result can be corrected by the atmosphere density model [1]. The influence of hydrosphere include the total of rainfall, soil moisture, groundwater level variation and so on. Those effects can be corrected by meteorological data and soil moisture. Some research results had been obtained in geosciences by using the satellite gravity data, for example, Trung [2] studied the relationship between the satellite gravity anomaly and the main geological tectonics in the South China Sea. Chen [3] investigated the co-seismic and post-seismic deformation by using satellite gravity data. Wahr [4] studied the possible effect on satellite gravity by the hydrology and ocean changes. Mikhailo [5] made digital simulation and statistic

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analysis for the possibility of gravity field variation caused by tectonic deformation. Sun [6] discussed the possibility to measure the co-seismic deformation by using satellite gravity technology. The strong earthquake (Ms9.0) which occurred in Japanese northeast sea area on March 11, 2011 is one of the strongest earthquakes in the world since the earthquakes firstly recorded by scientists. Because the quakes occurred in sea, traditional spatial and ground deformation method cannot monitor the deformation. The GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite which was launched on March 17, 2009 measures the gravity gradient using three-axis gradiometer and has 1 mGal precision and less than 100 km spatial resolution, and the coefficients of spherical harmonic series to 300 degrees. Till to this paper is written, the results to study gravity anomaly in Japan Ms9.0 strong earthquake region from GOCE data have not been reported. In this paper, the gravity anomaly is calculated in Japan seismic region by using satellite gravity gradiometer data. The computed result is compared with the geological tectonics and seismic activity in this region. The result shows that the Ms9.0 strong earthquake occurred in gravity steep gradient zone. This phenomenon can be explained by the extrusion from the Pacific plate to northeastern Japan.

2 Theory and method to calculate regional gravity anomaly from GOCE satellite data

2.1 Theoretical model

There are two kinds of gravity anomaly. One is the result of the gravity value subtract the normal gravity value at the same point. In this case, it is also called pure gravity anomaly. Another is the result after the gravity value on the geoid subtracts the normal gravity value on the corresponding reference ellipsoid. It is also called mixed gravity anomaly. In this paper, mixed gravity anomaly is computed and discussed by using GOCE data. If gravity potential and normal gravity potential have the same centrifugal potential, the disturbing potential does not contain the effect of centrifugal potential. The gravitational potential spherical harmonic series is given by (Heiskanen/Moritz, 1967) [7]:

$$V(r,\theta,\lambda) = W(r,\theta,\lambda) - Q(r,\theta,\lambda) = \frac{GM}{r}\sum_{n=0}^{N_{\max}}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\overline{C}_{nm}\cos m\lambda + \overline{S}_{nm}\sin m\lambda)\overline{P}_{nm}(\cos\theta) \qquad (1)$$

In formula (1), V is the gravitational potential at computation point, W is the gravity potential, Q is centrifugal potential, GM is gravitational constant times total mass of the Earth (solid Earth, atmosphere, ocean). a is equatorial radius of the Earth ellipsoid used for the determination of the harmonic coefficients, n is degree of spherical harmonic series, $N_{\max}$ is maximum degree of spherical harmonic series. m is order of spherical harmonic series, r is radius distance of computation point from geocenter, θ is geocenter co-latitude of computation point, λ is geocentric longitude of computation point, $\overline{P}_{nm}$ is normalized associated Legendre functions of degree n and order m, $\overline{C}_{nm}$ 、 $\overline{S}_{nm}$ are coefficients of the spherical harmonic series. After rescaling the spherical harmonic coefficients to the set of constants of the reference potential, the disturbing potential at a point P can be computed by:

$$T_P = W_p - U_P \qquad (2)$$

In equation (2), W_P is gravity potential at point P (including centrifugal potential), U_P is normal potential of reference ellipsoid at point P(including centrifugal potential), T_P is disturbing potential at point P. By subtracting the centrifugal potential from the normal potential, the result can be expanded into a spherical harmonic series[8]:

$$U(r,\theta,\lambda) - Q(r,\theta,\lambda) = \frac{GM^{REF}}{r}\left(1+\sum_{n=2}^{8}\left(\frac{a^{REF}}{r}\right)^n \overline{C}_n^{REF}\,\overline{P}_n(\cos\theta)\right) \qquad (3)$$

In equation (3), GM_{REF} is Factor of GM for the reference ellipsoid potential, a^{REF} is Equatorial radius for the reference ellipsoid, $\overline{C}_n^{REF}$ is normalized coefficient of spherical harmonic series of the reference ellipsoid of degree n and order 0, $\overline{P}_n$ is normalized Legendre polynomial of degree n.

If gravity potential and normal gravity potential have the same centrifugal potential, the disturbing potential then becomes:

$$T(r,\theta,\lambda)=\frac{GM^{REF}}{r}\sum_{n=0}^{N\max}(\frac{a^{REF}}{r})^{n}\sum_{m=0}^{n}(\Delta\overline{C}_{nm}\cos m\lambda+\Delta\overline{S}_{nm}\sin m\lambda)\overline{P}_{nm}(\cos\theta) \quad (4)$$

In equation (4), $\Delta\overline{C}_{nm}$ 、 $\Delta\overline{S}_{nm}$ are residual coefficients of the spherical harmonic series after subtracting the coefficients of the normal potential from the gravitational potential.

In spherical approximation, gravity anomaly can be written as:

$$\Delta g=g_P-\gamma_0=-\frac{\partial T}{\partial r}-\frac{2}{a^{REF}}T \quad (5)$$

By applying the spherical approximation of (5) to equation (4), gravity anomalies expressed in spherical harmonic series is：

$$\Delta g(r,\theta,\lambda)=\frac{GM^{REF}}{r^2}\sum_{n=0}^{N\max}(n-1)(\frac{a^{REF}}{r})^{n}\sum_{m=0}^{n}(\Delta\overline{C}_{nm}\cos m\lambda+\Delta\overline{S}_{nm}\sin m\lambda)\overline{P}_{nm}(\cos\theta) \quad (6)$$

Gravity anomaly reflects the difference betweent the theoretical model and acctually observed results. It also includes effects of asymmetry material density distribution in the earth.

2.2 Calculation method of gravity anomaly from GOCE data

The GOCE satellite carries on the gravity gradients measurement in three mutually perpendicular direction on the satellite orbit altitude, providing the satellite gravity gradiometry (SGG) data products in the different coordinates framework. For example, the EGG_NOM_2 (available after two weeks of observation) are observed gravity gradients data after the temporal gravity variation correction and calibration in the Gradiometer Reference Frame (GRF). The EGG_TRF_2_ (available after one month of the observation) are observed gravity gradients data which had been calibrated in the Local North Oriented Frame (LNOF). The main methods to calculate gravity anomaly from the satellite gravity gradiometry data can be summarized as the least-squares collocation (LSC) and generalized Stokes integral method. Least-squares collocation [9-13] based on the covariance function between the observation point P and estimated parameters which is derived under assumption of isotropic and homogeneous is used to solve the unknown parameters. Least-squares collocation can combine data observed by different ways, such as the various kind of satellite gravity （CHAMP、GRACE、GOCE）data, the airborne gravity measurement data and the ground gravity observation data to determine regional gravity field[14]. Generalized Stokes integral method is used to carry through the second-order or the first-order partial derivative calculation of the gravity potential in the Poisson integral or gravity in the Stokes integral formulas to obtain the same amount of satellite gravity gradiometry data [15-24]. Then the first-order partial derivative results of the gravity potential in the Poisson integral are carried on upward continuation to Gradiometer Reference Frame and compared with SGG data measured by GOCE. Finally, least squares method is used to inverse the Earth gravity field. In the actually data processing, spherical function of the disturbing potential can be written as [7]:

$$T_P=\frac{GM}{\mathrm{r}}\sum_{n=2}^{N}(\frac{a}{r})^{n+1}\sum_{m=-n}^{n}t_{nm}Y_{nm} \quad (7)$$

In formula (7), a is the semi-major axis of the reference ellipsoid, r is radial distance of computation point from geocenter. Y_{nm} is spherical function, t_{nm} is coefficients of the spherical harmonic series. In addition,

$$Y_{nm}=\begin{cases}\mathrm{P_{nm}}(\cos\theta)\cos m\lambda\\ P_{nm}(\cos\theta)\sin m\lambda\end{cases} \qquad t_{nm}=\begin{cases}\Delta C_{nm}\\ \Delta S_{nm}\end{cases}$$

The Local North Oriented Frame (LNOF) is a right-handed North-West-Up frame with the X-axis pointing North, the Y-axis pointing West and the Z-axis Up. The second order partial derivatives of the disturbing potential in LNOF are defined as follows [23]:

$$T_{xx}(P)=\frac{GM}{a^3}\sum_{n=2}^{N}(\frac{a}{r})^{n+3}\sum_{m=-n}^{n}t_{nm}(-(n+1)Y_{nm}(P)+\frac{\partial^2Y_{nm}(P)}{\partial\theta^2})$$

$$T_{yy}(P)=\frac{GM}{a^3}\sum_{n=2}^{N}(\frac{a}{r})^{n+3}\sum_{m=-n}^{n}t_{nm}(-(n+1)Y_{nm}(P)+\cot\frac{\partial^2 Y_{nm}(P)}{\partial\theta^2}-\frac{\partial Y_{nm}(P)}{\sin^2\theta\partial\lambda^2})$$

$$T_{zz}(P)=\frac{GM}{a^3}\sum_{n=2}^{N}(n+1)(n+2)(\frac{a}{r})^{n+3}\sum_{m=-n}^{n}t_{nm}Y_{nm}(P)$$

$$T_{xy}(P)=\frac{GM}{a^3}\sum_{n=2}^{N}(\frac{a}{r})^{n+3}\sum_{m=-n}^{n}t_{nm}(\frac{1}{\sin\theta}\frac{\partial Y_{nm}(P)}{\partial\lambda\partial\theta}-\frac{\cos\theta}{\sin\theta}\frac{\partial Y_{nm}(P)}{\partial\lambda})$$

$$T_{yz}(P)=\frac{GM}{a^3}\sum_{n=2}^{N}(n+2)(\frac{a}{r})^{n+3}\sum_{m=-n}^{n}t_{nm}\frac{\partial Y_{nm}(P)}{\sin\theta\partial\lambda}$$

$$T_{xz}(P)=\frac{GM}{a^3}\sum_{n=2}^{N}(n+2)(\frac{a}{r})^{n+3}\sum_{m=-n}^{n}t_{nm}\frac{\partial Y_{nm}(P)}{\partial\theta} \qquad (8)$$

Based on the GOCE gradient data after the correction of the atmosphere and the water influence as the observation and the second order partial derivation of the disturbing potential in Local North Oriented Frame, the observation equations can establish between the satellite gravity gradiometer data and the disturbing potential coefficients. Then the spherical harmonic coefficients of the disturbing potential can be inversed by using the least squares method. After getting the spherical harmonic coefficients, the gravity anomalies can be computed through the formula (6).

3 The gravity anomaly computed from GOCE data in Japan's seismic region

Japan is located among the intersection zone of Philippine Sea plate, Eurasia plate, North American plate and the Pacific plate. The tectonics is very complex and strong earthquakes occurred there frequently. On March 11, 2011, the Ms9.0 strong earthquake occurred in northeastern Japan (142.6° E, 38.1° N). The relationship between location of the epicenter and Japanese Inland is shown in Figure.1.(a). In order to investigate the distribution characteristics of gravity anomaly in seismic region，the GOCE satellite data were downloaded from European Space Agency website (http://earth.esa.int/EOLi/EOLi.html). The gravity anomaly in seismic regional (135° -150° E, 32° -45° N) was computed by the inversion method [24]. The result is shown in Fig.1.(b). Comparing the gravity anomaly in spatial distribution with location of Ms9.0 earthquake epicenter in Fig.1.(b), it can obviously found that the epicenter locates coincidently in high gradient zone of gravity anomaly. This phenomenon is extremely similar with that of the spatial distribution of gravity anomaly in many strong earthquake areas [25] in Chinese mainland. In fact, the gravity anomaly in Fig.1.(b) can be explained by the regional tectonic movement.

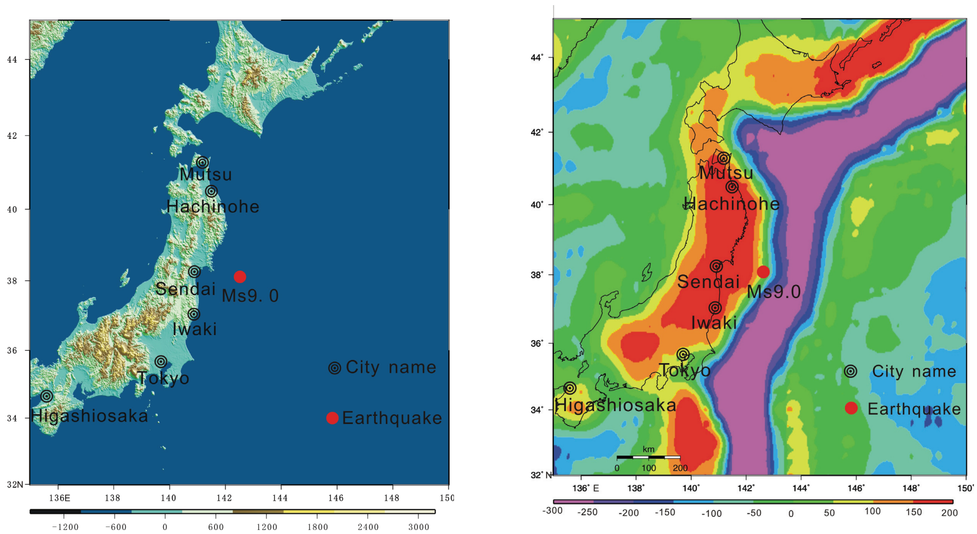

Fig.1.(a) relationship of Ms9.0 earthquake and topography in Japan; (b) relationship of Ms9.0 earthquake and gravity anomaly in Japan

The spatial distribution of gravity anomaly in Ms9.0 earthquake zones (Fig.1.(b)) and the seismic activity are the results of long-term tectonics movement in this area .This can be interpreted by the geological model in Fig.2.(a)[26]. The Pacific plate extruded the lower part of the Japanese mainland at the speed of 8cm/yr. This led to the relative motion between the Japanese mainland and the Pacific plate. It is easy to form the stable slide area of non-seismic activity in the smooth area between the two plates. However, a local locked area is easy to form in the asperity area of the two plates. The crustal deformation and elastic potential energy constantly accumulated in the asperity area. When the elastic potential energy reached to the limit which this asperity system can not withstand, the intense slip would occur in a short time. As a result, different magnitudes of earthquakes would occur in asperity area.

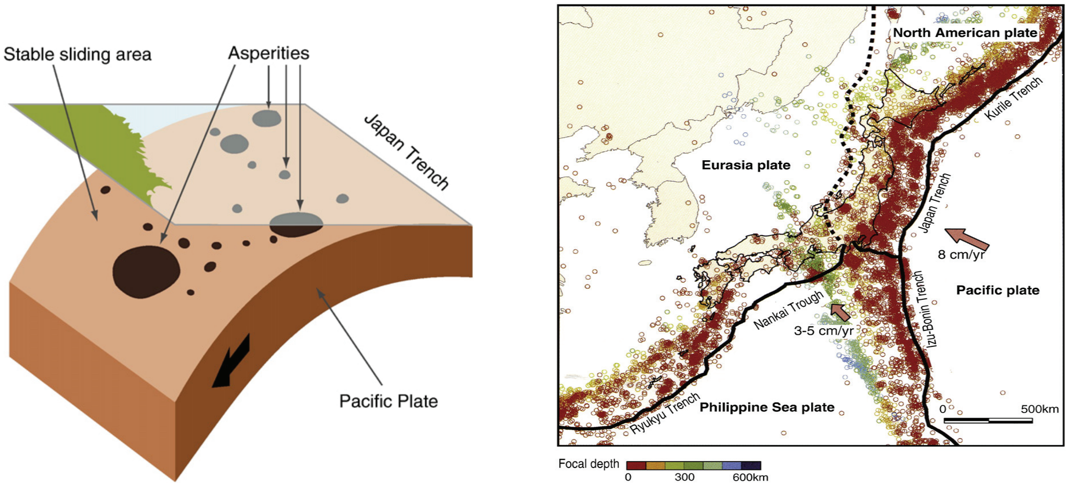

Fig.2.(a) Schematic illustration of asperities and stable sliding areas on the plate boundary east of NE Japan; (b) Epicenter distribution of M > 4.0 earthquakes for the period 1995–2005 in Japan

When the Pacific plate extruded northeastern Japan, the Pacific plate sunk at a shallow dip angle simultaneously. As a result, the negative value of gravity anomaly forms. In the convergence of plates, the thrust dip-slip reversed faults emerged. The footwall is the Pacific plate and the hand wall which forms high value of gravity anomaly is northeastern Japan at a dip angle between 30° to 50° . Comparing the seismic activity of Fig.1.(b) and Fig.2.(b), we find the spatial distribution of high gradient belts and seismic activity has good consistency.

4 Conclusions

By comparing and analyzing among the gravity anomaly calculated from GOCE data, theoretical model and seismic activity in northeastern Japan, conclusions can be obtained as follows: (1) The gravity anomaly observed by GOCE can reflect the spatial distribution characteristics of regional tectonics and seismic activity. This new technology provides a new observed method to study seismic activity. (2) The Ms9.0 strong earthquake occurred in high gradient belts of gravity anomaly, which is significant to investigate the seismic activity by using gravity data. (3) The spatial distribution of gravity anomaly in northeastern Japan and seismic activity can be explained by the extrusion from the Pacific plate to northeastern Japan.

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