Measurement Techniques, Vol. 37, No. 3, 1994

ESTIMATING SEASONAL DEFORMATIONS IN THE EARTH'S CRUST IN CORRECTING FOR EFFECTS ON THE DETERMINATION OF THE EARTH'S ROTATIONAL PARAMETERS

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Estimates are made of the vertical deformations in the Earth's crust produced by variable loads on regions having characteristic dimensions of the order of thousands of kilometers, which arise from the development and displacement of cyclones and anticyclones and also from the accumulation of snow and the passage of floods on large rivers. It is found that the total deformation in Siberia can attain 30 cm. It is necessary to correct for the periodic displacements in observational points in the service for determining the Earth's rotational parameters. Suggestions are made on organizing experiments on the deformations.

The stability in the positions of the points defining the terrestrial coordinate system TCS has a substantial effect on the accuracy in determining the Earth's rotation parameters ERP as elements in the orientation of that coordinate system relative to the inertial with the contemporary accuracy in observational facilities.

Geodynamic observations are used to determine the Earth's rotation parameters, but corrections are applied only for the regular vertical movements of the points on account of lunar–solar tides, and the same applies to research on contemporary crustal movements. All other displacements are perceived as errors of measurement. On the other hand, the vertical deformations considered in this paper exceed the instrumental errors of the means of measurement by about an order of magnitude.

There are considerable random fluctuations (up to 2 msec in universal time [1]) in the Earth's rotation after those factors have been excluded: the constant tidal retardation and the effect from changes in the atmospheric angular momentum, and these have not yet been satisfactorily explained in geodynamic models. Filtering the measurements to remove these deformations in the observational network enables one to reduce the noise component in the fluctuations of the Earth's rotational rate by about an order of magnitude. It is thus possible to examine more detailed effect from the influencing factors.

Here we develop a theory and experimental methods for determining vertical displacements of points on the Earth's surface due to time-varying loads from atmospheric, snow, and water masses, and we also examine the effects of those displacements on ERP observations (variations in the angular velocity and polar coordinates).

It is assumed that the crust is deformed elastically by variable brief loads on regions with characteristic dimensions of the order of thousands of kilometers, which arise from the development and displacement of cyclones and anticyclones, from the accumulation of snow, and also the passage of snow and rain floods in large rivers. The additional crustal load produces vertical and horizontal displacements. Here we consider only the vertical deflections. The theoretical estimates have been made from the Boussinesq treatment [2] for a semi-infinite planar elastic medium loaded by a distributed pressure q(x, y). We neglect the mass forces (gravitational attraction) and the effects of the Earth's surface curvature to a first approximation. Those simplifications allow one to obtain exact solutions, which give an indication of the order of the effects.

The vertical displacements of a plate surface in the Boussinesq treatment are given by

$$W(x,y)=\theta \iint \frac{q(x',y')dx'dy'}{\sqrt{(x'-x)^2+(y'-y)^2}}\ , \tag{1}$$

Translated from Izmeritel'naya Tekhnika, No. 3, pp. 5-7, March, 1994.

0543-1972/94/3703-0239$12.50

in which x and y are the coordinates of the point at which the deformation is determined, x' and y' are the coordinates of the current point, $\Theta = (1 - \sigma^2)/\pi E$, σ is Poisson's ratio, and E is Young's modulus.

We now consider some particular cases. Let a region bounded by a circle of radius R in the crust be subject to a constant load

$$q = \pm p_0 = \text{const}.$$

With some idealization, this represents the situation under a large water basin when the surface level alters. The exact solution for the region within the circle ($r < R$) gives

$$W_1(r) = \pm 4\Theta p_0 R E(r/R), \tag{2}$$

in which $E(r/R)$ is a complete elliptic integral of the second kind.

Outside the loaded region ($r > R$) we get

$$W_2(r) = \pm 4\Theta p_0 R \frac{r}{R}\left[E\left(\frac{R}{r}\right) - \left(1 - \frac{R^2}{r^2}\right) K\left(\frac{R}{r}\right)\right], \tag{3}$$

in which $K(R/r)$ is a complete elliptic integral of the first kind.

From (2) and (3) we get

$$W(0) = \pm 2\pi\Theta p_0 R \quad \text{for } r = 0;$$
$$W(R) = \pm 4\Theta p_0 R \quad \text{for } r = R;$$
$$W(r) \approx \pm \pi p_0 R \frac{R}{r} \quad \text{for } r \gg R.$$

If the constant load acts within a region bounded by a rectangle having sides x_0 and y_0 ($y_0 > x_0$), then the deformation at the center is

$$W_t = 2\Theta p_0 \left(x_0 \operatorname{Arsh} \frac{y_0}{x_0} + y_0 \operatorname{Arsh} \frac{x_0}{y_0} \right). \tag{4}$$

The deformations at the mid-points of the long sides of the rectangle (at the shores of an elongated body of water) are

$$W_s = \Theta p_0 \left(x_0 \operatorname{Arsh} \frac{2y_0}{x_0} + 2y_0 \operatorname{Arsh} \frac{x_0}{2y_0} \right). \tag{5}$$

We now consider a model having a Gaussian pressure distribution, which corresponds approximately to the situation where an anticyclone (+) or a cyclone (−) lies above the observation point:

$$q(x, y) = \mp p_0 \exp\left(- \frac{x^2 + y^2}{2s^2} \right),$$

in which s is the radius of the region, at the boundary of which $p = 0.606 p_0$, and p_0 is the pressure at the center.

Integration in (1) gives

$$W = \pm \pi \sqrt{2\pi}\, \Theta p_0 s I_0 \left(\frac{r^2}{4s^2} \right) \exp\left(- \frac{r^2}{4s^2} \right), \tag{6}$$

in which I_0 is a modified Bessel function.

TABLE 1. Vertical Crustal Uplifts in Cyclone Region

Model p = const from (2) and (3)			Exponential model from (6)		
r/R	r, км	W, см	r/S	r, км	W, см
0	0	11,0	0	0	13,7
0,4	300	10,5	0,6	470	12,5
0,8	600	8,9	1,1	821	10,4
1,0	750	7,0	1,4	1060	8,8
2,0	1500	2,8	2,0	1500	6,4
4,0	3000	1,4	4,0	3000	2,8

In the particular cases

$$W=\pm 7{,}87\Theta p_0 s \text{ for } r=0;$$
$$W=\pm 6{,}23\Theta p_0 s \text{ for } r=s; \qquad (7)$$
$$W=\pm 6{,}28\Theta p_0 s\,\frac{s}{r} \text{ for } r\gg s.$$

We now transfer from the theoretical models to estimates of the crustal deformations due to dynamic loads.

The main geological structures in the Russian Federation are [3] the East European (Russian) plate having a diameter of about 2000 km, the West Siberian plate 1500 × 2000 km, and the Siberian platform 1700 × 2500 km. These enormous crustal blocks are surrounded to the south by the mountain systems of the Caucasus, Altay, and Sayan, and to the east by the Kamchatka and Kuril volcanic belt. The northern margin of the plains gradually descends into the Arctic Ocean and does not have sharp boundaries of divergent or convergent type. The Baikal rift zone lies in the SE of the Siberian platform. Ancient latent faults dissect the platform and plates in all directions. They are filled by sedimentary rocks and do not disrupt the monolithic structure. Some of the faults emerging on the surface lie along the Ural ridge and along the valleys of the Enisey, Angara, and Lena.

Amongst the factors influencing the seasonal crustal deformations, we consider cyclones and anticyclones together with winter snow and river floods.

The mean annual precipitation on Siberia is [4] 400 mm. In the frost-free period (from 120 to 60 days), the precipitation is more rapid and we assume that half the annual norm falls in the winter. About half of the fallen snow evaporates. Then the mean height of the snow cover accumulated by the Spring is equivalent to a layer of water with thickness 100 mm.

We calculate the load in application to granite, for which [3] $\sigma = 0.25$; $E = 7.7 \cdot 10^{11}$ dyne/cm^2, so $\Theta = 3.88 \cdot 10^{-13}$ cm^2/dyn. Replacing granite by limestone reduces Θ by about 20%. Correspondingly, from (4) with $x_0 = 2000$ km, $y_0 = 4500$ km, we get that the vertical deflection produced by the snow accumulated by the Spring in Central Siberia is 3.8 cm.

We now estimate the vertical deflections caused by floods on the Siberian rivers. The Ob', Enisey, Amur, and Lena are amongst the ten largest rivers in the world as regards length and catchment area. The distinctive features are that the water level falls considerably in the winter and there are large spring–summer floods. For example, the Ob' [5] has a length of 5400 km and a flood plain width in the middle flow of 25-30 km, while the rise in flood water relative to the standard level is 11.3 m. The mean height of the flood in the Enisey [6] in the part between Yartsevo and Dudinka (length 1300 km) attains 19.4 m.

We take the flood-plain width in (4) and (5) as $y_0 = 20$ km and the length of the part of the river with high floods as 2000 km, the height of the flood being 10 m. Correspondingly, we get a deformation of the crust at the bank $W_b = 5.5$ cm and at the center of the flood plain $W_c = 9.5$ cm.

Cyclones and anticyclones are major forms of atmospheric circulation. The diameter of the outer closed isobar for a cyclone in latitudes away from the tropics can attain 3000 km [4]. A diameter of about 1000 km is usual. The pressure difference between and the edge of a cyclone is 3-5 kPa. A cyclone usually migrates from west to east with a mean velocity of 30-50 km/h. Table 1 gives calculations on the lifting of the crust in the region of a cyclone having a diameter of 1500 km and a pressure difference of 6 kPa from (2), (3), and (6). It shows that the two models give a discrepancy of about 30% for the center of the cyclone or by a factor two at the edge.

In the winter months, there is a stable anticyclone above Northern Asia with its center between Irkutsk and Ulan Bator [4]. The January isobars for this global atmospheric formation have the following diameters: 900 km at 104 kPa, 1650 km at 103.6 kPa, 3750 km at 103 kPa, 6000 km at 102.4 kPa, and general background 101.8 kPa.

The pressure over the whole of Siberia is low in the summer months [4] (in July on average 100.6 kPa), so (7) gives the seasonal crustal deformation in the region of Irkutsk as 25.4 cm ($\Delta p = 2.2$ kPa, $s = 2500$ km). We add this estimate to the deflection of 3.8 cm produced by the snow cover (see above) to get the total seasonal vertical deformation of the crust at the center of Siberia as about 30 cm.

To compare theory with experiment, we take the deformation of the Caspian coast. At the start of the 20th century, the level of the Caspian was 27 m below the level of the world ocean. After 50 years, it had descended to −29 m. Leveling along the Syzran'–Astrakhan' line repeated every half century [7] showed that Astrakhan' rose by 100 ± 15 mm. The configuration of the sea is close to rectangular, so we can use (5) for estimates. We find that Astrakhan' rises by 9.7 cm when the sea level alters by 2 m. The agreement with the leveling results is good.

Increasing use is being made of phase observations on the signals from the GPS and GLONASS satellite navigation systems [1] for determining ERP. The instrumental error in such observations is 1-2 cm. It is clear that systematic movements of the observation points over a range of some decimeters will have a substantial effect on the overall error in determining ERP. Therefore, the above seasonal crustal deformations need to be examined theoretically and experimentally.

Experimental studies on the seasonal deformations employ differential phase determinations by the space navigation systems and laser location by passive earth satellites. The deformometric network should be based on the stationary points of the service for determining the Earth's rotational parameters under the Delta system in Russia [8] at Mendeleevo (Moscow Oblast), Novosibirsk, Irkutsk, and Khabarovsk. Continuous observations are made at those points and it is planned in the near future to install phase receivers for the GPS and GLONASS space navigation systems.

Additional points in the deformometric network are proposed for location at points of forecast largest vertical crustal displacement caused by these dynamic loads. The additional network should be constructed on a hierarchic scheme with three levels: local (as bases with characteristic scales up to 100 km transverse to the flood plains of large rivers), regional with characteristic baseline scale of 1000 km, and subcontinental based on the stationary points. Precision methods of observing the deformation may be employed in the local network on the basis of GPS phase equipment in monitoring mode during periods of brief loading. The observations in the regional networks are planned to be constructed by traditional methods of differential geodesic determination, with the length of each session from a day to a week. The additional points in the subcontinental network require continuous observations throughout the time of action of the dynamic loads in research on atmospheric effects or twice a year to examine the effects of snow cover.

The vertical crustal deformations in the region of an observation point are calculated as the increments in the geocentric radius vector of the receiver's antenna. The position of the antenna during the measurements should be reliably related to the basic ground reference point.

The expected errors in determining the vertical deformations in the local networks are 5 mm, as against 20-30 mm in the regional and subcontinental ones. A metrological check on the observations with the space navigation system can be provided by laser ranging by passive satellites performed at the Mendeleevo and Irkutsk stations.

Information is to be obtained on flood levels, groundwater levels, and snow cover from the existing hydrometeorological posts, while the atmospheric pressure pattern is taken from current synoptic maps.

The measured deformations should be compared with those calculated from the theoretical model by correlation-analysis methods. This should provide conclusions on the significance level of the hypothesis.

An alternative is the use only of laser observations from passive satellites, measurements on existing geodynamic polygons, or repeat high-precision leveling.

The existing network of laser satellite rangefinders contains about 30 stations, most of which are in Western Europe and North America. There are only two such stations in Russia: Mendeleevo and Irkutsk. It is not economically justified to equip special points in the deformometric network with the latest laser locators (the cost of a single rangefinder exceeds 4 million dollars) and is organizationally undesirable (the operation of a laser in the transpolar area is complicated by the polar day in the summer and by the heavy frosts in the winter).

Geodynamic polygons in Russia lie in regions of active crustal movement (faults, rifts, and island arcs). The present suggestion is designed to research the deformations in highly-stable continental formations, so geopolygon observations can only be of auxiliary character.

Periodically repeated leveling in the state height network for Russia is of considerable interest for estimating vertical crustal deformations. Unfortunately, leveling over distances of hundreds or thousands of kilometers is a lengthy business and can therefore hardly be linked to a definite synoptic situation. Also, the field season usually excludes the winter months, so it is difficult to envisage using leveling to determine deformations produced by snow. Under flood conditions, which at times are catastrophic, one can hardly perform precision leveling. Finally, there are systematic errors in leveling (primarily due to vertical refraction of light in the ground-level air), so there is no hope of obtaining an objective judgement on the deformations at the level of a few centimeters over baselines of thousands of km, particularly in the presence of large height differences along the lines.

Research under the program formulated from the above basis could be a component in the fundamental international geodynamic projects Crustal Dynamics and Wegener [9].

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