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CHARACTERISTICS OF SPATIAL AND TEMPORAL GRAVITY CHANGES BEFORE AND AFTER MODERATE STRONG EARTHQUAKES IN CHINA

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ABSTRACT

This paper collected the data of gravity changes of high precision gravity resurveys networks and earth tide stations during 1970-1985 in china. The relationship between the gravity changes and 11 earthquakes M⩾5.0 around the 6 routes and 5 stations has been analyzed. And then the possible mechanisms and characteristics of gravity changes with time have discussed. It is believed that if the moderate strong earthquakes will occur within certain distance from the station, then gravity changes of proper measure would appear before and after earthquakes. The duration T or Tc of gravity change is dependent on the magnitude M, the epicentral distance L and the area of aftershocks S or volume of source V. The gravity changes accompanying an earthquake are mainly caused by underground mass density change apart from crustal deformation. Different features of earthquakes may be verified by the data of gravity and deformation.

INTRODUCTION

Investigation of gravity changes with time during the earthquake preparation process is one of the difficult problem in gravity studies. Gravity changes were measured during the following earthquake case histories: the Alaska earthquakes (M=8.4) 1964 in U.S.A.[1] and the Niigata earthquake (M=7.4) 1964 in Japan[2], and then the Matsudai earthquake swarms during 1965-1967 in Japan[3], before and after the Inangahua earthquake 1968 in New Zealand[4] and the Izu earthquakes (M=7.2) 1978 in Japan[5]. After the xingtai earthquakes (M=6.8, 7.2) 1966 in China, in order to investigate the gravity changes during the earthquake preparation process, high precision gravity resurveys was carried out in China. Some reliable data of gravity changes and earth tides were obtained before and after moderate strong earthquakes. Chen Yuntai et al.[6] calculated the gravimetric effect of the mass migration theoretically.

The authors have collected the data of gravity changes of high precision gravity surveys networks and earth tide stations during 1970-1985 in China. The relationship between the gravity changes and 11 earthquakes M≥5.0 around the 6 routes and 5 stations has been analyzed. And then the possible mechanisms and characteristics of gravity changes with time have discussed. Thus an understanding on the gravity changes during the earthquake preparation process has achieved.

DATA

All data of gravity surveys networks and earth tide stations since establishment have been checked in 1984, including the reexamination of the field data, recalculation of the calibrations and measured gravity values, and reestimation of the survey accuracy of gravimeters, and analyzed the possible influence factors around stations.

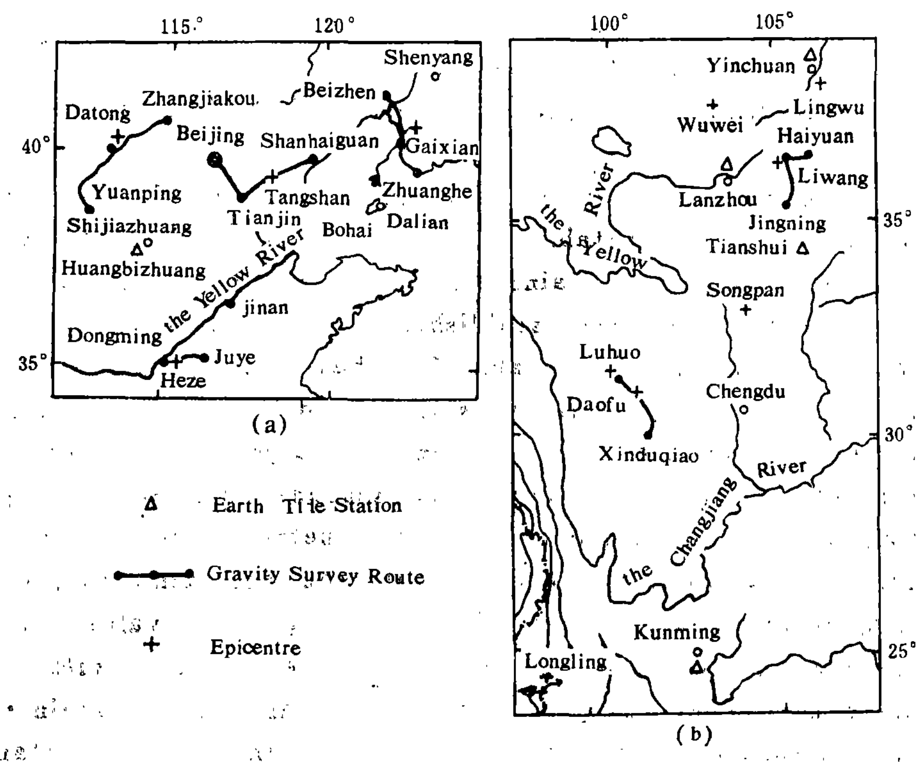

Fig. 1 The distribution of gravity survey route, earth tide station and epicentres
(a) Northeast China and North China
(b) Northwest China and Southwest China

Table 1 The Routes of High Precision Gravity Surveys

Survey Route	Established Date	Meter Type	Gravity Change Station	Influence Factor
Beizhen-Zhuanghe	1972	CG-2	Gaixian-Donghuangdi	Ground Water 5.4μg
Beijing-Shanhaiguan	1971	CG-2	Beijing-Tangshan I	Ground Water 15μg
Zhangjiakou-Yuanping	1978	CG-2	Yanggao-Datong	Coal Mining 20μg
Dongming-Juye	1978	CG-2	Dongming-Heze	
Liwang-Jingning	1979	CG-2	160km-Haiyuan	
Xinduqiao-Luhuo	1978	CG-2	161-162-Station	

Table 2 The Stations of Earth Tide Observation

Station	Established Date	Meter Type	Influence Factor
Huangbizhuang	1972-1980	Askania GS-11-117	Ground and Reservoir Water 25μg
Yinchuan	1975	GS-15-115	
Tianshui	1970-1982	GS-11-150	
Lanzhou	1983	GS-11-150	
Kunming	1975	GS-15-211	

Through this work, the gravity changes from 6 routes (Table 1) and 5 stations (Table 2) in Northeast China, North China (Figure 1a) and Northwest China, Southwest China (Figure 1b) were found.

The number of mainshocks M≥5.0 within 50 km around 6 routes of gravity survey since establishment are shown in Table 3. At the same time the numbers of mainshock M≥5.0 within 600 km around 5 stations of earth tide since establishment are shown in Table 4. Among them 11 mainshocks (Table 5) have gravity changes.

The data of gravity resurveys was treated by following numerical methods[7]. Because the quartz suspension gravimeters have been used in the study, in order to remove the seasonal influence, using the linear regression and multinomial trigonometric fitting method, the rationale correlations between the calibration and temperature were obtained. When calculating the difference of gravity values between adjacent stations, we considered the earth tide and drift with different observation time. The gravity difference values were obtained in a three-way measurement by using two inter locking loops. The standard deviation of data was evaluated by using different formulas in different cases. The mean square errors of one gravimeter and two gravimeters were used, at the same time coincident accuracy between them was calculated.

From Figure 2 and Table 6 one can see: (1) The gravity changes were in epicentral areas or near-field which appeared mainly in the range of 1-50km from epicentres; (2) The continuous time of gravity change is Tc = T − t, the shortest is 370 days and the longest is 1622 days; (3) The minimum gravity changes of resurveys before shock is 51μg, and the maximum is 98μg. The minimum square error measured is ±18μg and the maximum is ±50μg. The gravity change of the Haicheng earthquake as shown in the Table 6 is the relative value before and after the main shock; (4) The annual mean rate of gravity changes before some earthquakes is:

Beijing-Tangshan I: +22μg/year,

Haiyuan-160km: −56μg/year.

Generally the daily mean values of drift with respect to gravity earth tide measurement data are linear. The time of start and durations of nonlinear drift (increase or decrease) are selected from earth tide daily mean values as anomalous marks. The relative variation values of wave M are also selected from earth tide as anomalous amounts and at the same time the measurement accuracy is used as mean square error for judging the anomaly.

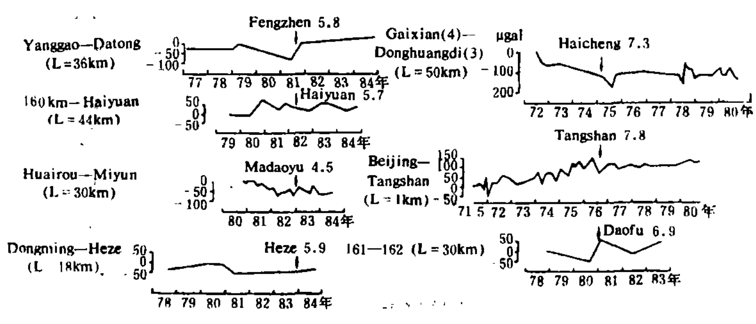

Fig. 2 The variations of high precision gravity surveys

From Figure 3, 4 and Table 7 one can see: (1) The variations of earth tide appeared mainly in the area of far-field, the minimum distance L of the anomaly from the epicentre is 40km and the maximum distance is 580km; (2) The duration of daily mean values of earth tide is Tc = T − t, the least is 54 days and the most is 238 days. The minimum continuous time of anomalous tide factors is 98 days and the maximum continuous time is 260 days; (3) All the relative values of the earth tide factors are negative anomalies, the minimum value is 3% and the maximum is 9%. The minimum mean square error of the relative variation is 1% and the maximum is 3%.

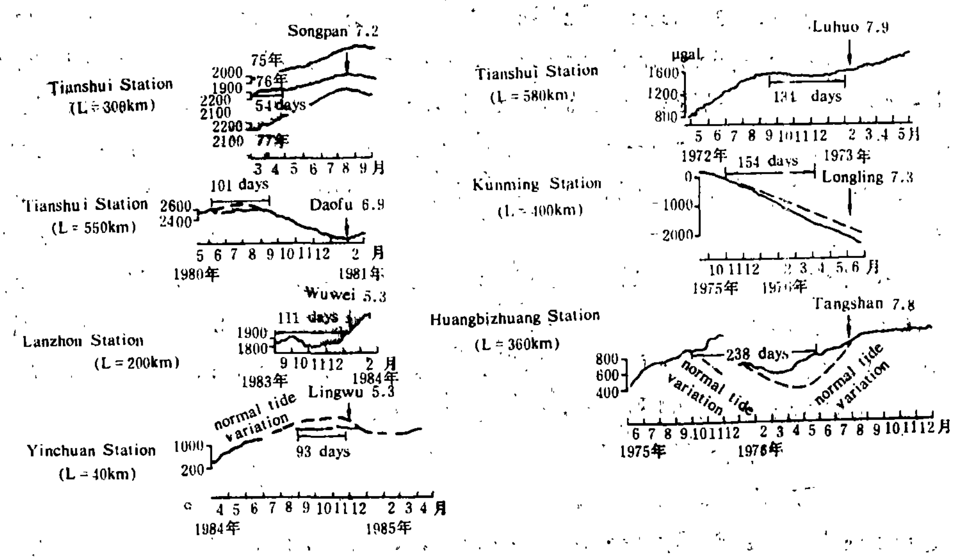

Fig. 8 The variation of daily mean values for earth tides

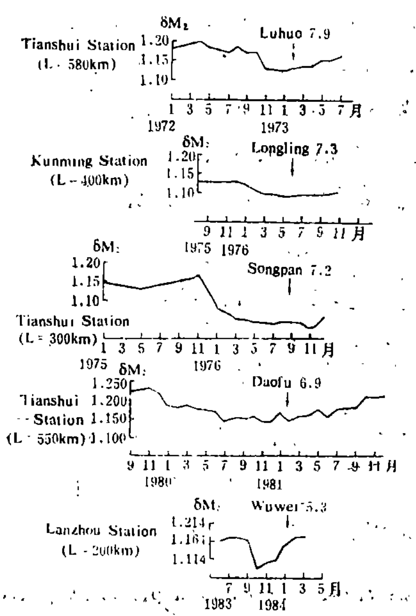

Fig. 4 The variations of monthly mean values for earth tide factors

The influences of the underground water level, coal mining and reservoir water level on gravity change before and after 3 earthquakes are considered respectively (Table 1, 2), the maximum values of influences among does not exceed 25μg.

CHARACTERISTICS

It can be seen from Table 3, 4 that the gravity changes with earthquakes between the gravity resurveys and earth tide observation are difference.

The whole gravity changes before and after mainshocks were obtained in route range of 50km. So the numbers of mainshocks M≥5.0 in every route within the range of 50km are listed in Table 3. Altogether 8 mainshocks have been occurred from establishment to 1985 for each route. Only before and after two mainshocks of lower magnitude around route Liwang-Jingning and Xinduqiao-Luhuo are without gravity changes which amount to 25% of the total mainshocks shown in Table 3. It may be regarded if the precision gravity lines pass through future epicentre or nearby possibility of observing the gravity changes before and after earthquakes would be larger.

The whole variations of earth tide data before and after mainshocks were obtained in a range of 580km from the station. So the numbers of mainshocks with M≥5.0 in range of 600km from every station are listed in Table 4. Totally 52 mainshocks occurred from establishment to 1985 for each stations. The variations of earth tide before mainshocks appeared amount to 13% of the total mainshocks only. The variations of earth tide before 5 mainshocks with M≥6.0 have been appeared around the stations of Huangbizhuang, Tianshui and Kunming amount to 63% of the total mainshocks in the three areas. Meanwhile, the variations of earth tide before 2 mainshocks with M≥5.0 have been appeared around stations of Yinchuan and Lanzhou that amount to 25% of the total mainshocks in these two areas only. Therefore it seems that the possibility of appearance for variations of earth tide before mainshocks with M≥6.0 are may be greater than that before mainshocks with M≥5.0 in a range of 600km from stations.

Table 3 The Mainshocks M≥5.0 within the Range of 50km from Route

Gravity Route	Period	Amount of Mainshocks			
		M=5.0-5.9	M=6.0-6.9	M=7.0-7.9	Total
Beizhen-Zhuanghe	1972—1985			1(1)	1(1)
Beijing-Shanhaiguan	1971—1985			1(1)	1(1)
Zhangjiakou-Yuanping	1978—1985	1(1)			1(1)
Dongming-Juye	1978—1985	1(1)			1(1)
Liwang-Jingning	1979—1985	2(1)			2(1)
Xinduqiao-Luhuo	1978—1985	1(0)	1(1)		2(1)

Table 4 The Mainshocks M≥5.0 within the Range of 600km from Earth Tide Station

Station	Period	Amount of Mainshocks			
		M=5.0—5.9	M=6.0—6.9	M=7.0—7.9	Total
Huangbizhuang	1972—1980	3(0)	1(0)	1(1)	5(1)
Yinchuan	1981—1985	4(1)			4(1)
Tianshui	1970—1982	7(0)	1(1)	2(2)	10(3)
Lanzhou	1983—1985	4(1)			4(1)
Kunming	1975—1985	26(0)	2(0)	1(1)	29(1)

*The figure in brackets is the number of mainshock with change of gravity or earth tide.

It can be seen from the gravimetric resurveys and deformation data (Table 6 and Figure 2), that there are two different forms of the gravity data after earthquakes. One form is that the gravity values do not return to the beginning anomalous values after quakes, and there are only several tens of millimeters of crustal deformation after mainshocks in such regions. Such as the maximum deformation value prior to the Tangshan earthquake in epicenter area was +28mm and +15mm before Haicheng earthquake respectively. When the mainshocks occur, after earthquakes are accompanied by greater surficial deformations, most of them are strong earthquakes M>7.0. For example, after the Tangshan earthquake, there were 220mm and 290mm bench marks uplift 200m away from the gravity station I in the highest intensity area of Tangshan. After the Haicheng earthquake, there were 25mm uplift near Gaixian station 47km away from the epicenter and 140mm of subsidence in the highest intensity area of Haicheng. Agter the Tangshan earthquake, the elevation correction of the gravity change is about 60μg. After the Haicheng earthquake, the elevation correction of gravity. Change is only about 3μg. The gravity changes do not recover to the beginning anomalous value.

Another form is the part recovery of gravity changes after earthquakes. There are several millimeters to several centimeters of deformation during the whole process of the earthquakes preparation and occurrence. Most of them are moderate earthquakes with M=5-6, such as Daofu, Haiyuan, Heze earthquakes. The gravity changes can recover to the beginning anomalous value, if the gravity values are corrected by the amount of elevation.

On the basis of the data from Tables 6 and 7 the statistical equations among the M, L, T or Tc can be obtained using multivariate

Table 5 Earthquake Parameters

Date	Latitude N	Longitude E	M	Aftershock Region: Depth H(km)	Major Axis a(km)	Minor Axis b(km)	Location
Feb. 6, 1973	31.3°	100.7°	7.9	11	110	[illegible]	Luhuo
Feb. 4, 1975	40.7°	122.8°	7.3	16	70	30	Haicheng
May. 29, 1976	24.5°	99.0°	7.3	24	90	45	Longling
Jul. 28, 1976	39.4°	118.0°	7.8	22	145	50	Tangshan
Aug. 16, 1976	32.6°	104.1°	7.2	15	80	25	Songpan
Jan. 24, 1981	31°20′	101°20′	6.9	12	53	20	Daofu
Aug. 13, 1981	40°30′	113°20′	5.8	18	13	5	Fengzhen
Apr. 14, 1982	36°47′	105°18′	5.7	20	12	12	Haiyuan
Nov. 7, 1983	35°18′	115°36′	5.9	12	12	8	Heze
Jan. 6, 1984	37°48′	102°30′	5.3	12	15	9	Wuwei
Nov. 23, 1984	38°10′	106°20′	5.3	14	15	5	Lingwu

linear regression analysis and which are up to F standard, the results are shown in Table 8. The gravity changes and the variations of earth tide start near the epicenter and propagate away with time. This shows that the anomalous accumulation time of different magnitude mainshocks is difference, the formation of complete

Table 6 The Data of Gravity Change and Deformation

Earthquake	Gravity Change: Date	Distance L(km)	Epicentral Station	Anomalous Days Start T(d)	Anomalous Days End t(d)	Δg (μg)	δ	Deformation: Date	Station	Elevation Δh (mm)
Haicheng	1972—1973	50	Gaixian-	964	0	-60	±50	1968—1970	Gaixian	+15
	1972—1975*		Donghuangdi			-90		1970—1975*	Gaixian	+25
Tangshan	1971—1976.4	1	Beijing-	1625	3	+98	±25	1971—1976.6	Tangshan	+25
	1976.4—1976.12		Tangshan I			-86		1964—1979	Tangshan	+290
Daofu	1978.10—1980.8	30	161—162	823	159	-53	±18	1974—1980.11	162 Station	+8
	1980.8—1981.1*		Station			+100		1980.11—1981.2	162 Station	+32
Fengzhen	1979.3—1981.5	36	Yanggao-Datong	897	101	-80	±35			
Haiyuan	1980—1981	44	160km-	698	164	+81	±25	1976—1981	160km	-26
	1981—1982*		Haiyuan			+29		1981—1982*	Haiyuan	0
Heze	1980.4—1983.9	18	Dongming-	1311	64	-51	±20	1980.10—1983.5	Heze	-15.2
	1980.4—1983.11*		Heze			-38		1980.10—1983.12	Heze	-9.7

*The date is date after earthquake.

Table 7 The Data of Earth tide before and after Earthquakes

Earthquake	Station	Epicentral L(km)	Earth Tide: Anomalous days: Daily Mean: Sign	Start T(d)	End t(d)	Tide Factor: Days (d)	Value δ%	Error δ%
Luhuo	Tianshui	580	+	141	7	98	-5	1
Longling	Kunming	400	−	210	56	150	-3	1
Tangshan	Huangbizhuang	390	+	301	63	/	/	/
Songpan	Tianshui	300	+	168	114	260	-9	1
Daofu	Tianshui	550	−	234	133	208	-3	1
Wuwei	Lanzhou	200	−	126	15	126	-7	3
Lingwu	Yinchuan	40	−	93	0	/	/	/

Table 8 Statistical Relation of Multivariate Linear Regression

Survey Method	Statistical Relation	N	F Value
Gravity Survey	$T=991.52+79.83M-15.96L$	7	$F=3.73$, $F_{0.05}=6.94$
	$T_c=716.46+113.68M-17.21L$	7	$F=5.40$, $F_{0.10}=4.32$
Daily Mean of Earth Tide	$T_c=-103.42+39.05M-1.06\cdot10^{-1}L$	7	$F=7.00$, $F_{0.05}=6.94$

Table 9 Statistical Relation of Correlation

Survey Method	Statistical Relation	N	Relation Coefficients	Mark
Gravity Survey	$T=1.59\cdot10^{-1}S+713.88$	8	$\gamma_\alpha=0.71$, $\gamma=0.77$	
	$T_c=0.18S+621.01$	8	$\gamma_\alpha=0.71$, $\gamma=0.78$	$S=\pi\cdot\frac{a}{2}\cdot\frac{b}{2}$
	$T=7.48\cdot10^{-8}V+725.9$	8	$\gamma_\alpha=0.71$, $\gamma=0.77$	
	$T_c=8.25\cdot10^{-8}V+634.75$	8	$\gamma_\alpha=0.71$, $\gamma=0.77$	$V=\frac{4}{3}\pi\cdot\frac{a}{2}\cdot\frac{b}{2}H$
Daily Mean of Earth Tide	$T_c=2.14\cdot10^{-2}S+78.13$	7	$\gamma_\alpha=0.75$, $\gamma=0.80$	

anomalies more stronger earthquakes need longer time.

On the basis of the data in Tables 6 and 7, the statistical relations between the S or V and T or Tc can be obtained using correlation analysis which are shown in Table 9. The size of aftershock's distribution area or the source volume are related to the duration time of gravimetric anomalies.

ANALYSIS

The remarkable variations in the earth tide amplitude prior to major earthquakes with greater magnitude have been suggested by theoretical investigations. Theoretically studies by Beaumont and Berger[8] indicated that amplitude of tidal strains and tilts could change by 60% if seismic P wave velocity decreases by 15% in a dilatant zone embedded within the crust. They suggested that the amplitude changes could be detected within a distance of 1.5 times of the typical dimension of the dilatant inclusion. Besides, some observations of the earth tide amplitudes changes have been reported also in relation to earthquakes of Japan and Soviet Union[8].

The variation of the local crustal elasticity can be studied using the variation of earth tide factor δ. If the earth is regarded as a rigid body, the tidal factor δ is the ratio of the earth tide of each order at one point on the earth's surface to the tide of the solid earth of the rigid earth of the same order. If $n=2$, δ_2 is given by

$$\delta = 1 + h_2 - \frac{3}{2} k_2, \tag{1}$$

where h is the ratio of the tidal height of n-order solid tide of the elastic earth surface to that of the equilibrium tide at the corresponding point. K equals to the ratio of the n-order additional generating force potential caused by the earth's tidal deformation on the earth surface to the original tide generation force potential of the same order. Obviously, the Love number h and k of the elastic earth is in relation to the density distribution and elastic property inside the earth. According to experimental result, the elasticity modulus of the rock decrease before it is compressed to break.

Comparing with our survey data of the earth tide factors, the anomalous variation of the tidal factors before earthquakes decreases and stations where anomaly appears are farther from the epicenters. We may consider that the variations of earth tide factors mirror the variations of density in focal region and in wider range of the upper crust.

Chen Yuntai et al.[6] conjectured that some certain great events might be associated with some sort of mass migration under the ground within the crust or in the upper mantle. This migration would cause a large part of the gravity change observed. These authors have made a theoretical analysis of this effect, even though they were not yet clear about the physics of it.

If only the gravimetric effect, namely Bouguer correction δ_{gD} caused by the crustal deformation (elevation change) before earthquakes is considered, then

$$\delta gD = -2\pi G \left(\frac{4}{3}\rho_E - \rho\right) h, \tag{2}$$

where $G = 6.670*10^{-8}\ cm^3/g.s^2$, $\rho_E = 5.517 g/cm^3$, $\rho = 2.67 g/cm^3$, h is the elevation change. The gravity change of Tangshan station the only one above focal region, is 98 microgals (Table 6). But the value and sign of all the elevation change data of Tangshan earthquake can not be explained.

It can be found from the Table 6 that during the earthquake preparation process, the gravity changes are either positive or negative, most are in focal region or the nearby fracture zones and value of the elevation change is not too large. Thus, the density variation of the media or mass migration is in the vicinity of the earthquake preparation region before earthquake. These can be explained using the gravimetric effect δgM of mass migration,

$$\delta g M = 2\pi G\rho_F\left[1 - F\left(\frac{H}{a}\right)\right]h', \qquad (3)$$

where ρ_F is the density of the mass migration, H is the void or the cylinder height in the magmatic aggregation region, a is the radius, h′ is the void space caused by the surface deformation. F(H/a) is the function of the ratio of the cylinder height H to the radius, which influences the gravity change

$$F\left(\frac{H}{a}\right) = \left[\sqrt{1+\left(\frac{H}{a}\right)^2} - 1\right]\frac{a}{H} \qquad (4)$$

For the Tangshan earthquake, suppose H=16km, a=77km, $\rho_F=\rho$, when h′=98cm, there produces 98μg gravity change, this moment, such phenomenon can be regarded as mass movement, to vicinity of the earthquake preparation region. For the Haicheng earthquake, suppose H=12km, a=38km, $\rho_F=\rho$, when h′=−95cm, there produces 90μg gravity change, this moment, such phenomenon can be taken as mass movement out.

In comparison with the data of the gravity resurveys, it can be seen that all the stations of gravity changes are in the vicinity of the fracture zones in or nearby the focal regions. The range of gravity change is relatively local and limited to one or two stations. This can held that the gravity change of resurveys reflects the density variations caused by the move-in or move-out of crust or upper mantle of fracture zones in or nearby the focal region.

Another problem which is not often considered is the phenomena the recovery of gravity changes after earthquakes. In accordance with the above data, there are two different types. The first type is that the gravity changes with earthquake do not recover to the beginning.

Its preparation and occurrence are probably caused by the mass migration effect and the masses are permanently retained and leave the focal region. There are no obviously active fractures through the focal region and no elevation in the surface before earthquakes. Due to the action of the stress field, the mass migrate out and in. After the accumulation there occurs sudden stress release in the focal region, and simultaneously, greater surficial deformation. After the move-out and move-in of the mass, these masses remain there or they are squeezed out before the action of the neotectonic stress field. The Tangshan and Haicheng earthquakes belong to this type. The second type is that there is recovery tendency for the gravity changes after earthquakes and a part of them recovers to the beginning. Such earthquakes are probably caused by the creep of main active fracture in the vicinity of epicenter some time before the earthquakes. when close to the occurrence of earthquakes the intensified activity produces slip, and reduces after earthquakes, but the creep remains at a certain level. Such earthquakes are the results produced by the intense movements under a particular tectonic condition and the background of the normal tectonic movement. Generally, such shocks occur in the active faults well-known to all. For examples the Daofu earthquake occurred in vicinity of Xianshuihe river fracture and the Heze earthquake occurred near the Liaokao fracture zone.

CONCLUDING REMARKS

The following points may be reached from gravimetric data before and after 11 mainshocks with $M \geqslant 5.0$ in China:

1. If the moderate-strong earthquakes will occur in proper range from the gravity station, then there will be a certain amount of gravity changes before and after the earthquakes.

2. The duration T or Tc of gravity change is dependent on the magnitude M, the distance between the station and the epicenter L and the area of aftershocks S or volume of source V.

3. The changes of gravity values accompany an earthquake are mainly caused by the density changes of underground mass, apart from crustal deformation.

4. Different features of earthquakes may be verified by the data of gravity and deformation.

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我国中强震前后重力场的时空变化特征

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摘要

本文汇集了1970—1985年中国的高精度重复重力测网和固体潮台站的重力变化资料，分析了在6个测网和5个测点周围的11个M≥5.0地震与重力变化的关系，并且探讨了重力场随时间变化的可能机制和特征。作者认为，在重力测点附近一定范围内如果发生中强以上地震，那么会伴随地震出现一定量的重力变化，重力变化的时间与震级M和震中距L以及余震面积S或震源体积V之间有一定的依赖关系。伴随地震出现的重力变化除由地壳形变引起外，主要可能是地下物质密度变化所引起。不同类型的地震特征可以用重力和形变资料来佐证。