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Temporal variation of gravity-field in North China before and after the 2011 Japan *M*w9.0 earthquake

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Abstract: By using absolute and relative-gravity data recorded by the gravity network in North China, we obtained some large-scale and high-spatial-resolution images of gravity variation in this area for the first time. By analyzing these images, we found that the gravity in Liaodong peninsula area showed an obvious increase of $80 \times 10^{-8} ms^{-2}$ during about one- and-half year before the 2011 Japan *M*w9.0 earthquake, and a rapid decrease after the earthquake. This gravity variation is similar to that observed previously for the 1976 Tangshan *M*7.8 earthquake.

Key words: gravity network of North China; Japan *M*s9.0 earthquake; gravity variation

1 Introduction

Detection of gravity anomalies by repeated gravity survey is one of the most important methods in earthquake prediction research[1-4]. The key region for such research in China is North China, which has suffered frequent and violent seismic activities, and is where mobile gravity survey was firstly carried out. In spite of decades of efforts, which gained much achievements[4-7], there are still some outstanding problems in the relative-gravity monitoring system in this region, including dispersed survey network, limited valid monitoring areas, different observation cycles, and lack of absolute-gravity datum. These problems led to serious problems in the application of gravity data to seismic monitoring and research. To improve the network performance, the Department of Monitoring and Prediction, China Earthquake Administration (CEA), has combined small relative-gravity monitoring systems into a single network in North China (Figs. 1 and 2). The improved mobile gravity monitoring network includes

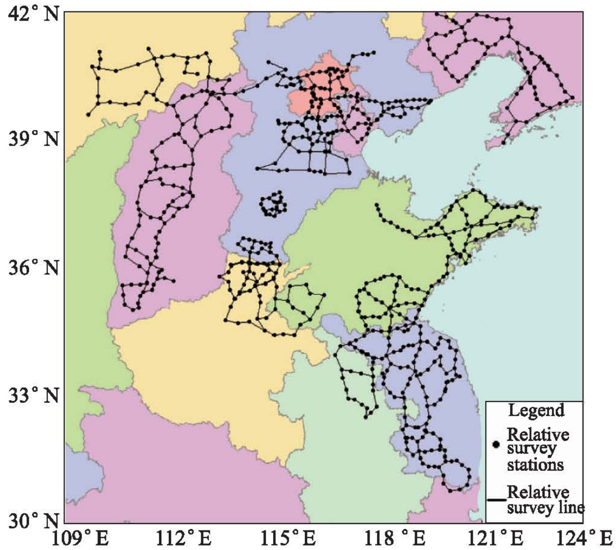

Figure 1 Gravity networks in North China before 2009

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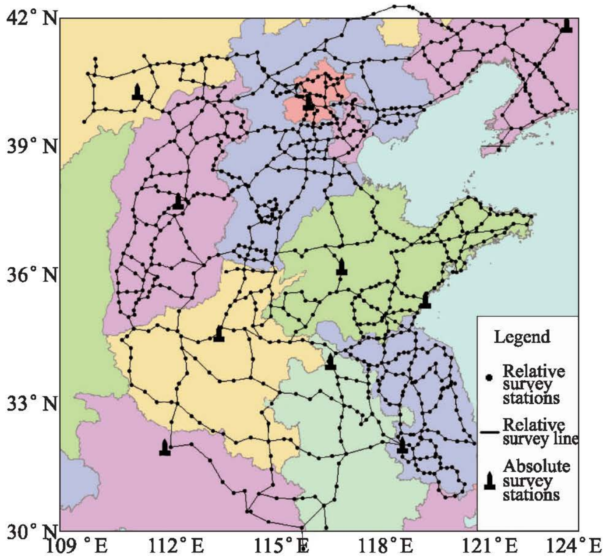


Figure 2 Unified gravity network in North China after upgrade in 2009

about 1000 relative-gravity stations, 10 of which are also absolute-gravity stations[8], covering the whole region (109° – 124°E, 30° – 42°N).

In this paper, we present some temporal-variation images in North China for the first time, based on the absolute and relative-gravity data of 4 surveys during 2009 – 2011 with a unified gravity datum. We also discuss how the observed gravity variation was related to the 2011 Japan *M*w9.0 earthquake.

2 Gravity survey and data

Four absolute and relative-gravity surveys have been carried out since the last half of 2009, when the improved gravity network in North China began to work. In order to observe gravity variation based on a single gravity datum, we used absolute-gravity data to set a priori gravity datum and as constraint in the network, then employed the method of weighted-constraint adjustment on relative gravity measurements, and finally obtained the high-accuracy gravity variation result in the entire region.

2.1 Relative-gravity survey

Relative-gravity surveys were carried out jointly by nine departments of China Earthquake Administration, including the Geophysical Exploration Center (GEC), the National Earthquake Response Support Service (NERSS), the Institute of Geophysics (IG), the Institute of Seismology (IS), Earthquake Administration of Hebei province (EQHE), Earthquake Administration of Lining province (EQLN), Earthquake Administration of Shandong province (EQSD), Earthquake Administration of Anhui province (EQAH), and Earthquake Administration of Jiangsu province (EQJS). In the relative gravity surveys, two types of high-precision gravimeters were used: LCR-G and CG-5. In order to reduce measurement error, the scale factors had been calibrated along the "Wuhan-Zhengzhou-Beijing-Shenyang" long baseline. Table 1 shows the division of labor among the various organizations in the gravity surveys.

Table 1 Relative-gravity surveys in North China area

Organization	Monitoring area	Gravimeters used			
		2009, 2nd half	2010, 1st half	2010, 2nd half	2011, 1st half
GEC, CEA	Shanxi, Henan, Hebei	G808, G818	G808, G818	G808, G818	G808, G818
NERSS, CEA	East of Capital Circle area	G1147, G853	G1147, G1149	G1149, G596	G1149, G853
IG, CEA	West of Capital Circle area	G1149, G853	G570, G596	G570, G1147	G570, G1147
EQLN, CEA	Liaoning	G829, G843	G1003, G1134	G1003, G1134	G829, G843
EQHE, CEA	Hebei	G829, G843	G1003, G1134	G1003, G1134	G1003, G1134
EQSD, CEA	Shandong	G999, G1027	G999, G1027	G999, G1027	G999, G1027
EQAH, CEA	Anhui	G999, G1027	G808, G818	G808, G818	G808, G818
EQJS, CEA	Jiangsu	G854, G1027	G999, G1027	G999, G1027	G999, G1027
IS, CEA	Hubei	G1003, G1134	G808, G818	CG – 509, CG – 524	CG – 216, CG – 217

2.2 Absolute-gravity survey

From August 2009 to June 2011, four absolute-gravity surveys were carried out by the Institute of Earthquake, China Earthquake Administration, at 10 stations: Shenyang, Tuoketuo, Baijiatuan, Taiyuan, Zhengzhou, Rizhao, Taian, Nanjing, Huaibei and Xiangyang. In data processing, we made corrections for earth tide, light speed, local barometric pressure, polar motions, and vertical gradient[9], and obtained absolute-gravity values with a high precision of mostly better than $3 \times 10^{-8} ms^{-2}$. Because the gravity values of the 10 absolute stations basically covered the whole range of gravity values of all stations (Fig. 3), the absolute-gravity stations constituted a high-precision control network for the relative-gravity data and helped to reduce system and random errors.

2.3 Data processing

Because different gravity surveys were carried out by different departments of China Earthquake Administration, a key point in data processing is to consolidate the different data sets into one. Firstly, we gave a unique serial number to each station to form a unified gravity network. Secondly, we used absolute-gravity data as the unique datum and control. Thirdly, we carried out adjustments, by using the application software LGADJ; the results indicated that the mean precision of the gravity values reached $10.7 \times 10^{-8} ms^{-2}$. Lastly,

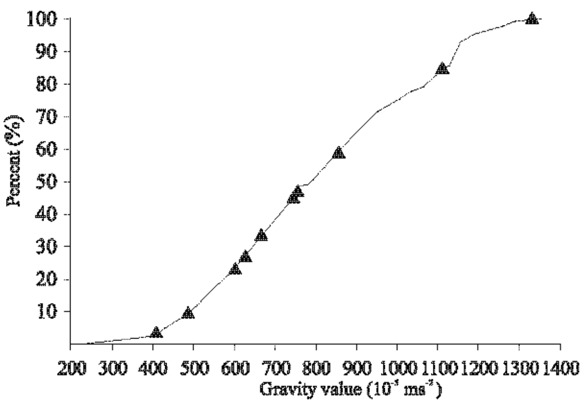


Figure 3 Gravity-value distribution of absolute-gravity stations and relative-gravity stations (▲ indicates absolute gravity stations; the curve indicates relative gravity stations)

we calculated the gravity variation and obtained the individual and accumulated gravity-field variation images from 2009 to 2011 (Figs. 4 and 5). As usual, we used 3 times of precisions, $30 \times 10^{-8} ms^{-2}$, as the threshold for identifying anomalous variation (the blue and orange areas in Figs. 4 and 5).

3 Analysis of gravity variations

3.1 Differential gravity variations

1) From the last half of 2009 to first half of 2010

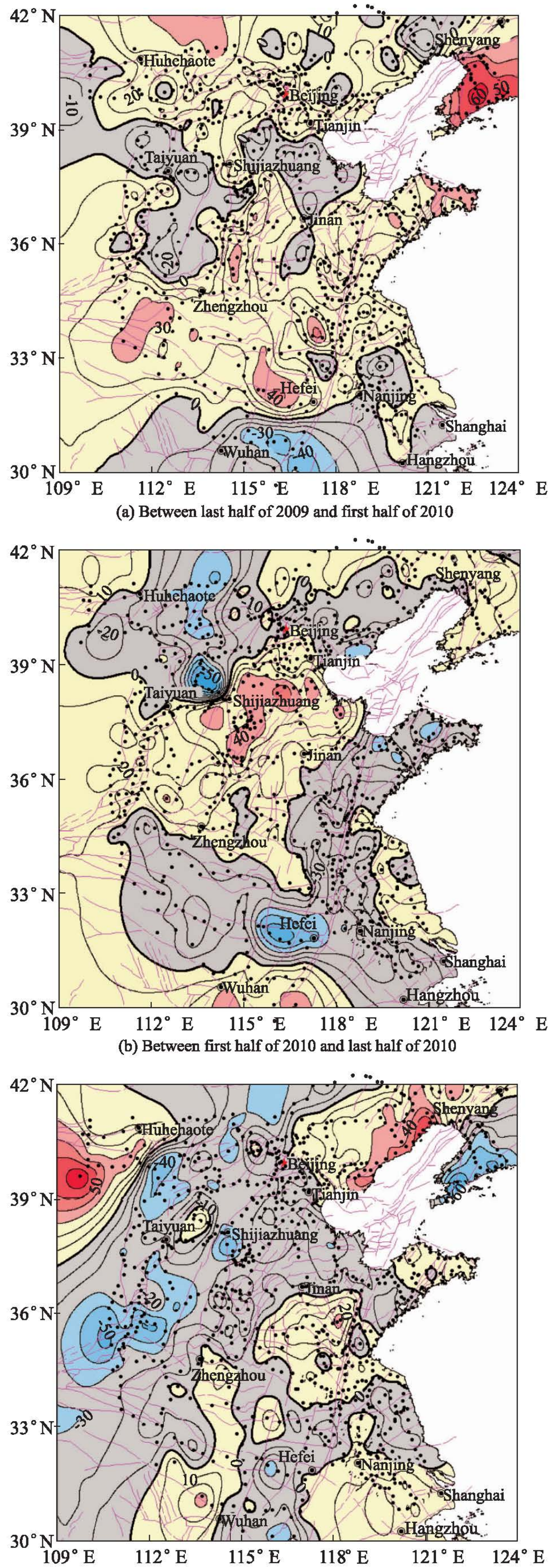
In most areas, the gravity showed mild variations of $-30 - +30 \times 10^{-8} ms^{-2}$. However, in Liaodong peninsula, which is the southern part of northeast China, there was a prominent positive anomalous variation amounting to $60 \times 10^{-8} ms^{-2}$, with contours (from Bohai bay to Shenyang) parallel to the northern part of Tanlu fault to the west. It's likely that the northern part of Tanlu fault played an important role in controlling the gravity variation in this area. In contrast, the gravity in the bordering area between Anhui and Hubei in the southern part of Tanlu fault showed negative variation amounting to $-40 \times 10^{-8} ms^{-2}$, which gradually turned positive towards north.

2) From first half of 2010 to last half of 2010

In most areas, the gravity variation was small. Liaodong peninsula showed a positive change of less than $20 \times 10^{-8} ms^{-2}$. On the north-western side of Baoding-Shijiazhuang fault, a dramatic negative variation of $-60 \times 10^{-8} ms^{-2}$ appeared and extended to Inner Mongolia to the north. In Hebei province on the south-eastern side of Baoding-Shijiazhuang fault, the gravity variation was positive, amounting to $40 \times 10^{-8} ms^{-2}$. The zero-contour line coincided with the eastern edge of Taihang mountain, across which the gravity difference was about $90 \times 10^{-8} ms^{-2}$ with a high-gradient zone trending north-east. In the southern part, the overall character was opposite to that during the previous period: The gravity variation in the bordering area between Anhui and Hubei in the southern part of Tanlu fault was moderately positive, and gradually turned negative towards south.

3) From last half of 2010 to first half of 2011

The gravity variation became larger than the previous

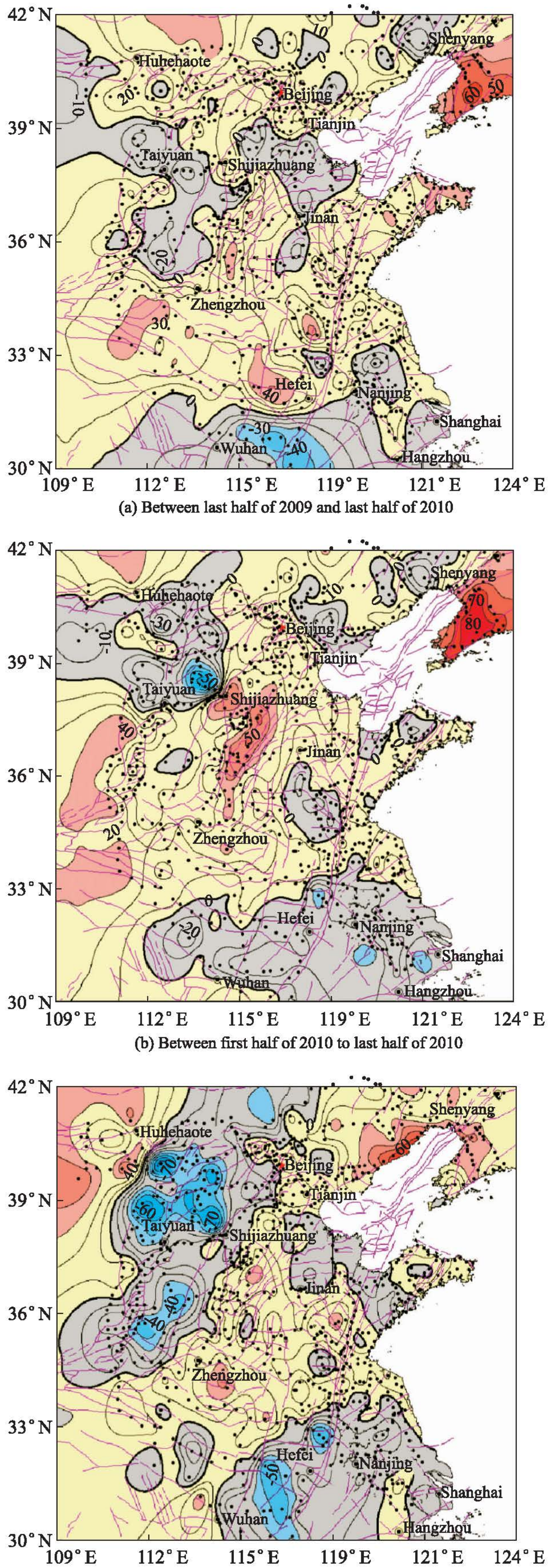


(a) Between last half of 2009 and first half of 2010

(b) Between first half of 2010 and last half of 2010

(c) Between last half of 2010 and first half of 2011

Figure 4 Differential gravity-variation image in North China (unit: $10^{-8}ms^{-2}$)



(a) Between last half of 2009 and last half of 2010

(b) Between first half of 2010 to last half of 2010

(c) Between last half of 2009 to first half of 2011

Figure 5 Accumulated gravity-variation image in North China (unit: $10^{-8}ms^{-2}$)

period. In Liaodong peninsula, the gravity field became negative, amounting to $-60\times10^{-8}ms^{-2}$, opposite to the variation during period of the last half of 2009 to first half of 2010. While on the other side of the Tanlu fault, the gravity variation was obviously positive in the bordering area between Hebei and Liaoning. It's likely that the northern part of Tanlu fault controlled the gravity variation once again. In the western part of the survey area, the negative gravity-variation areas became larger and dispersed, one of which was located in Linfen basin and the other in northern Taihang mountain. There was still positive gravity variation in the bordering area between Shanxi province and inner Mongolia.

3.2 Accumulated gravity-field variations

1) From the last half of 2009 to last half of 2010

The overall trend in the accumulated result is that the variation was enhanced. In Liaodong peninsula, the positive changes amounted to $80\times10^{-8}ms^{-2}$, and the controlling effect of Tanlu fault was clearer than during the first period alone. In the area between Zhengzhou and Shijiazhuang on the east side of Taihang Mountain, gravity showed a positive anomalous variation amounting to $50\times10^{-8}ms^{-2}$, while on the west side of Baoding-Shijiazuang fault along the edge of Taihang Mountain, the gravity showed a dramatic negative variation of $-60\times10^{-8}ms^{-2}$. It's very clear that the positive and negative areas were divided by Baoding-Shijiazhuang fault.

2) From the last half of 2009 to first half of 2011

Gravity showed mainly a decrease in this result. In Liaodong peninsula, the positive anomaly almost disappeared, but on the west side of Tanlu fault, there was a positive anomalous variation of $+60\times10^{-8}ms^{-2}$ along with the Bohai bay. It's likely that the positive anomaly variation moved to the west side of Tanlu fault. The positive anomaly on the east side of Taihang Mountain during period of the last half of 2009 to first half of 2010 disappeared, while the negative anomaly variation on the west side extended to the border area between Shanxi and inner Mongolia and turned sharply to positive with a high-gradient zone trending north-east.

3.3 The observed gravity variations and the 2011 Japan *M*w9.0 earthquake

On March 11, 2011, a great *M*w9.0 earthquake occurred on the east coast of Honshu Island of Japan as a result of thrust-faulting along the interface between the Eurasia plate and the subducting Pacific plate[11-13]. Recent tomographic studies indicate that the Pacific slab beneath the Japan Sea is stagnated in the mantle transition zone beneath northeast China. This situation is likely to be related to the occurrence of deep earthquakes at depths of 600 km in Mudanjiang and Huihun, and may have dramatic impact on the crustal stress, seismicity, volcanism, as well as tectonic evolution in North China and northeastern China[14-17].

Liaodong peninsula is located in the southern part of the northeastern China, and is the closest in our survey region to the underthrust area. As shown above, the gravity field in Liaodong peninsula was in a process of rapid-increase (from later half of 2009 to first half of 2010), and moderate increase (from first half of 2010 to later half of 2010) during about one and half year before the earthquake with an accumulated variation amounting to $80\times10^{-8}ms^{-2}$. But after the earthquake, there was a prominent negative variation amounting to $-60\times10^{-8}ms^{-2}$ (from later half of 2010 to first half of 2011). The overall process of "rapid gravity increase-moderate increase-earthquake occurrence-rapid decrease" is very similar to that of the 1976 *M*7.8 Tangshan earthquake[4]. Since environmental effects caused by changing air-pressure and continental – water movement, etc., were relatively small (ten $10^{-8}ms^{-2}$ or so)[18], it is probable that the observed gravity variations reflected the tectonic stress, crustal deformation, and mass movement associated with the preparation and occurrence of this earthquake.

4 Conclusions

1) By using the absolute and relative-gravity data of the gravity network of North China from 2009 to 2011, we obtained some large scale and high-spatial-resolution images of gravity variation in North China for the first time.

2) The gravity variation in eastern Liaodong Peninsula had obvious relation with the 2011 Japan *M*w9.0 earthquake. The gravity mainly showed continued increase before the earthquake and rapid decrease afterward, similar to the 1976 Tangshan earthquake. The northern part of Tanlu fault (from Bohai bay to Shenyang)

showed obvious control on gravity variation in eastern Liaodong Peninsula.

3) How the earthquake caused the observed gravity variation in North China and how may it affect tectonic activities in the future are both in need of further studies.

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