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Seismogenesis and occurrence of earthquakes as observed by temporally continuous gravity variations in China*

GU Gongxu[1], John T. Kuo[2], LIU Keren[1], ZHENG Jinhan[1], LU Hongyan[1] and LIU Duanfa[1]

1. Institute of Geophysics, State Seismological Bureau, Beijing 100081, China; 2. Lamont-Doherty Earth Observatory and Aldridge Laboratory of Applied Geophysics, Columbia University, New York, NY 10027, USA.

Abstract In the last decade and a half, a number of earthquakes of magnitude 4—5 have occurred in the Beijing-Tianjin-Tangshan-Zhangjiakou (BTTZ) region. On the basis of the analysis of the temporally continuous gravity variation data principally from the Baijiatuan (BJTN) semi-permanent gravity base station, a general picture of gravity variation related to the seismogenesis and occurrence of earthquakes has emerged.

As gravity variation is generally observed on the earth's surface, the predominant influence is that of the near-surface groundwater. The subsurface fluids are distributed throughout all depths in the crust and respond to the seismogenic processes of earthquakes as well. The influence of the subsurface fluid on gravity variation is, therefore, of equal importance. The fluids, which include the near-surface groundwater and the subsurface fluids distributed throughout all depths in the crust, play a more important role in the gravity variations in terms of the seismogenesis and occurrence of earthquakes than previously realized.

The abundance of accumulated data shows that the dilatancy instability (IPE) model seems not applicable at least to the seismogenesis and occurrence of earthquakes in the BTTZ region. In order to reflect the physical reality, the earlier proposed combined dilatancy model requires modification. The seismogenic area in the BTTZ region may be modelled as a large pre-stressed volume of a fluid-filled poroelastic medium, including not only the pre-stressed volume surrounding the impending rupture zone but also the volume containing the rupture of the fault zone itself. The pre-stressed volume outside the impending rupture zone is under a state of relatively small change of the pre-existing regional tectonic stress, while the volume containing the impending rupture zone is an induced region of very high local stress concentration, and/or pore over-pressure.

The calculated gravity variations based on the modified combined dilatancy model (MCDM) with the known physical parameters of the region resemble the observed residual gravity variations. Apparently the residual gravity variations, in addition to responding to the deep-seated seismogenesis and occurrence of earthquakes, predominantly respond to the near-surface groundwater, and the subsurface fluids, which themselves also respond to the seismogenesis and occurrence of earthquakes. On the basis of comparison between the calculated MCDM gravity variations and the observed residual gravity variations, the change of the regional tectonic stress field for the earthquakes of magnitude 4—5 in the BTTZ region could be approximately estimated to be in the neighbourhood of 5%—7%.

It is apparent that simultaneously monitoring the temporally continuous variations of the near-surface groundwater, subsurface fluids, and gravity coupled with modelling would provide vital information on the history and evolution of the seismogenic processes about 10 months to 1 year prior to the occurrence of an earthquake of magnitude 4—5 and tens of years prior to that of an earthquake of magnitude 7—8 such as the Haicheng earthquake in 1975 and the Tangshan earthquake in 1976 in the BTTZ region. These earthquakes of magnitude 4—5, which so far have occurred in the BTTZ region, may well be the precursory events to a larger earthquake.

Keywords: gravity variations, earthquake, groundwater, subsurface fluids.

THIS paper is intended to report the most recent findings pertaining to the gravity variation associated with the seismogenesis and occurrence of earthquakes in the BTTZ region as observed by temporally continuous recording mainly from the BJTN semi-permanent gravity station (SPGS).

Since the 1960s, spatial and temporal variations of gravity before and after earthquakes have been observed[1—4]. All these observed variations of gravity appeared to follow the free-air gradient and to be proportional to the change of elevation only. Chen *et al*.[5] estimated the observed gravity variations before and after the 1975 Haicheng and the 1976 Tangshan earthquakes in China and found that just free-air gradient did not account for the large values of the observed gravity variation. They in turn postulated the possibility of a mass transfer mechanism at depths.

The occurrence of earthquakes accompanied by the change of local gravity thus has been observed for some time in China and abroad by means of temporally discrete gravity observations that were made at a time interval varying from a few weeks to several months before and after an earthquake. However, a definitive conclusion concerning the nature of the local variation of gravity with respect to the seismogenesis and occurrence of earthquakes has never been reached.

* L-DEO, Columbia University, Contribution No. 5613.

In 1980, a US/China co-operative research project on the relationship between the local variation of gravity and the occurrence of earthquakes in the BTTZ region was launched by the Institute of Geophysics, State Seismological Bureau, China, and Columbia University, U. S. A. In the BTTZ region, seven semi-permanent gravity stations, which were connected by a network of 6 profiles of mobile gravity stations, were established. In addition to measuring temporally discrete gravity variations, temporally continuous gravity variation measurements have also been carried out.

Altogether 13 earthquakes of magnitude 4—5 occurred in the region from 1981 to 1995, among which 8 earthquakes were located within a radial distance of about 60 km from BJTN, and one was located at an epicentral distance of 11km from Baodi (fig. 1). These 9 earthquakes are included in the present investigation (table 1).

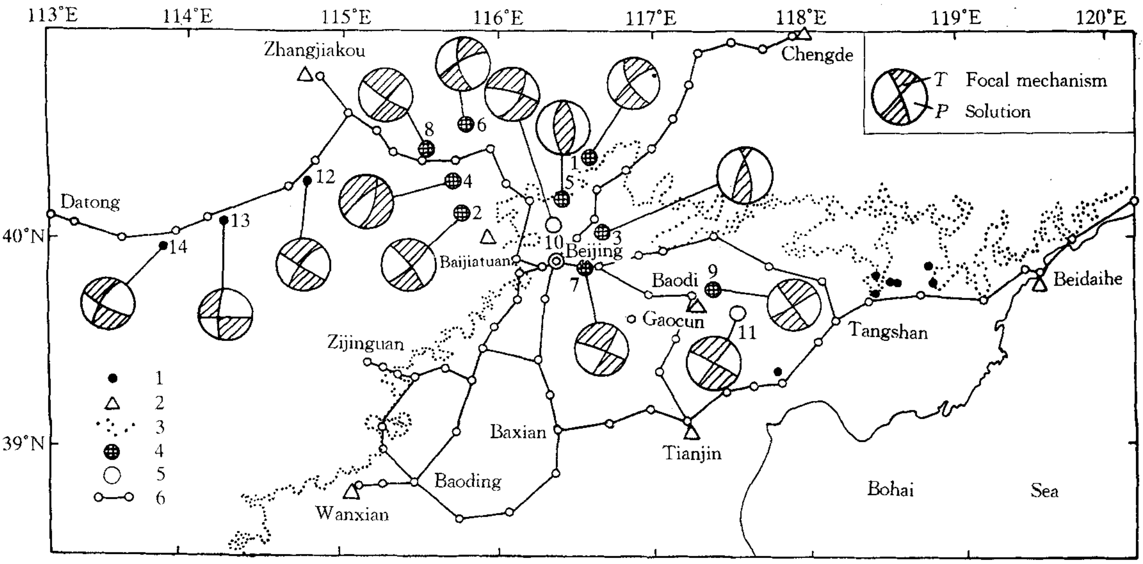

Fig. 1. The network of the semi-permanent and mobile gravity stations and distribution of the epicenters for the earthquakes of magnitude $M_L \geqslant 3.5$ occurring in the BTTZ region during 1981—1995. 1, Earthquakes far away from BJTN or occurring in the Tangshan area; 2, semi-permanent gravity station; 3, boundary between plain and mountains; 4, earthquakes discussed in this paper; 5, earthquakes not discussed in this paper; 6, station and line for mobil gravity measurement.

Table 1 The earthquakes of magnitude $M_L \geqslant 3.5$ occurring in the BTTZ region in 1981—1995 (not including earthquakes occurring in Tangshan area)

No.	Origin	Time	Epicentral location			M_L	Remark
			E long.	N lat.	area		
1	1982-12-10	02-16-46	116°33′	40°28′	Madaoyu	4.9	60 km NE of BJTN
2	1985-11-20	19-42-22	115°50′	40°05′	Youzhou, E	4.7	32 km NW of BJTN
3	1986-11-10	16-58-51	116°43′	40°03′	Shunyi, E	4.7	47 km E of BJTN
4	1989-05-07	20-57-04	115°43′	40°16′	Youzhou, N	4.1	48 km NW of BJTN
5	1990-05-23	14-13-02	116°27′	40°13′	Xiaotangshan, N	4.2	31 km NE of BJTN
6	1990-07-21	08-41-52	115°50′	40°35′	Dahaituo	5.6	60 km NW of BJTN
7	1994-11-13	04-52-26	116°29′	39°53′	Chaoyang, Beijing	3.5	30 km SE of BJTN
8	1994-12-23	13-13-40	115°33′	40°28′	Huailai	4.3	72 km NW of BJTN
9	1989-03-02	18-15-49	117°25′	39°44′	Xiacang	4.3	11 km E of Baodi
10	1990-09-22	11-02-20	116°32′	40°05′	Xiaotangshan	4.5	17 km NE of BJTN[a)]
11	1993-11-18	07-05-08	117°32′	39°39′	Baodi SE	4.4	23 km SE of Baodi[a)]
12	1987-11-11	21-18-04	114°48′	40°17′	Xuanhua	4.7	far away BJTN & Baodi
13	1988-07-23	13-51-43	114°13′	40°05′	Yangyuan	5.0	far away BJTN & Baodi
14	1989-10-19	01-01-34	113°51′	39°57′	Datong	6.1	far away BJTN & Baodi

a) Not analysed as data interrupted.

The Baijiatuan semi-permanent gravity base station is located in the basement of the Baijiatuan seismic station of the Institute of Geophysics, State Seismological Bureau (SSB) about 30 km northwest of Beijing. The annual temperature of the basement varies from 14° to 24℃, with a daily fluctuation within 0.1℃.

The BJTN SPGS is equipped with a Geodynamics TRG-1 tidal gravimeter, No. 804. A typical value of the standard deviation (or σ) for Geodynamics TRG-1 tidal gravimeter is ± 0.50 μGal. An experimental monitoring well is located 100 m away from the tidal gravimeter installation.

As the data of temporally continuous gravity variation have been accumulated, a general picture of gravity variation associated with the seismogenesis and occurrence of earthquakes in the BTTZ region has emerged. As yet, some of the crucial questions remain to be addressed, particularly how gravity variation responds to the deep-seated seismogenic processes.

1 Brief account of geological and seismo-tectonic settings

The North China intraplate of the tectonic province in North China, in which the BTTZ region is situated, mainly consists of the fault-block regions[6]. The northern boundary of the intraplate is the Yanshan-Yinshan east-west tectonic belt. The southern boundary borders on the northern edge of the Qinling-Dabieshan tectonic belt. The western boundary includes the Yinchuan Basin, and the eastern limit is marked by the Bohai Sea. The Tanlu (Tancheng-Lujiang) fault zone is situated along the eastern margin of the Northern Hebei and North China fault block and is a major seismo-tectonic feature of the tectonic province. During the late Cenozoic, especially the Quaternary, a new tectonic system of smaller-scale horsts and grabens was formed on the older, larger-scale system of uplift belts and basins.

Throughout geological history, the North China intraplate has undergone various stages of geological evolution and has been tectonically stressed with the pre-existing complex fracture systems. Therefore, the BTTZ region is a pre-stressed, pre-fractured, pre-flawed, and dynamically fatigued inhomogeneous region.

The seismicity of the tectonic province in North China is well documented in the historical records of China. Since 1000 AD, the province has experienced 5 earthquakes of magnitude greater than 8, 12 earthquakes of magnitude 7.0—7.9, and more than 60 earthquakes of magnitude 6.0—6.9[7].

Fault-plane solutions show that the orientation of the maximum stress is in the direction of NE-SW to ENE-WSW as inferred from the studies of the $M = 6.8$ Xingtai, $M = 6.3$ Hejian, $M = 7.4$ Bohai and $M = 7.3$ Haicheng earthquakes, and an E-W maximum-stress orientation for the $M = 7.8$ Tangshan earthquake. Moreover, results of the deep well stress measurements in the region support the orientation of the stress system and yield a maximum stress of approximately 100 MPa in the region[8].

The North China intraplate as a whole is currently under an east-west regional compressional stress and southerly compression from the South China intraplate. The entire BTTZ region presently is undergoing extremely rapid deformation and is especially vulnerable to large earthquakes in the areas of intersection of the uplifting blocks and the subsiding sedimentary basins.

2 Gravity variation data reduction

The integrity of the observed gravity variation data was first checked by the Nakai data test method. In order to achieve the previously stated objective of evaluating the gravity field changes related to the seismogenesis and occurrence of earthquakes in the BTTZ region, all the effects on gravity variation, including instrumental drift, earth tides, elevation and near-surface groundwater changes were corrected to yield "residual gravity variation", the term of which will be referred to in the sequel.

Geodynamics TRG-1 tidal gravimeter is barometrically well compensated, and its temperature is controlled to better than 0.01℃. The loading effects of atmospheric pressure variation and ocean tides are neglected, resulting in an error of less than ± 1 μGal. The instrumental drift of Geodynamics No. 804 has been virtually linear from January 1981 to September 1990 as shown in fig. 2(a). The effect of earth tides on gravity variation can be accurately corrected by the Pertzev filter method. After the removal of earth tides, the instrumental drift had a drift rate of -166 μGal/a or -0.46 μGal/d ("negative value" designated as "decrease of gravity"). Because a serious power problem occurred in the basement of the BJTN seismic station, the tidal gravimeter was forced to be removed from the site and later reinstalled.

As a result, when Geodynamics No. 804 resumed its operation, the instrumental drift reversed its drift direction with an exponential decay, i.e. increasing gravity in comparison with its drift direction of decreasing gravity in the past ten years. Since July 1993, not only the tidal gravimeter has completely recovered but also the characteristics of the instrument improved to the point that it is virtually free of drift since July 1993 as shown in fig. 2(b). For the removal of the instrumental drift before September 1990, a linear function was used, and after September 1990, a polynomial of order three was used.

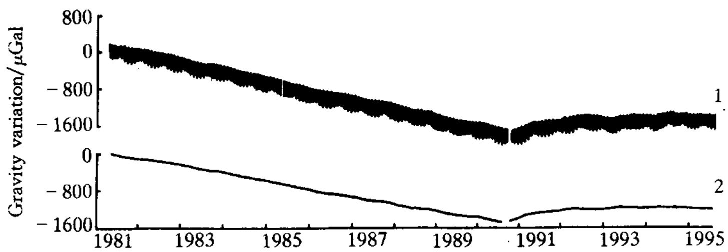

Fig. 2. 1, The 15 years original temporally continuous data of gravity variations recorded by Geodynamics TRG-1 tidal gravimeter No.804 in Baijiatuan; 2, the original gravity data with the earth tides removed showing the instrument drift.

The effect of elevation change on gravity variation can be corrected based on the free-air and Bouguer correction as

$$\Delta g(\mu\text{Gal}) = (3.086 - 0.4199\,\rho)\Delta H, \tag{1}$$

where ΔH is the change of elevation in cm, and ρ is the density contrast with the Bouguer density 2.0 gm/cm^3 for sediments and 2.6 gm/cm^3 for slightly fractured crystalline rocks.

The effect of water level change on gravity variation as observed in the BJTN experimental well generally follows a Bouguer approximation so that as the water level increases, the gravity also increases.

$$\Delta g(\mu\text{Gal}) = 42.0E * (S_y \delta W),$$

where δW is the water-level change in m as a function of time, E is an exponential function of time, and $*$ stands for convolution. One of the crucial factors in the Bouguer approximation is that the value of specific yield S_y in a square-meter area for every meter of the water-level drawdown must be experimentally determined.

In data reduction, the gravity variation, after the removal of the instrumental drift, earth tides and the effect of elevation change, was found to contain a strong annual component with an amplitude of 8 μGal principally due to the effect of annual variation of the near-surface groundwater. Fig. 3(a) shows the gravity variations at BJTN during the period of 1981 through 1995. With an experimental monitoring well located only 100 m from BJTN SPGS and the known geohydrological parameters for the aquifer at BJTN the annual component of the water-level change of the near-surface groundwater was determined to be 1.74 m as shown in fig. 3(b) through solving the flow equation for areal distribution of pressure well-head on the basis of Darcy's law. The corresponding induced amplitude of the annual gravity variation is 7.31 μGal, which agrees well with the observed annual component of gravity variation 8 μGal at BJTN.

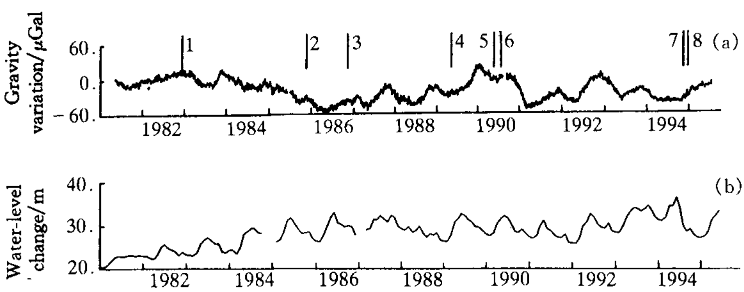

Fig. 3. (a) The temporally continuous gravity variations of 1981—1995 at Baijiatuan. (b) The water-level change of the BJTN experimental well from 1981 to 1995.

3 Importance of groundwater and fluids at depths with respect to gravity variation

We shall here differentiate the near-surface groundwater from the subsurface waters, which we shall refer to as "subsurface fluids."

3.1 Correlation between gravity variation and near-surface groundwater

Kuo *et al*.[9] earlier showed that there was striking correlation between the water-level variation in the near-surface groundwater well and the observed gravity variation, after the removal of the instrumental drift, earth tides, and the effect of elevation change in the northern part of the BTTZ region. Moreover, the correlation deteriorated about one year prior to the occurrence and about the same length of time during the post recovery of the 1982 Madaoyu and the 1986 Shunyi earthquakes as revealed by figure 4.

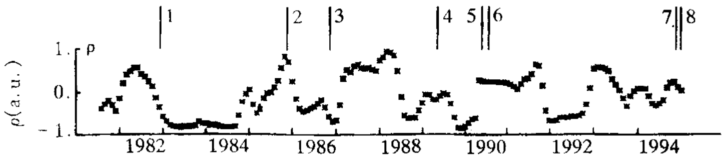

Fig. 4. Cross-correlation of the changes of the water level of the BJTN well and the gravity variations from 1981 to 1995 with a moving time-window of one year and a one-month time step.

During the last 15 years, there were only a few intervals without the occurrence of earthquakes in the region close to the BJTN SPGS, namely, in the time intervals from May 1981 to February 1982, from May 1983 to February 1985, and from August 1991 to February 1993. Figs. 5(a), (b) and (c) clearly show a close correlation between the variation of water-level of the BJTN experimental well and that of gravity at BJTN even by visual inspection. The correlation coefficients from the cross correlation analysis were −0.766, −0.843 and −0.830, respectively. A similar cross correlation analysis was also performed on the gravity variation data observed at the Baodi SPGS in the time interval between January 1989 and January 1990 as shown in fig. 5(d). The Baodi SPGS is located at the Baodi seismic station, and is equipped with Geodynamics No. 721. An experimental water well is about 20 m away from the tidal gravimeter installation. The correlation coefficient for cross correlation between the variation of water-level and that of gravity yielded a value of −0.831.

Cross correlation analyses of the gravity variation data and the water-level data observed at BJTN for the entire duration of the observation from 1981 to 1995 with a moving window of one year, which represents an annual seasonal cycle and a time step of one month, are shown in fig. 4. For gravity variations, "positive value" is designated as "increase of gravity," and for groundwater, "water level" is referred to "drawdown." The results of cross correlation analysis indeed have confirmed the earlier results of a close correlation. Fig. 6 also shows the residual gravity variations at BJTN, i.e. the observed gravity variations after the removal of the effects of instrumental drift, earth tides, elevation change, and also near-surface groundwater on gravity.

3.2 Subsurface fluids in the crust

Reports abound in changes in groundwater anomalies occurring on a time scale from minutes to weeks before many major earthquakes. On the basis of statistical calculations, Wang *et al*.[10] determined that pre-seismic water-level changes could be correlated to 110 earthquakes throughout the world. Of these, 60 have occurred in China; 26 of the Chinese earthquakes were for events with magnitudes greater than $M>6$. Wu *et al*.[11] found that of approximately 400 wells in the Hebei region, about 40 displayed identifiable behavior apparently not related to groundwater usage or to precipitation. They concluded that those wells which manifested precursory behavior seemed to be prevalent near the major faults and to infer that in response to tectonic loading, the strain at fault zones was intensified.

One of the most concrete proofs for the presence of fluids at all depths in the crust would be the recent results of the German's continental deep drilling, KTB, which reached a depth of 9101 m with a temperature of 280℃ in 1467 d. They found the presence of fluids at all depths; at the depths of 8—9 km, the pore pressure became highly overpressured. Moreover, they were surprised to find the dominance of the vertical structures in the crust to the depth they have drilled in the crystalline rocks. From the anal-

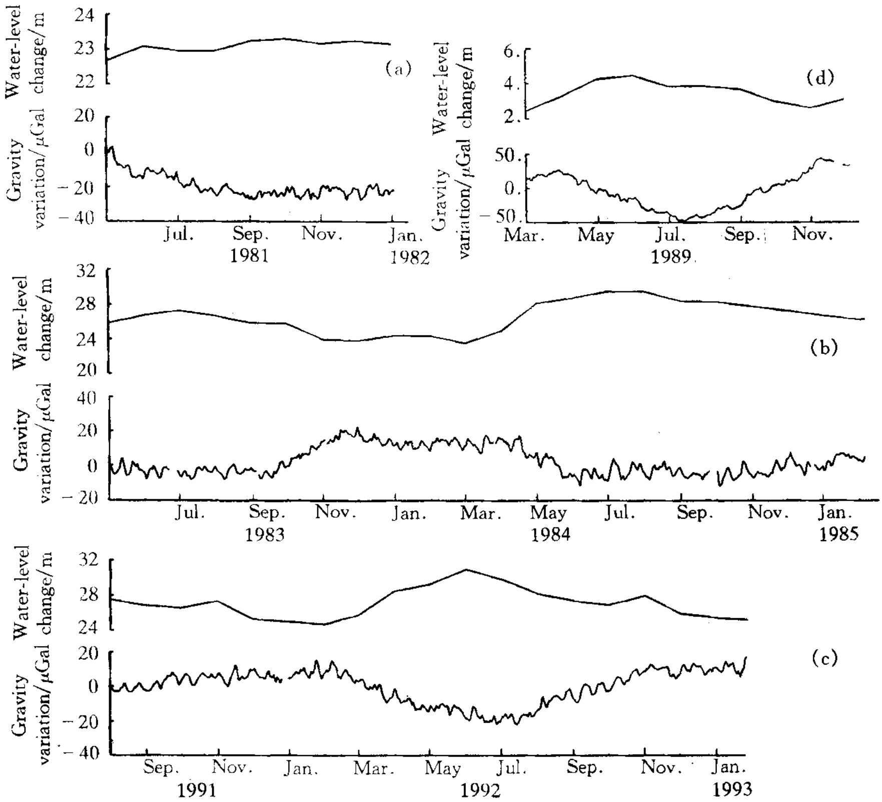

Fig. 5. The changes of water-level of well and gravity during the three intervals at Baijiatuan. (a) 1981-05—1982-02; (b) 1983-05—1985-02; (c) 1991-08—1993-02; (d) During the interval at Baodi (1989-01—1990-01).

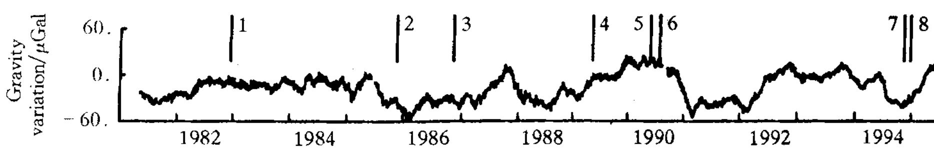

Fig. 6. The residual gravity variations at Baijiatuan after the removal of the effect of the change of groundwater on gravity variations.

ysis of the diametrical shapes of the core samples, they found that the shapes of the core were highly distorted including the shapes of the two-horizontal extensions at 180° apart, reflecting the release of the horizontal local stress fields.

A typical example illustrates that the subsurface fluids at depths respond to the seismogenesis and occurrence of earthquakes in the BTTZ region is that of the well-head level fluctuation of the Gaocun well, which was drilled to an aquifer with a depth of 3200 m, and is located at 39°37′N and 116°52′E, just 88 km southeast of BJTN. The well is virtually free from all the near-surface effects of precipitation and seasonal cycles with a nearly exponential decrease of well-head level as shown in fig. 7-1. Two drawdowns of the well-head level occurring in the period between January 1984 and January 1986 were entirely due to heavy water pumping[13]. During this particular period, there was no single earthquake occurring in the BTTZ region to complicate the data of the well-head level change for the two drawdowns. Fig. 7-2 shows the well-head level changes with the removal of the nearly exponential decrease. When the residual gravity variations at BJTN were compared with the two drawdowns of the well-head level of the Gaocun well, correlations are clearly shown (fig. 7-4), although the response of the residual gravity variations to the first drawdown was not as pronounced as the second.

During the time interval of 1987 and 1990, there were only 3 earthquakes, namely, the 1988-07

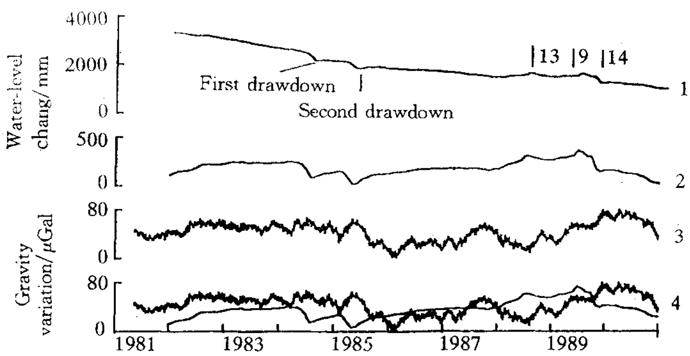

Fig. 7. The responses of the well-head drawdown of the Gaocun well and the residual gravity variation to two heavy pumping and three earthquakes, showing very strong correlations between the responses of the residual gravity and the drawdown of the Gaocun well to the two heavy pumping and the seismogenesis and occurrence of the three earthquakes.

Yangyuan, the 1989-03 Xiacang, and the 1989-10 Datong earthquakes (13, 9, and 14 as given in table 1, respectively) occurring in the BTTZ region. A sequence of events of an increase of the well-head level of the Gaocun well between January 1987 and January 1991 coincides with the occurrence of these three earthquakes. The epicentral distances from the Yangyuan, Xiacang, and Datong earthquakes to the Gaocun well were 232, 49 and 270 km, and to BJTN, 162, 129 and 204 km, respectively.

About ten months before the Yangyuan earthquake occurred, the well-head level of the Gaocun well had steadily increased by as much as 40 cm until the main shock occurred in July, 1988. There was a minor steady decrease and then an increase of the well-head level prior to the occurrence of the Xiacang earthquake in March 1989. In June and July 1989, there was a 15 cm increase of the well-head level, which was superimposed on the background of the well-head level, the Datong earthquake occurred about three months later in October 1989 as shown in fig. 7-1. Strong correlations were found between the residual gravity variations at BJTN and the changes of the well-head level of the Gaocun well for these three earthquakes as evidenced by fig. 7-4. Assuming that the epicenter and the epicentroid coincide, the residual gravity variations, however, would not be expected to respond to the deep-seated seismogenic processes of earthquakes without fluids at the epicentral distances of 160—200 km. Unless, in addition to the subsurface fluids, there are some other seismogenic processes of which we are totally unaware, the residual gravity variations, nevertheless, appear clearly to respond to the changes of the well-head level of the Gaocun well.

The characteristic patterns of the response of the Gaocun well to these three earthquakes resemble remarkably the response of the residual gravity variation observed at BJTN as shown in fig. 7-2 and 3. Both the residual gravity variation and the well-head level change of the Gaocun well apparently were responding to the same type of dynamic seismogenic processes of the earthquakes. There are many deep subsurface fluids in the crust like the one into which the Gaocun well was drilled. All the subsurface fluids at various depths in the total stressed volume in question likewise respond to the seismogenesis and occurrence of earthquakes.

One of the remaining puzzles is why the Gaocun well did not respond to the other earthquakes except earthquakes 9, 13 and 14 which occurred in the BTTZ region during the time interval from 1981 to 1991. Could one of the possible explanations be that earthquakes 9 and 13 were located in a separate hydrogeological province of the Jilu tectonic block from another hydrogeological province of the Yanshan tectonic block where the other earthquakes have been located, although the epicenter of the Yangyuan earthquake was actually located in the Taihang tectonic block? If so, these two hydrogeological provinces then may be possibly separated by an NW-SE, impermeable barrier, which trends approximately 40°30′N and 113°00′E—39°30′N and 120°00′E, and which may well be the intraplate boundary of the Yanshan and Jilu tectonic blocks. For the Gaocun well to respond to an earthquake at an epicentral distance of 270 km, there must be hydrogeological system, which is favorable to a communicable migration of subsurface fluids within the Jilu tectonic block. Each tectonic block may assume its seismogenic processes independently but may be mutually interactive with the adjacent tectonic blocks. Earthquake 11, which occurred on 1993-11-18 and was located nearly in line with earthquakes 9 and 13, would then belong to the same hydrogeological province. Unfortunately, the well-head level recording of the Gaocun well was disrupted after 1991 to prevent such a unique opportunity for verification of this hypothesis.

Also, there is a possibility that these tectonically stressed volumes involving the seismogenic processes of the Yangyuan and the Datong earthquakes are particularly susceptible to the migration of communicable subsurface fluids. Therefore, it is imperative that what was observed in the Gaocun well during the period of 1988 through 1990 was likely the response of the well to the seismogenesis and occurrence of these three earthquakes. If this interpretation is correct, then the duration of the seismogenesis for the 1989 Datong earthquake would have begun approximately two and a half years prior to the occurrence of the main shock, in comparison with that for the earthquakes of magnitude 4—5 about one year prior to the main shock in the BTTZ region.

4 Possible rupture mechanisms due to local stress concentration and hydraulic fracturing

4.1 Local stress concentration

Although the intraplate of the North China Plain is under a relatively uniform and stable stress system, the BTTZ region has a variety of local stress concentrations, due to inhomogeneities from intricate faults and a variety of complex geological configurations. As early as 1913, Inglis[13] showed that because of stress concentration, maximum stress occurs at the ends of the major axis of the elliptical cavity. Accordingly, the value of stress at the leading edge of the cavity becomes extremely large as the ellipse is collapsed. As the ellipse approaches a slit with a crack, the maximum stress approaches infinity, when the ratio of the minor axis to the major axis of the ellipse becomes zero. In nature, the maximum stress, of course, would never approach infinity, because a certain amount of plastic work is done in the propagation of a crack per unit area of the fracture surface and the other is elastic work done in the creation of two fracture surfaces. However, extremely high compressional, tensional, or the combination of compressional and tensional stresses may reach many orders of magnitude over the applied stress around the tips of the crack. Highly pre-fractured, pre-stressed, pre-flawed, and under the influence of the earth tides and ocean tidal loading, dynamically fatigued geological media are readily subjected to failure under the concentration of very high local stresses induced by an applied regional stress of relatively low magnitude.

4.2 Hydraulic fracturing

The processes of seismogenesis and occurrence of earthquakes with respect to the space and time would be further complicated by the constant presence of fluids virtually at all depths in the crust. Rupture may well be initiated by hydraulic fracturing, followed by shear fracturing and faulting that may be analogous to horizontal wellbore failure[15]. Such a possibility is also supported by the core analysis results of the German's continental deep drilling KTB as mentioned above.

As the local stress concentration intensifies, not only do the fluids lubricate the potential rupture surfaces but also the pore pressure in the microfractures at various depths may be increased to the point that the pore pressure exceeds the rupture strengths of the already weakened geological media causing hydraulic fracturing. These hydraulic fractures are tensional and thus perpendicular to the minimum principal tectonic stress and parallel to the maximum principal tectonic stress axis. Nevertheless, because the orientation of the microfractures are not necessarily in the direction of either the maximum or minimum principal tectonic stress axis, the initial tensile rupture would be accompanied by shear fractures. As the rupture extends in length, the rupture would seek its optimum direction of preferred orientation parallel to the maximum stress axis and perpendicular to the minimum stress axis.

When the failure criterion of hydraulic fracturing is applied to the seismogenesis of an earthquake in the BTTZ region, in addition to the complications of the pre-existing fractures (faults) and geological configurations, the mechanisms of generation and sustenance of pore pressure should be addressed. Under the influence of the tectonic stress changes in the framework of the seismogenic processes in the BTTZ region, the expulsion of fluids in the deep-seated aquifers may be somewhat analogous to that of a sedimentary basin, in the case of which the expulsion of fluid in the compaction of sediments capped by the impermeable strata may generate pore pressure greatly exceeding the hydrostatic head, and even approach a value close to the lithostatic load[16]. Furthermore, in the BTTZ region, heat flow and seismic studies indicate that the upper mantle of the high heat flow region is undergoing uplift[8]. The estimated thermal induced stresses reach 16.6 and 66.4 MPa, along the minor and major axes of the rift zone, respectively[17]. At the continental margin of the Bohai Bay, the pre-existing fracture-belt of en echelon faults, which is oriented in the NNE direction, interacts with the maximum principal *in-situ* tectonic stress, which is oriented in the NEE direction. The eastern portion of the BTTZ region lies in a rift zone of abnormally high heat flow and the uplift of the upper mantle around the margin where many major earthquakes including the Xingtai, Hejian, Bohai, Haicheng, Tangshan and Heze earthquakes have occurred in recent years. Thermally induced stresses in the region of uplift may provide another mechanism of generation and sustenance of pore pressure.

5 Modified combined dilatancy model

Kuo *et al*.[9] already observed that the residual gravity variation had distinct features of increasing and decreasing gravity nearly one year prior to the occurrence of the 1982 Madaoyu and the 1986 Shunyi earthquakes. The post recovery of the gravity variation, i.e. the return of the total stressed volume to its initial state, took an equal amount of time, about one year for each of these two earthquakes.

In searching for the relationship of the observed gravity variation and the occurrence of earthquakes in the BTTZ region, Kuo *et al*.[18] postulated a possible seismogenic mechanism for the region by means of a combined dilatancy model (CDM), which consists of the dilatancy-diffusion (D/D), the dilatancy-instability (IPE), and the fault-zone dilatancy (FZD) models.

The BTTZ region may be considered as a large pre-stressed volume including not only the pre-stressed volume surrounding the impending rupture zone but also the volume containing the rupture of the fault zone itself. The volume of the region involved in the seismogenesis and occurrence of an earthquake is not confined to the neighborhood of a major rupture zone only, but extends to a larger volume, confirming what Professor C.Y. Fu as early as the 1970s proposed as the "Red Swollen hypothesis." The surface of the pre-stressed volume outside the impending rupture zone is under a state of relatively small change of the pre-existing regional tectonic stress, while the volume containing the impending rupture zones is an induced region of very high local stress concentration, and/or over pore pressure. The total volume may be modeled to be elastically deformed, microfractured, and then stress-relaxed with or without invasion of fluid under the applied tectonic stresses, while the volume containing the impending rupture or fault zone is likewise modeled except that the volume is more severely fractured, and ruptured at the end of the termination of faults under the differential local concentration of the tectonically induced stress.

Since the combined dilatancy model was proposed, the observations of the gravity variation, the near-surface groundwater, and the subsurface fluids in the BTTZ region all pointed to the fact that in order to reflect the physical reality of the seismogenesis and occurrence of earthquakes, the earlier proposed CDM requires modification. The near-surface groundwater and the subsurface fluids which directly respond to the fluid invasion related to the change of the dynamic stress fields, play a far more important role in the seismogenesis and occurrence of earthquakes than previously recognized.

In view of the abundance of data supporting the presence of subsurface fluids from near-surface to all depths in the crust, the dilatancy instability (IPE), in contrast to the dilatancy diffusion D/D, seems not applicable in the seismogenesis and occurrence of earthquakes at least in the BTTZ region. The total stressed volume thus always contains fluids, if not completely then partially. The geological media would more appropriately be considered to be poroelastic type, the elastic skeleton of which may have an effective fluid-filled porosity as high as 5%—10%, although the *in situ* crystalline rocks themselves have a porosity of as low as 0.05%.

The variation of gravity, if the changes of strain are small, due to dilatancies may be written as[18]

$$\delta g = \delta g_1 + \delta g_2 + \delta g_3 + \delta g_4, \tag{3}$$

where on the right-hand side the terms are the variations with respect to density, the geometrical configurations, porosity, and the content of the fluids in the body. More explicitly,

$$\left.\begin{aligned}
\delta g_1 &\equiv \frac{\partial g}{\partial \rho} = f_1(G_0)\{\delta\rho(e)[1 - H(e - e_c)] + \delta\rho(e_c)H(e - e_c)\}, \\
\delta g_2 &\equiv \frac{\partial g}{\partial G}\delta G = f_2(\rho_0, G)\delta G(e), \\
\delta g_3 &\equiv \frac{\partial g}{\partial \phi}\delta\phi = f_3(\rho_0, G_0)\delta\phi(e, e_c)H(e - e_c), \\
\delta g_4 &\equiv \frac{\partial g}{C_f}\delta C_f = f_4(\rho_0, G_0)\delta C_f H[e - (e_c + e_w)].
\end{aligned}\right\} \tag{4}$$

Therefore, the modified combined dilatancy model (MCDM) only consists of the dilatancy diffusion (D/D) and the fault-zone dilatancy model (FZD). In eq. (3), the term of δg_4 would not in any circumstances be zero.

In MCDM, the gravity variation associated with the seismogenesis and occurrence of earthquakes in the BTTZ region may be considered as a four-stage process. The fluid-filled poroelastic medium may be assumed to dilate initially under pre-stressed conditions (stage 1); the gravity variation first comes from the density and geometrical-configuration changes in space. When the change of maximum strain reaches its critical value, the medium approaches a state of creep, and further dilatation is contributed to the newly developed microcracks, with the concomitant increase in void space (stage 2); while the volume and the spatial position in the body are changing due to the development of new microcracks, the total stressed volume as a whole remains unchanged so that the value of density change keeps its value constant after the change of maximum strain reaches its critical value. Then, when the maximum strain reaches the second critical value, the stress is relaxed with the invasion of fluid (stage 3). The fluid lubricates the newly cracked medium in the fault zone. Local stress concentration as well as pore over-pressure leads to the local rupture causing the occurrence of the earthquake (main shock) for the FZD model. In the original proposed CDM, the seismogenesis and occurrence of earthquakes are a three-stage dilatancy process without specifically stating the post recovery phase. Therefore, the proposed MCDM would include the fourth stage of post recovery. In stage 3 of the CDM, the total volume under the regional tectonic stress remains conserved as in the earlier stages, both the volume and the spatial position in the body continue to change. After the main shock occurred in a particular locality, the stress concentration in this particular locality is thus relaxed that generally takes the form of heat conversion. The complete local stress system is thus undergoing readjustment to the aftermath of the earthquake and a series of aftershocks is followed in the localities of the hypocentral region of the earthquake. Concurrently, the whole region gradually returns to its pre-stressed state, but with a different state of local stress configuration. Likewise, the fluids resume their initial pre-stressed state as a whole, but with local perturbations. The post recovery for an earthquake of magnitude of 4—5 may take the form of an exponential function. Nevertheless, other localities may continue to experience high local stress concentrations and/or pore over-pressure for the development of subsequent seismogenic activities (stage 4).

The MCDM for the seismogenesis and occurrence of earthquakes, without loss of generality, assumes a simple model of a linear superposition of deformations of a vertical, finite, right circular cylinder and a disc, corresponding to the D/D and the FZD models, respectively. A cylindrical geometry was chosen to represent the total volume, which may represent the shape of the stressed region above the likely existing detached zone at the depth of 15 km in the BTTZ region. The problem is thus reduced to determining the gravity variation on the earth's surface as a function of radial distances from the axis of the cylinder due to the modified combined dilatancy model for a given time and a given state of strain.

In considering the geological and seismo-tectonic settings of the BTTZ region, one of the best models tested for the BTTZ region assumes that: (i) the total volume is modeled as a large vertical cylinder of 40 km in radius and 15 km in thickness with the bottom of the cylinder coincident with the top of the detached zone; (ii) the fault-zone volume is modeled as a thin disk 2 km in thickness and 11 km in radius with the bottom of the disk at 15 km. The axis of the cylinder coincides with the effective center of mass of the cylinder; (iii) the applied tectonic compression force forms an angle of about 17° with the x-axis and an azimuthal angle of about 18° so that the microcracks developed lie in the plane perpendicular to the horizontal y-axis, and the orientations of the microcracks are parallel to the horizontal x-axis. This choice also supports the orientation of the stress system of which the regional tectonic stress is in the NEE direction (N83°E) in the horizontal plane, based on the fault-plane solution of the earthquakes in the region[17]. The microcracks lie in the plane perpendicular to the vertical axis (or the z-axis), and the orientations of the microcracks are parallel to the horizontal x-axis; (iv) results from the deep well stress measurements in the Huabei Plain in China yield a maximum tectonic stress of approximately 100 MPa in the region[8]; and (v) the density of the rocks is about 2700 kg/m^3, its Young's modulus is about 100 MPa, and its Poisson's ratio is 0.3.

Figure 8 shows the calculated MCDM gravity variations for the epicentroidal distances, as defined by Kuo *et al.*[18], of 10, 20, 30, 40 and 50 km, using the above basic parameters with a change of the regional tectonic stress of 7%, which seems to be most representative for the BTTZ region to be discussed in the following section. The expected time interval of occurrence of the main shock is marked by | ↓ |.

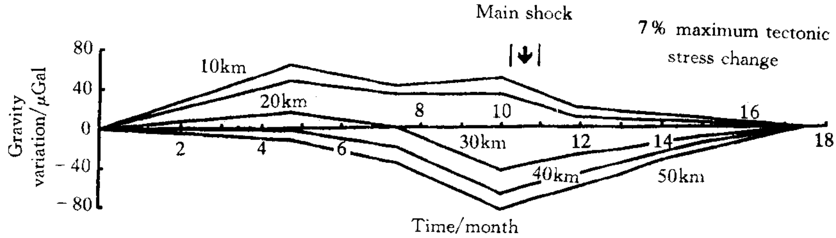

Fig. 8. The calculated gravity variations due to MCDM at the distances of 10, 20, 30, 40 and 50 km from the axis of the vertical finite cylinder for a maximum change of regional tectonic stress of 7%.

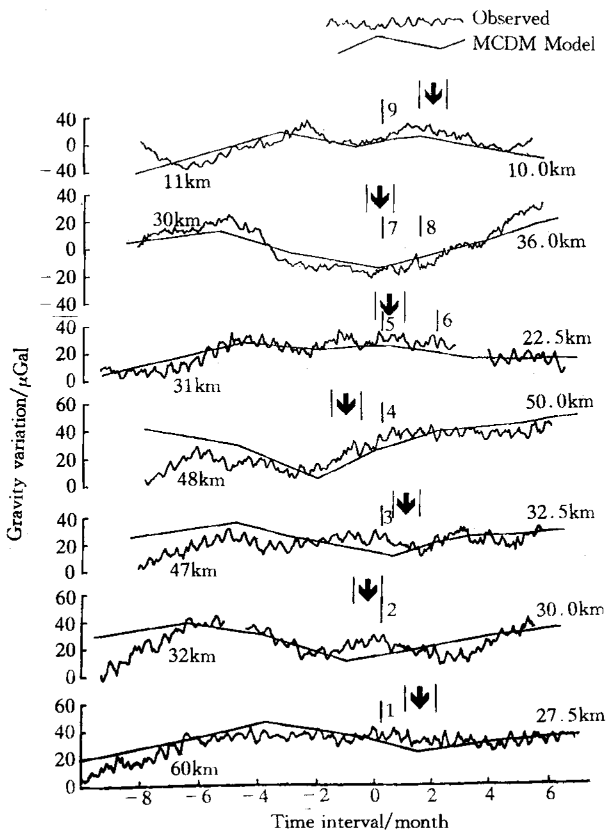

Fig. 9. Comparisons of the observed residual gravity variations and the calculated model results of MCDM for 9 earthquakes occurring in the BTTZ region.

6 Comparison of the calculated MCDM gravity variations and the residual gravity variations

Figure 9 shows the observed residual gravity variations for these eight earthquakes which occurred in the vicinity of the BJTN SPGS and one earthquake which occurred in the vicinity of the Baodi SPGS as listed in table 1. For comparison, the calculated MCDM gravity variations for each of these nine earthquakes, using a change of the regional tectonic stress of 7% for the BTTZ region are superimposed on the residual gravity variations with the expected time interval of main shock marked by | ↓ | and epicentroidal distances marked by numerals respectively. Comparison of the calculated MCDM with the observed residual gravity variations shows that: (i) the expected occurrences of and the actual occurrences of the main shock for earthquakes 2, 3, 5 and 7 are within one half month and for earthquakes 1, 4 and 9 are within nearly one month; (ii) earthquakes 6 following 5, and earthquakes 8 following 7 within a time interval of two months, respectively, seem to assume the characteristics of the one which occurred first; and (iii) the epicentral distances between the calculated and the observed for earthquakes 2, 4, 5, 7 and 9 are within 6 km, except for earthquake 1, the calculated is much smaller than the observed by as much as nearly one half of the epicentral distance and for earthquake 3, that calculated is smaller than one third of the epicentral distance.

The temporally continuous series of the residual gravity variations due to the seismogenesis and occurrence of these nine earthquakes occurring in the vicinity of BJTN and Baodi SPGS indicates that: (i) the general features of the deformational stages as reflected by the calculated MCDM gravity variations appear to agree with those of the observed residual gravity variation. This general agreement implies that the seismogenesis and occurrence of the earthquakes with a magnitude of 4—5 in the BTTZ region may well favor the modified combined dilatancy model; (ii) the seismogenesis and occurrence of an earthquake of magnitude 4—5 may involve a period of at least eight months prior to the main shock and the post recovery may take a shorter period of about six to eight months after the main shock; (iii) the residual gravity variations respond mostly to the subsurface fluids, and also to the deep-seated seismogenic activities. On the basis of a general agreement between the calculated MCDM gravity variations and the observed residual gravity variations, the change of the regional tectonic stress field in the BTTZ region may be now estimated to be in the neighborhood of 7% ; (iv) although the occurrence of these earthquakes is separated in time, the seismogenesis and occurrence of these earthquakes are overlapped in time, as indicated in the temporal continuous series of the residual gravity variations; (v) each earthquake involves a different size of the tectonically active regional volume, even though the size of the tectonically active region in the present calculation, for convenience, is assumed to be fixed for the earthquake of magnitude 4—5 in the BTTZ region; and (vi) as the epicenter is assumed to coincide with the epicentroid in this paper, the epicenter may or may not coincide with the epicentroid of an earthquake[18].

7 Discussion

The implications of the general agreement between the calculated MCDM gravity variations and the residual gravity variation are that the modified combined dilatancy model may be considered as a possible representation of the mechanism for the seismogenesis and occurrence of earthquakes at least in the BTTZ region. Nevertheless, some of the crucial questions remain: (i) how the near surface groundwater and the subsurface fluids respond to the seismogenesis and occurrence of earthquakes in the region; and (ii) how the residual gravity variation responds, in addition to the near surface groundwater, to the subsurface fluids, and other seismogenic processes in the depth.

As gravity variations are generally observed on the earth's surface, the obvious influence on the gravity variation is that of the near-surface groundwater. This is evidenced by the strong correlations between the gravity variation and the water-level variations in the near-surface well during the time interval without the seismogenic activities of earthquakes in the vicinity of BJTN. One of the important facts is that the near-surface groundwater is just one of the fluids, which is readily accessible for measurements. The subsurface fluids are not readily accessible for observation. The response of the Gaocun well to the 1988 Yangyuan, the 1989 Xiacang and the 1989 Datong earthquakes clearly demonstrates that the subsurface fluids respond to the dynamic seismogenic processes and occurrence of earthquakes at incredibly large distances. The Gaocun Well was responding to the dilatancy processes through the expulsion of the fluid from the aquifer resulting in an increased well-head level. The sequence of precursory events as revealed by the Gaocun Well indicates that the Gaocun Well is similarly responding to the seismogenic processes as the near-surface groundwater is, as well as the residual gravity variation.

If the near-surface groundwater and the subsurface fluids do not belong to the same aquifer and are not mutually communicable, the near-surface groundwater and the subsurface fluids would independently respond to the dynamic stress field changes in terms of the seismogenesis and occurrence of earthquakes. On the other hand, the gravity variation responds not only to both the near-surface groundwater and the subsurface fluids but also to the dynamic stress changes in the earth during the period of incubation, generation, occurrence and post recovery of the earthquake(s). These are the subtle differences among the responses of the near-surface groundwater, the subsurface fluids, and the gravity variations.

The residual gravity variation effectively responds to the subsurface fluids and the dynamic seismogenic changes in depths. Since the residual gravity variation, in principle, should no longer be influenced by the near-surface groundwater, the residual gravity variation and the water-level change of the BJTN experimental well would have excellent correlation. However, the residual gravity variation does contain the response to the subsurface fluids, and to the other deep-seated seismogenesis and occurrence of earthquake(s). Unless the response of the residual gravity variation to the deep-seated seismogenesis and occurrence of earthquakes is far greater than that of the subsurface fluids, the residual gravity variation thus would reflect mainly the response of the subsurface fluids to the seismogenesis and occurrence of earthquakes in the BTTZ region. This turns out to be indeed the case.

In confirmation of the fact that both the water-level variation of the near-surface groundwater and the residual gravity variation respond to the seismogenesis and occurrence of earthquakes, cross correlation analyses were also performed on the residual gravity variation and the water-level variation of the BJTN experimental well. Except the correlation coefficient for earthquakes 5 and 6 became as low as 0.156, whereas these two earthquakes occurred in a short interval, the correlation coefficients for all the other earthquakes occurring near the BJTN SPGS range from 0.628 to 0.952. Therefore, one of the important present findings is that the residual gravity variation predominantly responds to the near-surface groundwater and the subsurface fluids at various depths in the crust. What Chen *et al*.[5] postulated concerning the concept of mass transfer may well be the invasion of subsurface fluids in the modified combined dilatancy model (MCDM) at various depths in order to account for the large gravity variations they observed before and after the 1975 Haicheng and the 1976 Tangshan earthquakes.

The magnitude of the residual gravity variation for the earthquake of magnitude of 4—5 in the BTTZ region has also been approximately confirmed by the preliminary results of finite element modeling. Zhang *et al*.[19] have carried out finite element modeling of the seismo-tectonic effects at depths on the gravity variation at BJTN due to an earthquake of magnitude 4—5 in the BTTZ region. Their estimations were at a distance of 20 km from the epicenter, assuming that the epicenter is the barycenter of the total stressed volume.

(1) For a change of the regional principal stress orientation of 5% and of density of 0.10%, the corresponding gravity change would be about 4 μGal. And for example, in the 1976 Tangshan earthquake ($M=7.8$), the fault rupture length was estimated to be about 100—120 km with a total gravity variation of 98 μGal. Therefore, for an earthquake of magnitude of 4—5 in the region, a fault-rupture length could be about 8—10 km; the estimated gravity change for the Youzhou or similar magnitude earthquake at most would be about 3—5 μGal. These gravity changes would be balanced by a negative contribution to gravity variation, say, an increase of geothermal temperature of 0.5℃ in the BTTZ region which would give an expected gravity change of −5 μGal.

(2) For the water-level change of commonly 1 m of the near-surface groundwater, and for an accumulative rise and fall of the well-head of 2.5 m at all depths in the crust, assuming that the aquifer is of an infinite extent horizontally and an average of 10% porosity, the gravity change would already be ±15 μGal.

A total estimated gravity change at BJTN for an earthquake of magnitude 4—5 occurring at 20 km from the epicenter of the earthquake would be between 10 and 15 μGal, which is of the right order of magnitude for what we have observed in the BTTZ region. That means that the residual gravity variation responds primarily to the near-surface groundwater and the subsurface fluids, which themselves respond to the seismogenesis and occurrence of earthquakes effectively.

8 Conclusions

Through the analysis of the temporally continuous data of gravity variation from 1981 through 1995, a consistent picture of the seismogenesis and the occurrence of earthquakes of magnitude 4—5 in the BTTZ region has emerged.

The near-surface groundwater is most perturbed by precipitation, seasonal cycles, barometrical pressure changes, and irregular drawdowns. The deep-seated subsurface fluids are virtually undisturbed by precipitation and seasonal cycles but have a long time constant drawdown in the BTTZ region, as evidenced by the 3200 m Gaocun well. The residual gravity variation, the nearsurface groundwater, and the subsurface fluids all respond to the seismogenesis and occurrence of the earthquakes.

As yet, the near-surface groundwater and the subsurface fluids respond to the seismogenesis and occurrence of earthquakes independently, if the near-surface groundwater and the subsurface fluids are incommunicable. The gravity variation, on the other hand, then not only mostly responds to the near-surface groundwater and the subsurface fluids, but also responds to the deep-seated seismogenesis, incubation, occurrence and post recovery of the earthquake.

The agreement between the calculated gravity variation based on the modified combined dilatancy model (MCDM) and the observed residual gravity variation substantiates the fact that the fluids, which include all the fluids from the near-surface groundwater to the deep-seated fluids distributed throughout the crust, play a more important role in the local variation of gravity in terms of the seismogenesis and occurrence of earthquakes in the BTTZ region than previously recognized. The change of the regional stress field in the BTTZ region for the earthquake of magnitude 4—5, therefore, could be estimated to be in the neighborhood of 5%—7%.

It appears quite profitable that the near-surface groundwater, the subsurface fluids, and the gravity variation are monitored temporally continuously together with modeling that should render valuable information on the history and evolution of the seismogenesis and occurrence of earthquakes.

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