Charles University in Prague
Faculty of Science

Temporal gravity changes related to geodynamic phenomena and geomechanical processes

Ph.D. Thesis

Jan Mrlina

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Declaration

I declare that I have not submitted this Thesis or its substantial part anywhere else with the aim of receiving any other academic degree. I prepared the Thesis solely by myself.

The papers included in this thesis are either my single-author or first-author papers with only minor contribution of other authors.

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Abstract

My Thesis is based on five papers dealing with gravity changes related to various geodynamic, geomechanical and hydrological processes and phenomena. In the first part of the Thesis the gravity changes are defined as a geophysical quantity. The two principal causative parameters are highlighted – variation in elevation of the earth surface, and temporal excess of mass (negative or positive) in the subsurface.

I also discuss different groups of parameters and environmental phenomena disturbing the gravity measurements, as the data accuracy is an essential condition of gravity monitoring (4D gravity). I performed a special test with the LaCoste&Romberg D-188 gravimeter in a pressure chamber with notable result showing negligible impact of small and medium size air-pressure variations on this instrument. The calibration stability was proved during two world comparison/calibration campaigns of absolute and relative gravimeters in Sevres, France. The instrument's repeatability was evaluated as 2 μGal (0.02 μm/s^2). As well, calibration is being controlled by measurements on the Czech latitude calibration line between Prague and Dolní Dvořiště in South Bohemia.

In order to achieve best accuracy we developed special software Drift to control the gravimeter's drift. In principle the software provides a chance to check the value of each repeated reading during a daily loop, and to eliminate/disable the outliers. Final drift curves can also be improved using the option of changing the curve's rigidity, which is already interpretative style of data processing based on experience. Examples from both research and exploration gravity networks showed the improvement of accuracy up to 50 %.

The first case history is focused on gravity monitoring in the seismoactive region of West Bohemia, characterised by repeated occurrence of earthquake swarms. The gravity observation network was partly identical with the GPS one. The gravity differences observed since 1993 have shown quite strong correlation with the periods of swarms. Already before the Dec. 1994 swarm a sharp increase of gravity near Nový Kostel was identified. Similar amplitudes of about 20 – 40 μGal were evaluated during the Jan. 1997 swarm period. However, the most significant Autumn 2000 swarm gave a chance to investigate a complex geodynamic scene. Despite the magnitudes reached only M=3.2 in maximum, there were remarkable surface displacements identified from GPS and precise levelling networks. They prove the stress evolution during such an active period. After the 1998-1999 dextral movement on the active fault plane near Nový Kostel, the GPS vectors showed a reverse sinistral movement in 1999-2000 in good agreement with seismic fault plane motion solutions. We observed the same sense of gravity changes regime, completed in 2000 by indication of sinistral stress from increased relative gravity values on the eastern side of the fault near N.Kostel. The coincidence between gravity and GPS geodynamic indications corresponding with this significant earthquake period can be considered as valuable result.

The second case history is located in Upper Egypt, on the west bank of the Lake Aswan. This area is also tectonically active with M=5.5 in 1981. This earthquake on the Kalabsha E-W fault crossing the reservoir inspired a detailed geodynamic study in seismology, but also in geodetic observations. In 1997 we introduced gravity monitoring within the Kalabsha, Seyial and Kurkur networks. We observed significant positive gravity change in 2000, located south of the fault near the shoreline of the Lake. This shoreline is changing significantly due to water level seasonal, but also long-term variations. In 2000 the shoreline was relatively very close to the nearest observation station # 153. This station was already after the 2000 gravity campaign considered as affected by water infiltration from the Lake (about +50 μGal), while the rest of the area was still expected to exhibit small impact of tectonic stress change.

However, the next campaign in 2002 exhibited reverse drop of gravity values close to zero level, while station # 153 was the only one to add about +10 μGal. The recent analysis indicates that most likely all the regime of observed gravity changes is controlled by water infiltration. I also performed gravity/density modelling of such process with two possible models of hydrological events – water infiltration from the Lake surface water, and simple groundwater level rise. Further gravity observations are needed to identify in more detail the hydrological processes.

The third case history deals with the application of gravity monitoring to the investigation of geomechanical processes in the near subsurface. The usual problems in engineering geology comprise the propagation of voids with possible collapse of the surface, evolution of landslide process, fluids movement in reservoirs, and stress changes in deep coal mines. Two examples are studied in more detail.

The rocks disintegration in the form of the so called 'arch effect' above underground voids can be detected by gravity monitoring due to the propagation of the disintegration process to surface. The physics behind is that such process results in significant decrease of bulk density of the rock formation, as well as propagation to surface with time. Both these phenomena are favourable for detection by repeated gravity measurements as the anomalous rock volume gets closer to surface, and to the gravimeter. So, even if the void itself is too small and deep to be reflected in the gravity data, the disintegrated volume can be observed.

I also described how the gravity monitoring can identify variations of groundwater level in case of a waste dump of an open-pit coal mine. The data from four profiles on such man-made 'geological' body were corrected for elevation and terrain correction changes and correlated with direct observations of groundwater in monitoring wells. Based on such controlled correlation, the groundwater level inside the dump was evaluated. At certain stage, the data clearly showed an increased groundwater level that triggered a disastrous mass slide down the valley.

Theoretical modelling showed that a water movement in both horizontal, as well as vertical directions in reservoirs can be identified by 4D gravity. Even in great depth of e.g. 3000 m, relevant to current producing hydrocarbon reservoirs could be observed, but the signal may become too smooth and wide, so that practical determination of e.g. water-gas contact at such depth is tentative.

I concluded that gravity monitoring can contribute to geodynamic investigations, as well as to solving some problems of engineering geology, provided high resolution data are acquired and properly processed.

1. Introduction

Gravimetry has been always considered as a principal geophysical technique. It was, in fact, the first technique applied to oil and gas exploration, when the Nash Salt Dome in Texas was discovered in 1924. Despite gravimetry lost this priority due to enormous development in seismic prospection, it still provides important constraints in the investigation of salt structures and basin composition on the whole. The method is used in mining for direct or indirect detection of ore bodies (sulphides, bauxite, etc.), as well as in hydrogeological surveys as an additional technique for aquifers delineation. Gravity data are extensively utilized for basic geological research and geological mapping.

In a very detailed scale, microgravity is applied for the detection of any type of voids (caverns, caves, cellars, galleries, tombs, etc.), and for near subsurface anomalous structures important for engineering geology.

Specific application of gravimetry is represented by **gravity monitoring**, the target of which is to observe temporal changes of the gravity field related to geomechanical, hydrological or geodynamic processes. For this purpose, extremely high precision data represent a condition for achieving good results, as well as the elimination of environmental effects. In this Thesis, some results of gravimeter tests, especially air-pressure effect, are presented, and examples of other impacts on gravity observations are discussed.

My Thesis is focused on various aspects of gravity monitoring and on some case histories that document the difficulties and outcomes of the technique. These case histories are subject of the five attached papers. Three of them present geodynamic investigations in the West Bohemia earthquake swarms region, with the principal objective being the analysis of the relation of earthquakes to observed gravity changes and surface displacements. One paper describes the investigation of gravity changes in the seismoactive area on the west bank of the Lake Aswan in Egypt, where both tectonic stress and groundwater movements are considered as causative phenomena. The last paper demonstrates how the observation of gravity changes in microgravity scale can help in solving problems of engineering geology. The presented results should provide an idea on how wide is the range of applications of 4D gravity in various branches of geology.

Chapter 5. deals with the progress in observations or interpretation of results since the papers were published till present, and extends the conclusions drawn in those papers.

2. Target of Thesis

Based on large number of gravity projects I have participated in up-to-now, I decided to concentrate on various applications of gravity monitoring in my Thesis. I selected three principle areas of investigation:

a) **geodynamic/geotectonic investigation**
b) **monitoring of fluids**
c) **geomechanical processes in engineering geology**

For each area an introduction is given and some former and recent results of other authors are presented to provide an idea on the range of applications of gravity monitoring. Technical and scientific goals of my Thesis were

- to highlight the conditions for successful gravity monitoring – observation techniques, accuracy, data processing
- to evaluate environmental impact on gravity measurements
- to investigate the processes causing temporal gravity changes
- to provide real-life examples of gravity changes
- to evaluate ‘chances and limitations’ of the technique

The substantial part of the Thesis consists of five selected published papers related to gravity monitoring. Some results achieved by other authors in the studied field are presented in Chapter 3.2., in other chapters of the Thesis where appropriate, as well as in the 5 papers included in the Thesis.

Before the main section (Chapter 5.) related to the published papers, I focused on some important conditions affecting successful application of gravity monitoring. In particular, tests of gravimeters, elimination of various disturbing effects and improved data processing.

On the other hand, it is not the target of this Thesis to deal with all aspects (e.g. gravity referencing, network adjustment) and applications (e.g. borehole 4D gravity, satellite gravity) of temporal gravity changes, as this topic is too large. I preferred to concentrate on the issues related to the projects I performed, and give some general basis in theory, procedures, corrections and evaluation.

Note: Three different professional terms are used in relation to this subject, with practically the same meaning.

1) Gravity monitoring	(geodynamics, geoengineering)
2) 4D gravity	(oil exploration, geoengineering,)
3) Time-lapse gravity	(oil exploration)

All of these terms are used in the Thesis.

3. Gravity changes – quantity definition and applications

Gravity changes (changes of the gravity field) are caused by the combined effect of vertical movement of the observation site on one side, and the integral effect of all mass displacements or density changes in the whole subsurface space on the other side.

In the Thesis, in most cases I use a simple expression ***gravity changes.*** More accurate, but impractical expression is “spatiotemporal non-tidal changes of the Earth’s gravity field”.

3.1. Definitions

The effect of elevation change can be approximated by the Free–air correction and the Bouguer slab effect (Torge, 1989):

$$\Delta g\ (H) = (-2g/R)\ \Delta H + 2\pi\ G\ d\ \Delta H \quad [\ \mu ms^{-2}/m \ \sim\ 10^{2}\ \mu Gal/m\ ] \qquad [1]$$

If $g = 9.8\ ms^{-2}$, $R = 6370$ km, $d = 2670\ kg/m^3$, $G = 6.67 \times 10^{-11}\ Nm^2 / kg^2$, then we get approximation:

$$\Delta g\ (H) = -2\ \mu ms^{-2}/m = -200\ \mu Gal/m = -2\ \mu Gal/cm. \qquad [2]$$

This means that we definitely have to control the elevation changes of the sites. However, considering the average accuracy of a precise gravity network of about 5 µGal, we can deduce that vertical movements below 1 cm that we can expect in regions like the Bohemian Massif represent a minor effect.

Now we have to account for the mass change. Considering a spherical source of expansion/compression (negative/positive change of effective bulk density), the respective change of gravity can be given as:

$$\Delta g\ (M) = G\ \Delta M / r^2 \qquad [3]$$

where r is distance to source, G is gravitational constant and ΔM is mass of the new source. Practically, the difference of mass before and after rock massif deformation can be, for example, water filling pores and caves, or magma filling fractures/dykes and voids.

In case we move our observation from the vertical projection of source in horizontal sense to any direction on the surface, and we define z as vertical coordinate of the source (x,y,z), then the formula will be

$$\Delta g\ (M) = G\ \Delta M\ z / r^3 \qquad [4]$$

In ideal case, when $z = r$ (as in fact in equation [3]), we observe maximum gravity change exactly above the source. I calculated the decrease of the signal from such a source with weighted distance from source (decreasing ratio z/r). For selected depth with unit depth $z = 1$ I was increasing the radial distance r by 0.1 of the unit depth. The curve in the graph in Fig. 3.1. reflects the rapid decrease of the studied ratio z/r^3 from equation [4]. It is clear that the signal drops down to less than 40 % when surface distance s equals the depth of source z (at the distance $s = z$ the ratio $r/z = 1.4$ on x-axis).

I attempted to put the equations [1] and [4] together to account for total **temporal gravity change** $\Delta g\ (t)$ (equally used will be ***dg(t)*** expression, or just ***dg*** in figures). In fact, it is possible, in simplified way, just combine the two:

$$\Delta g\ (t) = \Delta g\ (H) + \Delta g\ (M) \qquad [5]$$

This is only the first approximation. My comment to such equation is that the first part by Torge (1989) is not accurate as it assumes infinite Bouguer slab effect. This is not fully true with regard to the fact that the supposed elevation change is hardly infinite (constant in the complete half-space); rather it is just local feature the size of which depends on the size of the mass change source and its deformation effect on the surrounding massif. It could often be approximated by a positive or negative spherical cup due to tectonic bulge or subsidence. We can, however, estimate that the horizontal extent of such deformation will be larger than the depth of the source (s > z). Then the impact of the above mentioned discrepancy decreases sharply, as demonstrated in Fig. 3.1.

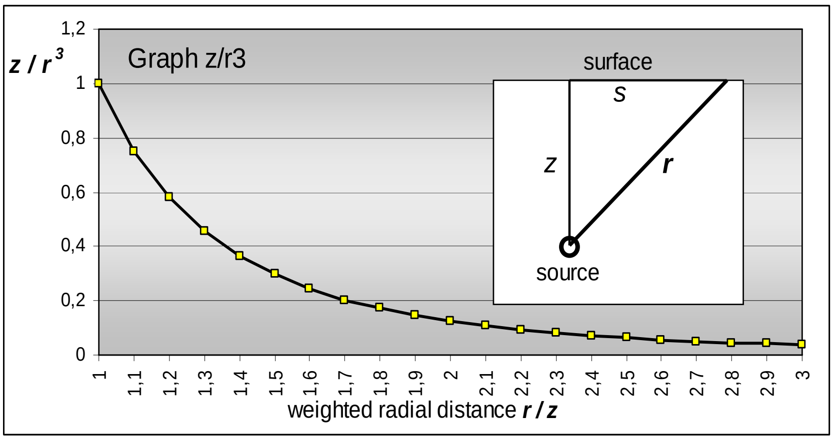


Fig. 3.1. Graph related to equation [4]; it demonstrates the impact of increasing distance from source of gravity, where ***r*** is radial distance, ***z*** and ***s*** vertical and horizontal distance, respectively.

As all applications that I deal with are rather of local character, the equation [5] is acceptable. On the contrary, Charco et al. (2007) use similar formula without the Bouguer slab member for elevation change correction. This seems to be less accurate as we obtain the correction -*3 μGal/cm* instead of *-2 μGal/cm* which represents “50 % overcorrected”. This question was also addressed by d’Linage et al. (2007) who also concluded that the Bouguer slab correction should be considered as well, but the exact value depend on the compressivity of the uppermost layer of the crust. As it is very low or none, they arrived to almost the same result as given by Torge (1989). These authors did not consider the subsurface mass changes that I present in the equations [3] and [4].

The problem is that all these theoretical formulae cannot comprise the other geomechanical effects, mainly the impact on change of the surrounding massif. The pressurisation of the massif around the anomalous excessive mass, that causes displacement, is difficult to quantify (Battaglia and Segall, 2004). Therefore, any attempts to evaluate the source of gravity change are speculative.

Nevertheless, identification and location of areas exhibiting temporal gravity changes is already significant result in geodynamic and geoengineering investigations.

3.2. Applications

Gravity changes originate from various sources. I will discuss the technical ones later, but from those which we consider as targets of geodynamic or geoengineering investigation, I want to mention the following:

- Vertical surface displacements
- Tectonic stress, earthquakes
- Magmatic activity
- Groundwater and other fluids movements
- Geomechanical processes in near subsurface

I present a few typical examples of gravity changes studies related to the sources listed above. One of the pioneers of the monitoring of temporal changes of the gravity field was Wolfgang Torge. Besides testing the instrumentation, both relative and absolute gravimeters, he was developing observation procedures, as well as performing real measurements. One of his principal projects was targeted at the gravity changes related to magma fissure eruptions in Northern Iceland around the Krafla volcano (Torge et al., 1992) in the 1970s and 1980s. The gravity changes were analyzed together with elevation variations that were considered by far the main source of gravity signal. As the average relation resulted in approx. -2 μGal/cm, there were likely good reasons to develop the equation [1] discussed above. The magma itself and its reservoir depletion were not taken into account. If there was any chance to do so, the evaluated uncertainties up to ±50% of the above given ratio dg/dH might have been explained.

Later, some other authors attempted to observe gravity changes related to active volcanism with the aim of detection of magma movement, density changes and internal stress evolution inside volcanoes. Jentzsch et al. (2004) presented results of repeated gravity at three different volcanoes (Merapi/Indonesia, Mayon/Philippines and Galeras/Colombia). Temporal gravity changes reached the amplitudes of 100 – 160 μGal. Considering almost no vertical displacements, the signals were explained by mass and/or density changes, and deep fluids migration. Very detailed study performed at the Etna volcano was analysed by Carbone and Greco (2007) where both repeated network, as well as permanent observations were carried out. They modelled the source of eruptions of lavas, and also showed the impact of eruption-related micro-earthquakes on semi-permanent gravity observations. Furuya et al. (2003) reported significant decrease of gravity by about 150 μGal shortly before a collapse of a Miyakejima volcanic caldera in Japan (origin of a big void). During the surface subsidence the increase of gravity could not be explained by decrease of elevation, but perhaps by magma ascent into the void space.

Berrino and Riccardi (2004) studied gravity signals related to large earthquakes and found that there is usually a disturbance noise on gravity records caused by surface waves, as well as longer change of the level of gravity readings related probably to regional stress shifts.

Very clear picture of gravity changes related to the Sumatra earthquake 2004 were obtained from GRACE satellite, as will be shown in the next chapter (Han et al., 2006 a,b). However, satellite techniques are still far behind the accuracy needed for investigations in small regional, local and micro scales.

Mrlina (PAPER 1 and 2) demonstrated indications of empirical relation between weak earthquake swarms and gravity changes in West Bohemia, as will be also discussed later in the Thesis. Similarly, Mrlina (2001) showed possible relation of gravity changes in 1997-2000 to continuous uplift of the southern coast of the Gulf of Corinth. Gravity changes in 2000 – 2002 indicated tectonic compression on the crossing of normal faults parallel to the

axis of the Gulf of Corinth Rift with a transverse fault at the period of the earthquake swarm 2001 (Mrlina, 2004).
On the other hand, Mrlina (PAPER 4) has recently changed the former 'tectonic stress' interpretation of gravity changes to a groundwater infiltration causative process, in case of gravity monitoring near Lake Aswan, Egypt (Chapter 5.2.). The impact of groundwater fluctuations on observed gravity was studied by a number of authors, who focused on various effects, as groundwater level change, rainwater and ground humidity effects, large reservoir infill effect, and so on. Kroner et al. (2004) found that groundwater variations can be well recognized from superconducting gravimeter record. However, more applicable for gravity investigations using relative gravimeters are the results of Naujoks et al. (2007). They established a local gravity network with maximum station distances of 65 m in a hilly area around the Geodynamic Observatory Moxa, Germany. Using LaCoste&Romberg relative gravimeters repeated measurements were carried out in a seasonal rhythm as well as at particular events like snowmelt or dryness in 17 campaigns between 11/2004 and 04/2007. Spatial gravity changes of up to 170 nm/s^2 (17 μGal) could be proven. They correlate with changes in the local hydrological situation. Zhang et al. (1996) predicted that the construction of the Three Gorges water reservoir in China would change the local gravity field by up to 4.7 mGal with about 20 mm of surface subsidence. This is, of course, an extreme case of filling up a huge water reservoir. Nordquist et al. (2003) showed how repeated gravity monitored the behaviour of the exploited Bulalo geothermal field. The decline in gravity of up to −600 μGal was interpreted by density changes in the reservoir due to mass withdrawal (pumping hot water) that was later compensated by recharge from outside of the producing reservoir. The gravity data were corrected for subsidence.

I wish also to mention the fluids movement monitoring in hydrocarbon reservoirs by 4D gravity. There are only very few successful examples from around the world, e.g. reservoir water-flooding monitoring in Prudhoe Bay, Alaska. Ferguson et al. (2007) showed that the water–gas contact can be monitored even in such difficult polar-arid conditions, if high accuracy measurements are performed. Mrlina (2007a, 2007b) carried out theoretical modelling for various cases of gas-water contact movement and concluded that the great depth of 2.5 – 4.5 km, common at currently exploited oil-gas fields, is a strong limitation factor for 4D gravity, as well as the tight reservoir conditions with reduced porosity/permeability.

In geoengineering, there are some geomechanical processes observable by gravity monitoring. Among them are:

- Propagation of voids to surface by disintegration process in the overburden
- Dilatation in landslide tension zones
- Stress accumulation in mines
- Surface subsidence related to any underground exploitation

Bláha et al. (1998) presented number of examples of gravimetric investigations of landslides, starting from landslide body composition and shape, and ending by examples of gravity monitoring. This field was studied in detail by Goryainov et al. (1987). He provided a few examples of temporal negative gravity changes related to the progress of dilatation in tension zones at the back of the landslide bodies. The amplitudes reached the level of about 20 - 30 μGal. Fajklewicz (1997) determined gravity changes caused by the stress field development during mining in deep coal mines. This process is considered a direct hazard phenomenon for miners, as well as for technology in the mines. For the same reason, 13 repeated campaigns of gravity measurements were performed in three galleries of the CSA mine in Karvina, Czech

Republic, at the depth of 950 – 1100 m (Mrlina, 1994 and PAPER 5). Temporal changes of gravity (corrected for surface subsidence) preceded strong rock-bursts in the mine.
Repeated gravity measurements also substituted large scale precise geodetic monitoring of subsidence. An example from the urban area of extensive coal mining in England was given by Styles (2003). He presented microgravity surveys results showing potential hazard from mine cavities on one side, and gravity monitoring of related subsidence on the other side.

As conclusion, we can state that gravity monitoring has definitely been recognized as a efficient technique for investigations in geodynamics and geoengineering. However, in many cases the application is limited by the weakness of the target signal, or by the resolution of the used instrumentation.

4. Instrumentation, observations and data processing

Gravity monitoring is based on repeated gravity observations at fixed locations (monuments, benchmarks). In case of relative gravity measurements, it is important to focus on the following issues:

- Feasibility study – to evaluate expected gravity signals
- Design of observation network and establishment of observation sites
- Selection of reference station(s)
- Preparation of gravimeter(s) – calibration, drift tests
- Design of measurement procedure
- System of data processing, corrections of disturbing effects and accuracy evaluation.

I will shortly comment on the instrumentation, disturbing effects, processing technique and accuracy evaluation.

4.1. Gravimeters

The development of prospection land gravimeters has been ongoing since the ‘torsion balance era’ one century ago. The principal progress was achieved by Prof. Romberg and his student LaCoste who developed contemporary type of gravimeter that was later called LaCoste&Romberg gravimeter (LCR). It is a ‘zero-length’ spring based model where relative value of gravity is observed from a small mass (attached to the spring) up or down displacements (astatic system). The system is made of metal and exhibits drift changes during operation. The LCR-G model was aimed as a prospection one with resolution of 0.01 mGal, while the LCR-D model is a microGal-level high resolution gravimeter. LCR became the most popular land gravimeter for decades in the second half of the 20th century. The production was stopped in 2005. Similar system is used by the producers of the ZLS Burris gravimeter. Simple vertical string made of pure quartz is the basis of other group of land gravimeters (Scintrex, Worden, Sodin). Only Scintrex is still developing gravimeters at present, and the CG-5 model (digital display and recording, microGal resolution) will probably be the by far prevailing model in the market.
I measured myself about 100000 gravity stations with LCR and Scintrex gravimeters in various conditions in Africa, Europe and the Middle East – sand and rocky deserts, savannah, mountains, urban, agricultural, forests, swamps, industrial zones, deep mines, in buildings, etc. Also I practiced various transport conditions – on foot, personal cars, 4WD vehicles,

helicopter, small airplane. The experience obtained from this field work, including a few non-intentional shocks during operation, or overheating of the instrument, can be summarized as follows:

- Car transport itself has no serious impact on readings, excluding strong vehicle jumps.
- Gravimeter tends to work well in regular regime without breaks; in microgravity, even distance to gravity base station from a profile plays a role.
- In difficult condition, many instruments reach the state of calm drift only after about one week of regular operation.
- Any overheating due to external high temperatures practically results in the loss of the working day.
- If storage temperature differs from the outdoor one, there is usually stronger drift at the beginning of the observation programme.
- Air-pressure impact is almost negligible, except sharp changes, as in helicopter surveys.
- A tare from even small instrument shock (hit on transport box, or base plate, etc.) produces significant shift in data, from 10^1 to 10^3 μGal. Compensation takes hours.

Gravimeter tests:

These are just some of the conclusions of long-term work with gravimeters. With respect to the fact that I was using mainly a LCR-D gravimeter in the studies presented in my publications, I will focus on some tests performed with this instrument. This gravimeter is usually very sensitive to any **shocks**, mainly the mechanical ones during transport or measurements.

The instrument is also strongly affected by **earthquakes**, both the weak local ones, as well as strong distant ones from any location on the Earth. Therefore, we performed series of tests on a vertical vibrating platform (Tobyáš et al., 1999) in order to evaluate the impact of seismic waves on gravity readings. We concluded that the response of the given LCR-D188 gravimeter to vibrations relevant to common microseismic noise with peak-to-peak amplitude of 2 μm and period T = 6 s is bellow 1 μGal. On the contrary, for Raleygh surface waves of large earthquakes with higher p-p amplitudes (10 μm) of the vertical motion we got disturbances up to 70 μGal for two different periods (T = 4.8 s and 40 s). This is valid for the given coupled system of the gravimeter's beam and its electronic feedback readout (feedback was installed acc. to principles developed by Röder et al., 1988). Such tests have to be performed should we expect working in seismically disturbed environments.

Another specific test I performed in the military **air-pressure** chamber. This test requires even special medical control of the gravity operator. I positioned the gravimeter inside this chamber and stayed inside to control the recording. The air-pressure was changed according to the agreed system. Surpricingly, small changes of pressure did not produce any significant changes in observed gravity. Then, we used big changes of 200 hPa that were achieved by 5 min of pressure linear decrease, then stayed constant for 30 min and returned back to normal during another 5 min. Only small drops of 6 μGal were observed in the last part of this cycle during the return of air-pressure to normal, see Fig. 4.1.

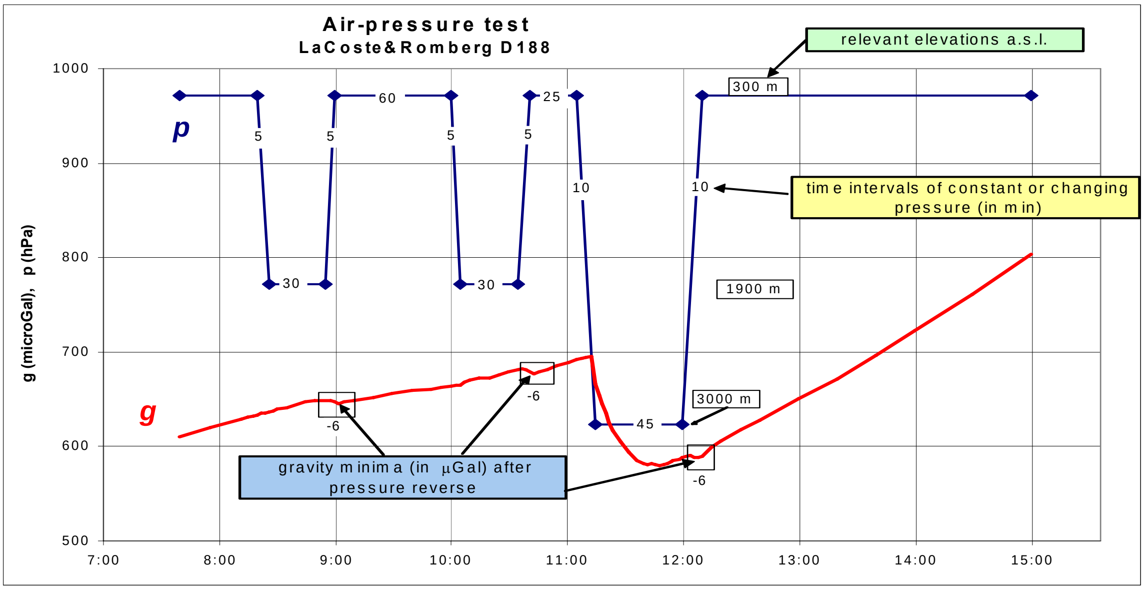


Fig. 4.1. Test of LCR D-188 in an army air-pressure chamber: simulation of strong barometric (p) changes (as short semi-vertical flights in a helicopter) down to relative -350 hPa. Periods of pressure decrease were (time/pressure change) 30/-200, 30/-200 and 45/-350 (min/hPa). Only the strongest barometric change caused significant tare (slip) in observed gravity (g).

Eventually, we simulated a helicopter flight from 300 m to 3000 m altitude. In this case we experienced sharp tare of 120 µGal (and a small drop at the end of cycle as before). This huge tare was too strong and did not allow the gravimeter's system to come back to original trend of readings until the end of the experiment. The conclusion was that the gravimeter is well resistant to usual air-pressure variations and a good drift control during precise measurements is enough to compensate for the air-pressure direct impact on the gravimeter's mechanical system. It is important to point out that this is the result of just one particular gravimeter. Other instruments may have different response to such test.

One of the important parameters of any relative gravimeter is the **calibration** function. Normal domestic procedure is to repeat calibration measurements on available calibration line. Such line exists in the Czech Republic in the form of well-monumented stations between Děčín and Dolní Dvořiště. It is so called 'latitude calibration line' as it utilizes the northward gradient of increasing normal gravity due to the Earth's shape. I was using the section between Prague and D. Dvořiště that approximatelly fits the 200 mGal range of the LCR-D gravimeter.

Beside that, I participated in the 'world calibration and comparison campaigns' of absolute and relative gravimeters organized by BIPM (Bureau International de Pondes et Mesures) in Sevres, France. The result of comparison proved good resolution of our LCR-D188 gravimeter with sd = 2 µGal, as well as stability of calibration coefficients. In Fig. 4.2. both the FG-5 absolute, and the LCR-D relative gravimeters are shown.

Fig. 4.2. Absolute gravimeter FG-5 and relative gravimeter LaCoste&Romberg D-188 (IG ASCR, Prague) during the world comparison and calibration campaign of absolute and relative gravimeters in Sevres, Paris. Author participated in two of those campaigns in 2001 and 2005 (e.g. Vitushkin et al., 2002) with the aim, beside others, to investigate the stability of the calibration function. Standard deviation of LCR-D188 was about 2 μGal. Here LCR-D (right up) is measuring vertical gradients nearby FG-5 location. *(Photo J.Mrlina)*

As conclusion I can say that the LCR-D188 gravimeter exhibits good characteristics for high resolution gravity measurements and, therefore, is suitable for gravity monitoring applications.

4.2. Environmental effects

High resolution/accuracy 4D gravity investigations require careful application of corrections and reductions of various environmental effects. These effects may be divided into two main groups:

A] Effects on instrument ~ temperature, air pressure, seismic noise, transport, wind (Fig. 4.3.), sunshine, dust, sand, rain, unstable ground (swamp, asphalt), etc.

B] Effects on measured gravity ~ environmental phenomena (groundwater table, soil moisture, air-pressure mass load, earth tides, etc.)

While the group A effects should be tested and corrected (temperature, air-pressure), or at least minimized by either suitable methodology of measurements, or selecting suitable periods for measurements (microseismicity), or effective protection (wind, dust, sunshine, rain), the effects of the group B may require further data or observations (groundwater, soil moisture). As well, some of the phenomena of the group B can become a target of investigation (groundwater level, etc).

Group A - instrumental

Temperature is not a real problem, as all contemporary relative gravimeters have a thermostat unit keeping constant temperature around the measuring system. However, overheating may be experienced when working in deserts during the hot season. If this happens, usually the daily programme is lost with respect to low chance of closing the loops. From personal experience with LCR-G meters in research and exploration, the drift can rise up to a few mGal, while good G-meters normally keep daily drift below 0.05 mGal. Cooling the gravimeter's transport box with water, and air condition (if available in the car) can help to reduce the risk of overheating.

Air-pressure has, in general, strong effect on number of natural phenomena, as well as on delicate (geo)physical instruments. Nevertheless, gravimeters are usually well resistant to its effect, speaking on prospection level. In microgravity the care should be taken and the instruments tested, as described above (Chapter 4.1.).

Microseismicity – we performed tests mentioned in Chapter 4.1. which resulted in negligible impact on gravity readings (Tobyáš et al., 1999).

Earthquakes represent significant obstacle to gravity measurements due to surface seismic waves following the event. In case of an earthquake occurring in any part of the world with magnitude higher than 7, gravity readings will be disturbed for a few hours.

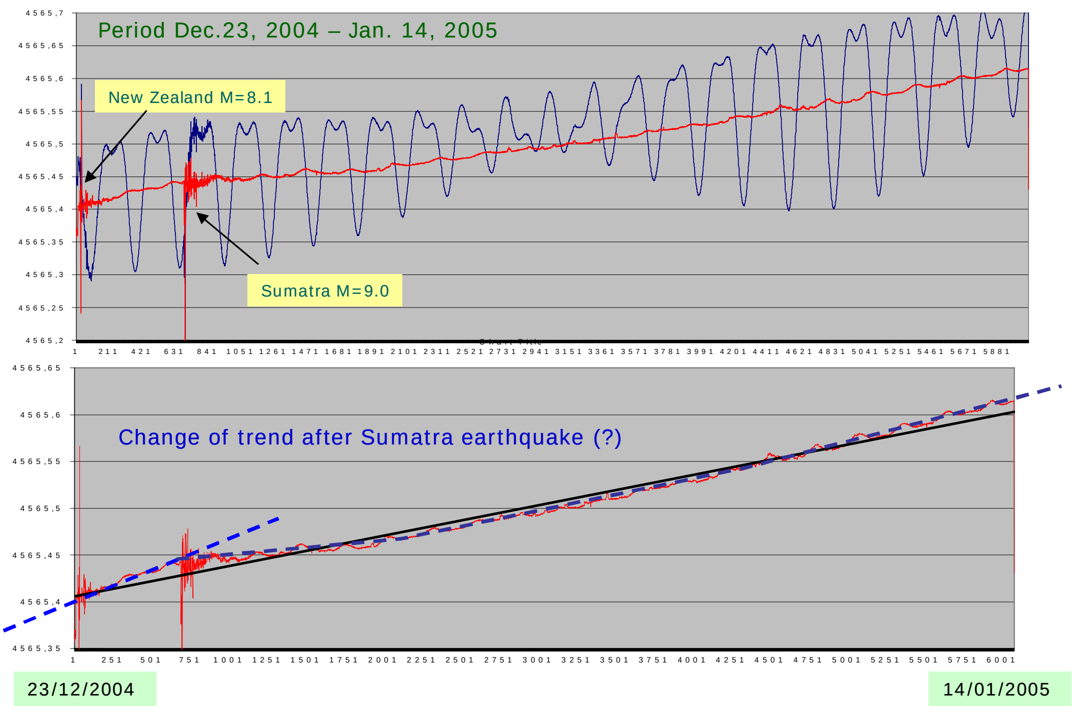
In case of the Sumatra 2004 earthquake, high noise was observed in the continuous record of a gravimeter at the observatory SKAL in Skalná, West Bohemia, for more than 12 hours, see Fig. 4.4. What was more important is the long-term change in the trend of recorded data (Mrlina in Boušková et al., 2007). From the lower graph in Fig. 4.4., after removal of the Earth tide effects, there is obvious decrease of gravity values forming a flat parabola with slow return to original trend during at least 2 weeks. Large scale aerial gravity changes, the first ones observed by a satellite system (GRACE) as related to an earthquake, are shown in Fig. 4.4. (after Han et al., 2006 a,b). It was possible to detect these changes only due to their enormous aerial extent, see the range of Latitude-Longitude. This case demonstrates that earthquakes are a significant disturbing factor. However, gravity changes related to earthquakes can also be the target of gravity observations.

As for the other directly disturbing factors form the A Group – each gravity operator should find his way to protect his instrument from such effects. One of the factors is definitely wind, directly causing vibrations of instruments, as well as ground instability, see Fig. 4.3.

Fig. 4.3. My colleagues were trying to keep protection, but even on a huge concrete platform we felt the strong wind effect on gravity readings (geodynamic investigations in Egypt). Here we used a blanket on a geodetic tripod. Later on, the wind cut the blanket to pieces.
(Photo *J.Mrlina*)

LaCoste&Romberg Graviton EG

Continuous gravity measurement in the observatory SKALNA, West Bohemia



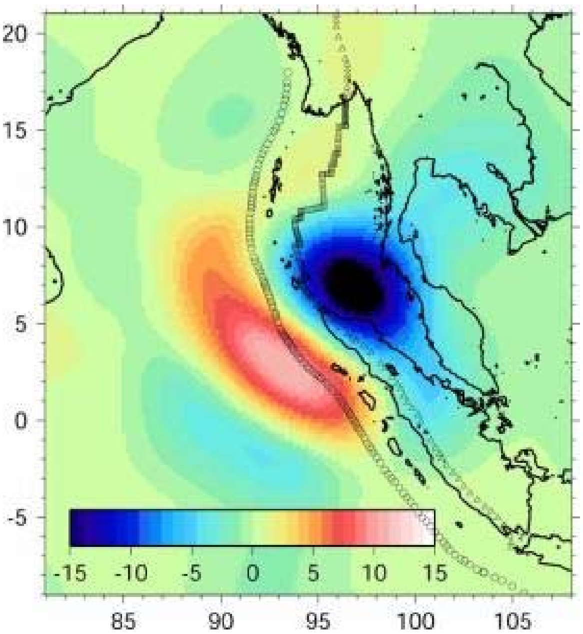


Fig. 4.4. Three-weeks record of Graviton EG (top) in SKAL observatory of GFU AVCR in Skalná, West Bohemia, during Sumatra 2004 earthquake. One scale gridline = 50 µGal. Composite image from GRACE satellite data (right) showing the gravity changes (µGal) for this earthquake (Han et al., 2006 a,b). Lat-Long co-ordinates in degrees. (Photo *J.Mrlina*)

Group B - environmental

I will focus only on those phenomena that have impact on observed gravity values in small regional, local or microgravity scales. I leave behind the global and regional effects like polar motion, variations of the Earth's rotation, ocean loading, etc., as these affect local relative gravity observations to the same (negligible) extent at all measured stations including the reference ones.

Air-pressure variations have, beside the direct effect on instruments described above, also indirect effect on gravity through ground deformation caused by air mass (atmosphere mass). It was proposes by IAG (1983) to use the air pressure reduction of

$dg\ (p)\ [\mu Gal] = -0.3\ dp\ [hPa]$,

where $dg\ (p)$ is reduction of gravity due to change of air-pressure dp (Torge, 1989).

Usual local changes of ±5 hPa may cause gravity variation of only ±1.5 μGal and can be neglected. However, in case of regional observation and/or long-term ones, the reduction should be applied.

Earth tides: There were numerous complicate theoretical formulae applied to calculate gravimetric earth tides reduction. Currently the formula including about 1200 periodic waves by Tamura (1987) is used. For specific investigations (permanent gravity station) a local model of earth tides effect can be derived from observed data. Total peak-to-peak amplitude of the earth tides can reach about 300 μGal in maximum.

Hydrological effects - soil moisture and groundwater level variations produce practically the same impact on gravity data in the form of direct gravitational effect. This can be approximated by a Bouguer slab. For example, we can test a water layer of e.g. 10 cm thickness, or 1 m of rock with 10 % porosity, and we obtain the same result of 4.2 μGal. Mrlina (PAPER 1) tested how this effect depends on aerial extent of such water layer as the value above represents unprobable approximation by a complete unlimited Bouguer slab. High resolution gravity monitoring requires control of groundwater variations. On the other hand, groundwater variations may become the target of gravity monitoring – some examples are given in Chapter 3.2.

4.3. Processing procedures

In relative gravimetry, serious attention has to be paid to gravimeters' drift, as this phenomenon may strongly affect the final data accuracy. As at the time there was no suitable software that would deal in detail with this problem, I decided to design the programme DRIFT – especially its logistical structure, expected inputs and outputs, graphical working screen, etc. The writing of the programme itself was performed by a specialist.

The principal condition of improving data accuracy using this software is that the measurement procedure includes enough repeated stations within a daily loop. If minimum of three readings throughout the daily loop is measured on those selected repeated stations, real improvement can be achieved (Mrlina, 2008). Based on the least square method, a spline technique is used to define drift curve from the repeated gravity readings.

Despite the software is still in development, I used DRIFT during most of the projects, and mainly in those described in my papers in this Thesis. I proved in a few cases where the data were processed by usual software, like Geosoft, that the accuracy could be increased by up to 50 % ! The reason is that DRIFT enables interactive removal of odd readings that may significantly disturb the calculated drift curve of the daily measurement loop, see Fig. 4.5. One of the examples of improved accuracy is derived from a gravity exploration network in difficult desert and mountain conditions where 2 LCR-G prospection gravimeters were used. After reprocessing of the data the standard deviation dropped even more than 50 % (Fig. 4.6.).

Error budget – considering all above discussed phenomena affecting the final accuracy of the gravity data in question, I conclude that it is possible to achieve the repeatability of about 2 – 5 μGal for a precise relative gravity campaign. This means that the uncertainty of gravity changes derived from such two campaigns can be 3 – 7 μGal in the best cases.

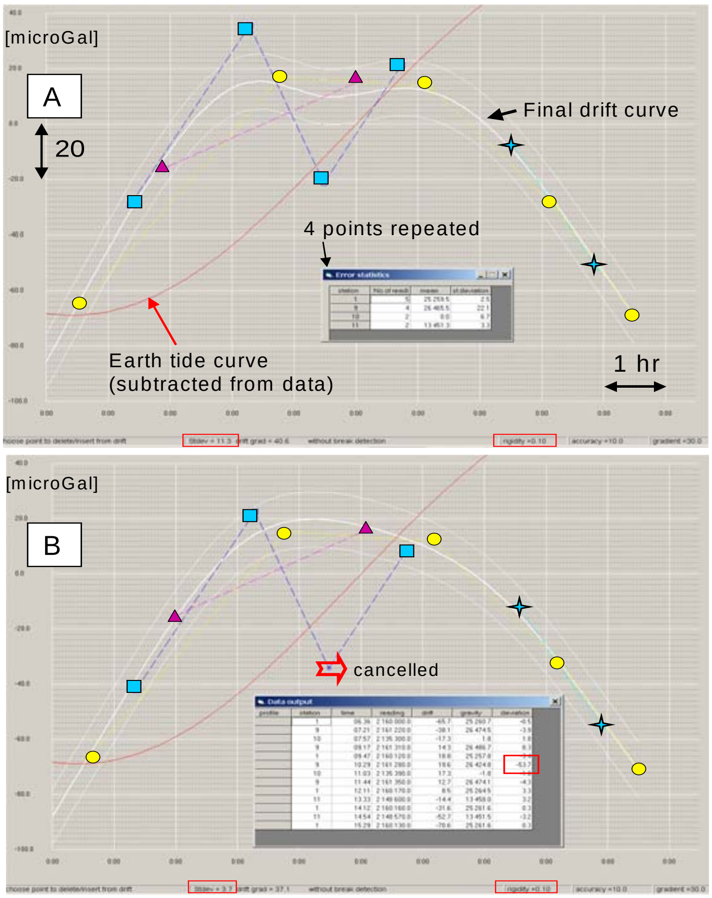
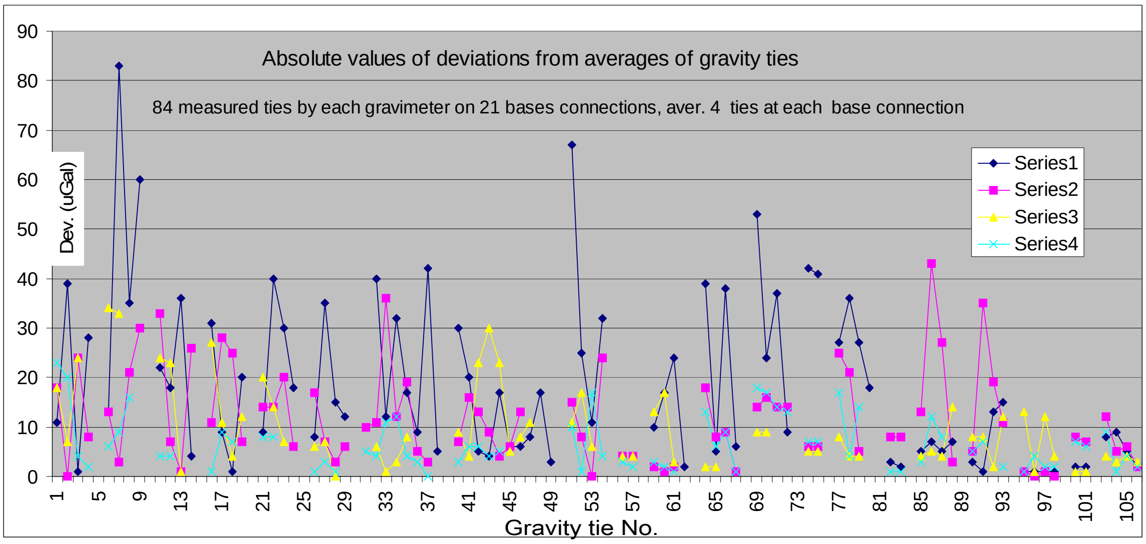


Fig. 4.5. Applied components of the drift analysis - subtracting the Earth tides effect (red line), decreasing drift curve rigidity ("strength") from 1.0 to 0.1. Elimination of one offset reading (disabled in figure B) improved standard deviation from 11.3 to 3.7 µGal.
Presented tables are "Error statistics" for repeated points in figure A, and "Data output" in figure B (note the large deviation of the disabled reading).
Final drift curve of this LCR-G gravimeter (thick white line) is far from linear, the amplitude is about 100 µGal.
One tick/label on y-axis is 20 µGal.



The accuracy (standard deviation) changed to less than 50 % as follows:

Processing software	Geosoft	DRIFT	unit
gravimeter I.	0.017	0.008	mGal
gravimeter II.	0.012	0.005	mGal

Figure 4.6. Gravity network ties by two LCR-G gravimeters were processed by common software (dark blue and purple) and then re-calculated by specialized DRIFT software (yellow and turquoise). Deviations changed from dark blue to yellow, and purple to turquoise. Not all readings persisted in the new processing output. Transport – 4WD vehicle. Conditions – difficult mountain and wadi tracks in a hot area (Middle East).

5. Gravity changes – case histories

In this principal chapter I will focus on observations and/or modelling of non-tidal temporal changes of the gravity field in various geological conditions. As stated in the introduction, three different geological fields will be addressed:

- geodynamic activity including earthquakes and surface displacements
- fluids movement in the upper crust
- geomechanical processes in the near subsurface

I will show that fluids are often involved in geodynamic activity, as well as in geomechanical processes in geoengineering. Therefore, the above division into three topics is not strict.

5.1. Gravity monitoring related to geodynamic activity in West Bohemia (PAPERS 1, 2 and 3)

West Bohemia/Vogtland is an intra-continental weak earthquake region with repeated seismic activity in the form of earthquake swarms with hundreds or even thousands of events of very low magnitude, with the strongest shocks of M = 4.5 (1985/86) or 3.2 (2000), as presented by Fischer and Horálek (2003). It is located on the crossing of two major tectonic zones – the SWW-NEE trending Ohře Rift (Eger Rift) and the NNW-SSE trending Cheb-Domažlice graben. Long-term tectonic activity of the Ohře Rift is documented by Cenozoic volcanism with the activity progressing from NE (28 my) to SW (most recent data show 300 ky, Mrlina et al., 2007) close to the main focal areas.

After the 1985/86 earthquake swarm extensive seismological observations were started. In 1993, after the Geophysical Institute purchased the first LCR gravimeter, the microGal model D No. 188, we decided to establish geodynamic networks for gravity, GPS and precise levelling that in some sites were identical. The target was to investigate general geodynamic phenomena, mainly horizontal and vertical displacements and temporal non-tidal changes of the gravity field. The initial periods of the network establishment and observations were presented by Špičák et al. (1999).

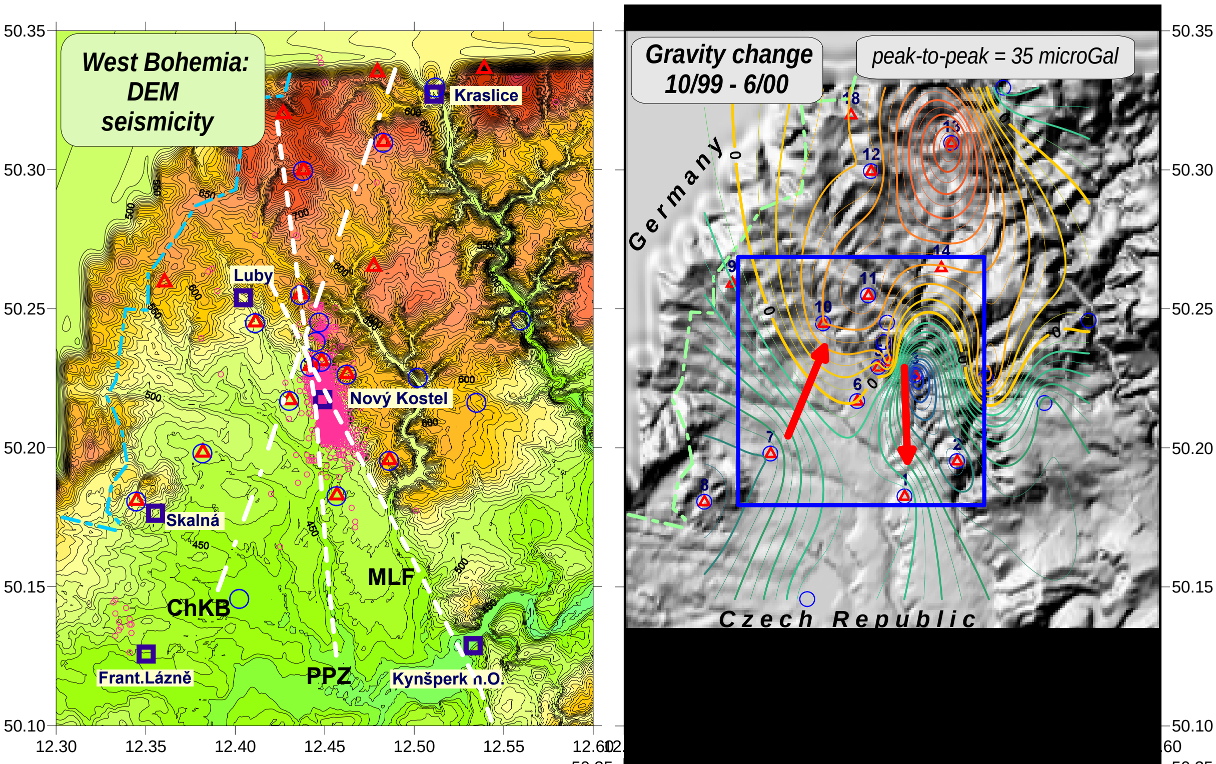
Already the first period of **gravity monitoring** in 1993 – 1995 showed a remarkable correlation of gravity changes with seismic activity in two areas – the main area of Nový Kostel and a “second order” area around Skalná (PAPER 1). Gravity maximum before the earthquake swarm 12/1994 is documented in Fig. 8 of PAPER 1. This result was a motivation to continue gravity observations and even some more stations were established to enlarge or densify the gravity network. In PAPER 2 the overview of the relation of gravity changes to seismicity (earthquake swarms) was presented with a clear message that there exists such a relation. Most of the statistically significant gravity changes were concentrated to the Nový Kostel focal area during the swarm periods. I was aware of the fact that it is not possible to exactly characterise the time correlation between the two phenomena with respect to epoch style of gravity observations (one to three campaigns per annum).

Important condition of the gravity data analysis was the knowledge of vertical movements of ground surface, as variations in elevation can, in some cases, cause recordable changes of gravity. However, Mrlina (2000, PAPER 2 and 3) proved that the vertical movements do occur, mainly during the seismically active periods, but the amplitudes are so weak that they cannot affect observed gravity signals. The maxima of less than 10 mm are relevant to 2 μGal only, which is significantly below the usual average standard deviation of approx. 4-6 μGal of the adjusted gravity values. As well, GPS observations revealed specific horizontal displacements characterised by reverse movements oriented mainly in the NNE-SSW in general, with more complex orientation statistics in detail around Nový Kostel (PAPER 2). Despite horizontal displacements do not directly affect observed gravity, we believed that they are of great importance for the complex geodynamic image of the region under study.

Therefore, recently we have reprocessed and re-analyzed all the **GPS data** of the 15-years–lasting observations in 1993-2007. We compared in detail our processing software TTC (Trimble Total Control) with the world-number-one Bernese software with the conclusion that there are no significant discrepancies in the output (PAPER 3). As well, we tested different processing approaches, in particular fixing the GPS points on the western part of the area in order to enhance relative horizontal displacements in the eastern part. From all these GPS (and **levelling**) results, as well as from my analysis of earthquake locations, I defined a new geodynamic feature in the region under study – the NNE-SSW trending Cheb-Kraslice GPS Boundary (ChKB), as described in detail in PAPER 3.

Now, the question is, whether there is also some relation of the **gravity changes** to ChKB. In order to address this challenging question I have recently re-evaluated the gravity data including the search for possible common features of both datasets, GPS and gravity, as they both may reflect the state of stress in the Earth’s crust. As indicated before, the most striking anomalies are related to the most seismically active period of the Autumn 2000 swarm, as given in PAPER 2. Contrary to Fig. 5 in that paper, where the overview of gravity indications was resulting from a „profile-based“ analysis, now I used more „spatial“ approach with contouring the epoch gravity changes.

Various types of gravity monitoring stations in West Bohemia.
(Photo *J.Mrlina)*



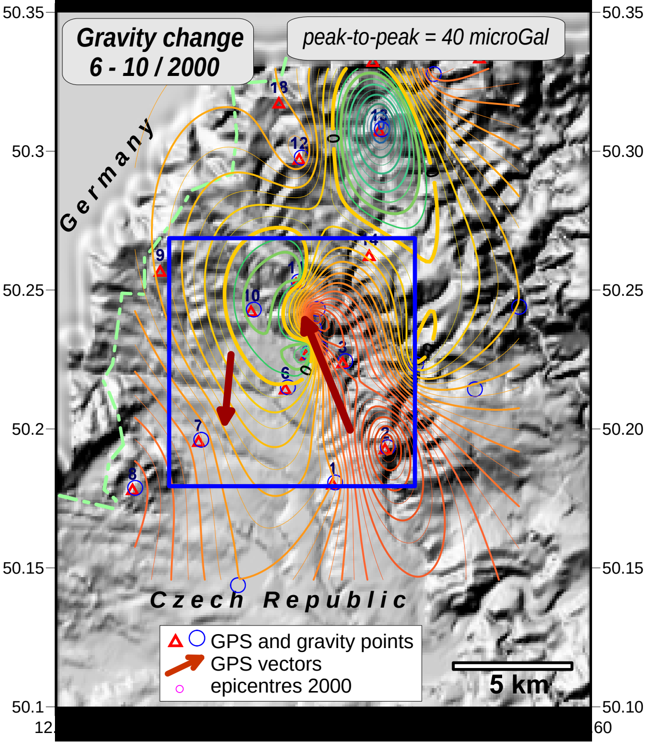


Fig. 5.1.
Top left – DEM with contours of elevation, position of GPS and Gravity points, map of seismicity. ChKB – Cheb-Kraslice GPS boundary, MLF – Mariánské Lázně Fault, PPZ – Počátky-Plesná zone.
Right top – grey shaded DEM with contours of gravity changes before Autumn 2000 swarm; generalized relative GPS vectors (from PAPERs 2 and 3) in red.
Right bottom – grey shaded DEM with contours of gravity changes during the first strong periods of Autumn 2000 swarm; generalized GPS vectors in brown.
Coloured contours were used rather than coloured maps in order to keep the visibility of the DEM and position of observation sites under the contours. On the other hand, contour interval is 1 μGal in order to enhance the image of gravity changes. “Zero” contour in yellow.

In Fig. 5.1. the coloured contours of gravity changes in the 10/1999 – 6/2000 and 6 – 9/2000 are positioned on top of the digital elevation model (DEM). Generalized relative GPS horizontal displacement vectors are presented in the principal focal area around Nový Kostel.
What we can deduce from this figure is that there is a more complex distribution of negative-positive temporal gravity changes ***dg(t)*** with obvious separation of the Kraslice area (North) from the Nový Kostel area (centre). However, if we focus on the NK area, we can see that in both epochs the maximum gradient of ***dg(t)*** is located exactly in the centre of the principal

focal zone reaching peak-to-peak amplitudes around 30 μGal, about 4 times greater than is the data confidence level. But mainly, the GPS vectors seem to be oriented from gravimetrically relaxed zones (negative ***dg(t)***) into gravimetrically compressed zones (positive ***dg(t)***), see Fig. 5.1. Despite this picture of the mutual relation of the two phenomena is based on irregularly distributed stations of both techniques (mostly identical), there is obviously a relation between them which fits the general logic – compression causes increase of gravity while relaxation decrease of gravity. I wish to point out that all the resulting ***dg(t)*** are relative, so we cannot exactly say whether positive (or negative) sense of change prevails.
At this stage we can only speculate on what is the source of these changes. The following may play a role:

- Compressive stress that reduces the pore volume, and consequently increases bulk density of the rock massif.
- Mass displacement at depth (fluids, magma ?)
- Minor effect of groundwater level variations
- Very small to negligible effect of elevation changes.

As the most probable source of gravity changes I consider the first option in combination with groundwater. The reason is that the horizontal gradient of ***dg(t)*** is relatively sharp in the centre of the Nový Kostel area and this excludes the source to be only at great depth. In order to estimate what kind of ***dg(t)*** we can obtain with small changes of density of the massif, I tested simple geometrical models. It turned out that already the density contrast of 0.02 g/cm^3 between relaxed and compressed blocks limited by the depth of earthquake foci (11 km) reveals the gravity signal of 20 μGal (Fig.5.2). This is very close to the above discussed signals in Fig. 5.1.

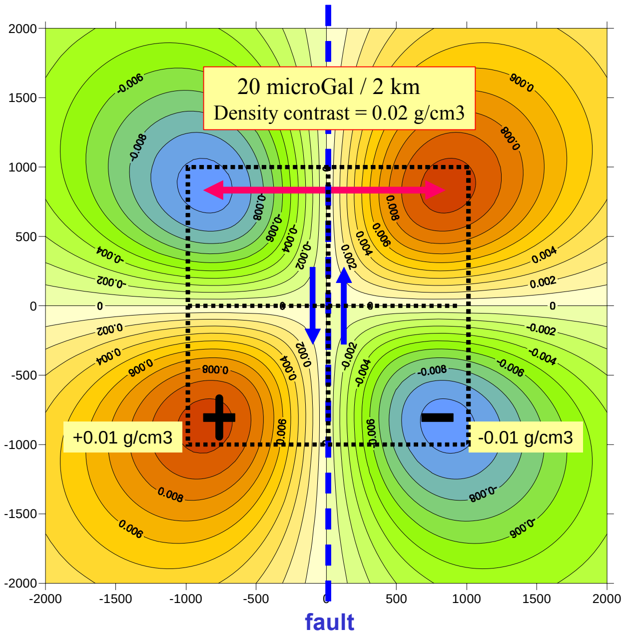


Fig. 5.2. Model of temporal gravity changes around a short left-lateral (sinistral) strike-slip fault due to shear stress polarity. Depth of model is 11 km. The four quadrants are characterized by almost negligible density difference of ±0.01 g/cm^3. The significant gravity signal is due to big volume of rock mass involved (2 x 2 km). In reality, the model would have to be optimized by considering real or expected length of seismoactive fault and concentration of stress at its singular points. This was not attempted due to lack of gravity coverage and detailed knowledge of fault parameters.

If I reconsider back to 1997 old Fig. 5.3., there was very similar amplitude of ***dg(t)*** of 30 μGal, while 35 μGal in 10/99-6/00 in Fig.5.1. Both these gravity indications are characterized by a minimum on the eastern side. It indicates that before a swarm starts, there is a right-lateral stress on the fault plane with relaxation on the eastern side of the Nový Kostel focal area. It is then compensated by the reversal of stress during swarm periods. This type of reverse behaviour of strain (derived from GPS displacements) was described in detail in PAPER 3. Now, it seems that gravity changes undergo very similar process. It could be characterized as ‘stress pulses’ rather then a continuous (permanent) stress orientation. Such pulses were reported by Koch et al. (2003) from fluids observations in Bad Brambach, SOOS and Bublák.

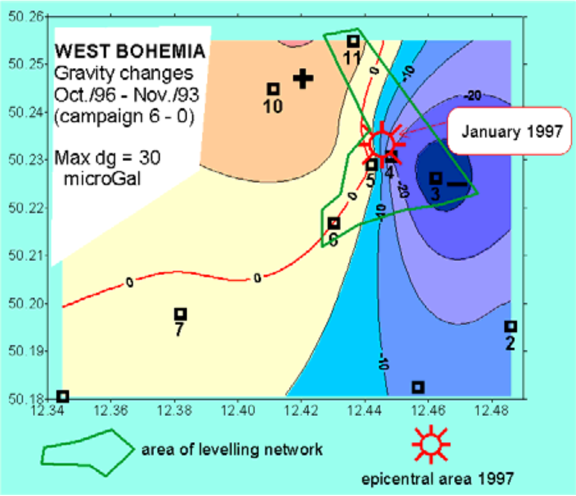


Fig. 5.3. Map of gravity changes before January 1997 swarm. Maximum gradient of the changes is located at the same place like before Autumn 2000 swarm, see Fig. 5.1 top-right for comparison. Point 4 is located close to NKC seismological station on the first slope of the Krušné hory Mts., while point 5 is on the Mar. Lázně Fault zone.

The source of stress seems to be located rather under the Cheb basin than in the block of the Krušné hory Mts. as the gravity change is sharply limited in the focal area and does not seem to simply progress to N. As well, it was proved that the direction of the MLF (Mariánské Lázně Fault) plays significant role in geodynamic activity, as can be estimated from the orientation of gravity compression zone (Fig. 5.1) and GPS vectors (Fig. 1 in PAPER 3) in the swarm period 2000. This compression zone is relevant to upper-right part of the model in Fig. 5.2. It turned out that there are not enough observation sites to provide a complete picture of gravity changes that would reflect such double bi-polar characteristics along the fault.

Bringing to light the principal result of PAPER 3 – the definition of the NNE-SSW oriented ChKB zone as a limitation of reverse surface horizontal displacements - it is obvious that this zone applies in the evolution of gravity changes, too. This I consider a remarkable result with regard to the fact that this ChKB zone now seems to have substantial influence on all three (four – vertical displacements as well) geodynamic phenomena as follows:

- ChKB acts as striking limitation of earthquakes distribution and character of seismicity (see Paper 3)
- ChKB separates areas (blocks) with opposite direction of surface displacements (Paper 3), as well as the vertical ones observed during the seismically active periods
- ChKB limits the temporal gravity changes, especially around Nový Kostel, where sharp contact of negative – positive changes was identified.

Similar character of gravity changes were first indicated during the Dec.1994 swarm (PAPER 1) when a group of stations around Nový Kostel exhibited notable positive change of gravity before the swarm. Later, as mentioned above, I found that during the following two swarms in Jan. 1997 and Autumn 2000 there were increased values of gravity changes, before, during and after the swarms. An overview of the time correlation of gravity changes and seismic activity was presented in Fig. 5 of PAPER 2.

The Kraslice area exhibits, in fact, similar and partly independent regime, but with respect to low number of observation stations it is difficult to derive more detailed picture of gravity changes. However, the two stations in the north part of the region show reversal gravity changes similar to the Nový Kostel area, see Fig. 5.1.

I want to point out that the whole picture of gravity changes suffers from irregular distribution of observation sites. The number of sites was increased throughout the project, but by far they do not cover the area in an ideal way. This is valid, in fact, also for the case history in Chapter 5.2.

We studied one more important indicator of tectonic activity – the **groundwater level**. The data from our two wells H3 and P1A (for location, see Fig. 2 in PAPER 2). These wells exhibit totally different behaviour of the groundwater level – in P1A there is very significant tidal regime overprinting the target signal, while in H3 we get relatively undisturbed groundwater level data. As shown in PAPER 2, the well H3 seems to exhibit long-term changes of the level to somewhat extent related to the swarms, while P1A, after tedious processing of tidal and barometric corrections, showed striking high-frequency residual variations shortly before the first strong earthquake of the Autumn 2000 swarm (Figs. 6 and 7, respectively, in PAPER 2).

Nevertheless, as discussed in PAPER 1, the amplitudes of the observed groundwater variations cannot produce gravity changes greater than 5 μGal, in extreme cases still less than 10 μGal. It means that gravity changes can be partly affected by groundwater variations, but by far not completely, as the maxima of ***dg(t)*** often exceeded 25 μGal.

Conclusion

The source of geodynamic activity cannot be fully explained by the regional NW-SE stress field. On the contrary, the local geodynamic processes and phenomena, here especially seismicity, surface displacements, changes of gravity field and groundwater fluctuations obviously reflect different sources of stress. We have to consider that active fluids emissions and Quaternary volcanism may indicate an active magmatic process beneath the Cheb Basin (Babuška and Plomerová, 2008, Bräuer et al., 2005, Geissler et al., 2007, Kämpf et al., 2007, Fischer and Horálek, 2003, Mrlina et al., 2008). Therefore, we feel the presented results should contribute to the study of this active part of the Bohemian Massif.

5.2. Geodynamic investigation in Egypt – Lake Aswan (PAPER 4)

This chapter deals with further progress made in the geodynamic investigation in the western side of the Lake Aswan in Upper Egypt, in the area of the active Kalabsha and Sayal faults with natural, but also induced seismicity. After the two campaigns the results of which are described in PAPER 4 (Mrlina et al., 2003a), in January-February 2002 we performed one more campaign of repeated gravity measurements in the same network. The periods of all gravity campaigns were as follows:

Campaign 1 – November 1997
Campaign 2 – November 2000
Campaign 3 – January-February 2002.

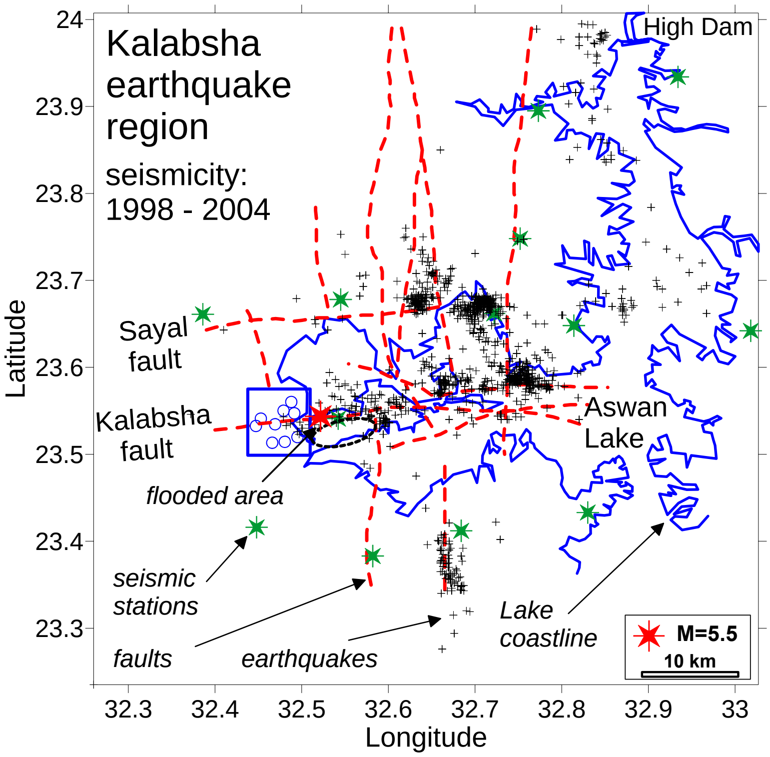


Fig. 5.4. Scheme of northern part of the Aswan Lake region, location of seismological stations (green stars) and observed earthquakes (black crosses). Lake coastline (blue) changes significantly due to seasonal and long-term water level fluctuations. The area under study is marked by a blue rectangle with gravity stations (blue circles). Known faults (red dashed lines) are oriented mainly E-W and N-S, the E-W Kalabsha fault transects the area under study.

The location of the study area is shown in Fig. 5.4., together with earthquakes distribution. The main earthquake in 1981 (M=5.5) occurred just at the eastern edge of this area.

I upgraded Table 1 from Paper 4, see Table 5.1. below, so that the accuracy of the three campaigns, as well as the level of confidence of gravity changes for the two differential periods 1997-2000, and 2000-2002 respectively, could be evaluated. It turned out that this level is about 7 μGal. This can be considered a good accuracy with respect to difficult desert conditions with high temperature and strong winds. Other technical details on data acquisition and processing are provided in PAPER 4. All data were processed using the inhouse DRIFT software (Mrlina, 2008). I wish to stress that the impact of vertical surface movements is negligible, as the GPS and levelling measurements revealed displacements of millimetric scale (10 mm equals approx. 2 μGal only).

Table 5.1. Total range of the Kalabsha gravity network, accuracy (*m*) of observations in particular campaigns 1997, 2000, 2002, and estimated uncertainty *m(dG)* of temporal changes of gravity between consequent campaigns, e.g. 7.7 μGal for the 1997-2000 difference. An overview of observed gravity stations (x) is given in the upper part of the table. Station 113 was destroyed after 1997 so it was replaced with Station 114.

year/station	KH0	111	113	114	122	152	153	161	181
1997	x	x	x	o	x	x	x	x	x
2000	x	x	o	x	x	x	x	x	x
2002	x	x	o	x	x	x	x	x	x

gravity network	***range***	***m 97 / 00 / 02***	***m (dG) 97/00***	***m (dG) 00/02***
	mGal	μGal	μGal	μGal
Kalabsha	11,20	4,8 / 6,0 / 5,1	7,70	7,00

The original idea that the gravity monitoring would reveal mainly the stress changes in the upper crust, as indicated in PAPER 4, has been recently revised. From the surface water level in the Lake (Fig. 5.5, and Fig. 2 in PAPER 4) we assume that the local gravity field may strongly depend on the water level seasonal variations, as well as on the long-term ones.

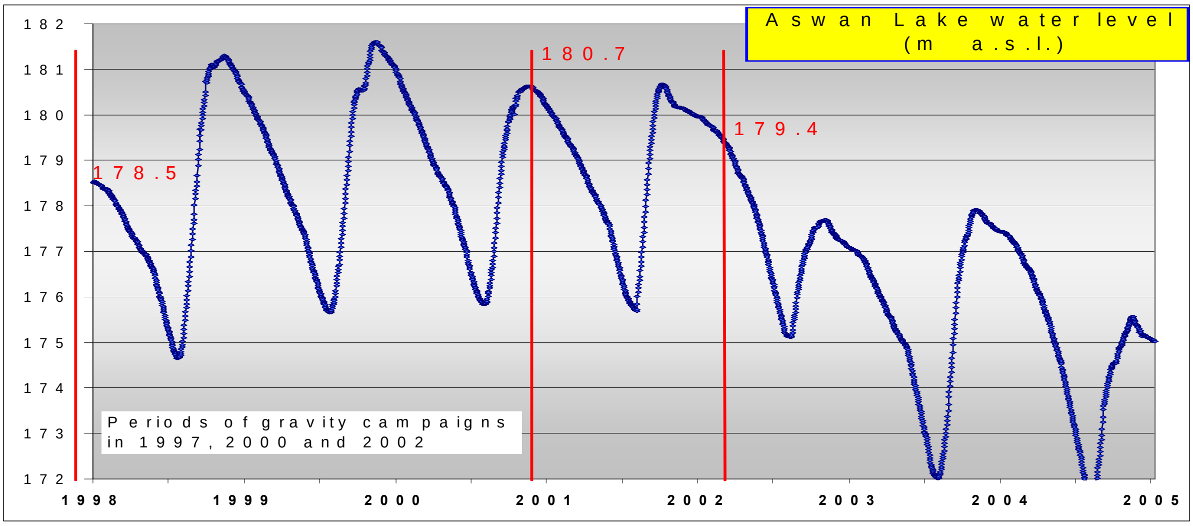


Fig. 5.5. Detailed Lake Aswan water level during the 3 gravity campaigns – differences up to 2.20 m between 1997 - 2000. The long-term maximum was reached in 1998-1999 (see also Fig. 2 in PAPER 4).

In Figure 5.6. the temporal gravity changes in the Kalabsha area are presented in the form of differential contour maps for 1997-2000, 2000-2002, and the total change of more than four years for the period 1997-2002. The first period 1997-2000 is characterized by pronounced gravity change increasing from W to E. This is particularly evident in the southern block (S of Kalabsha fault), where the highest value was observed at Station 153 (the closest one to the coastline of the Lake). The western station KHL0 and the central 111 display minima of gravity changes. The difference from KHL0 to 153 exceeds 40 μGal. The anomalous value at 153 was attributed to the water loading effect of the increased level of the Lake Aswan already by Mrlina et al. (PAPER 4). The difference in surface water level in the Lake from 1997 to 2000 was +2.2 m (Fig. 5.5.) with enlarged aerial extent ("flood") progressing to as close as about 200-250 m from Station 153, see Fig. 5.6. (bottom right). The effect of a 2-m thick water layer was estimated to less than 5 µGal. Recently I have proven that for the distance of 200 m, and vertical difference (12 m) between the Lake water layer and Station 153, the effect is less than 2 µGal. This means that the increased water level in these conditions does not produce practically any gravity effect at Station 153. Anyway, this layer was considered in the modelling stage in order to estimate its impact on possible new stations that may be established closer to the Lake in the future.

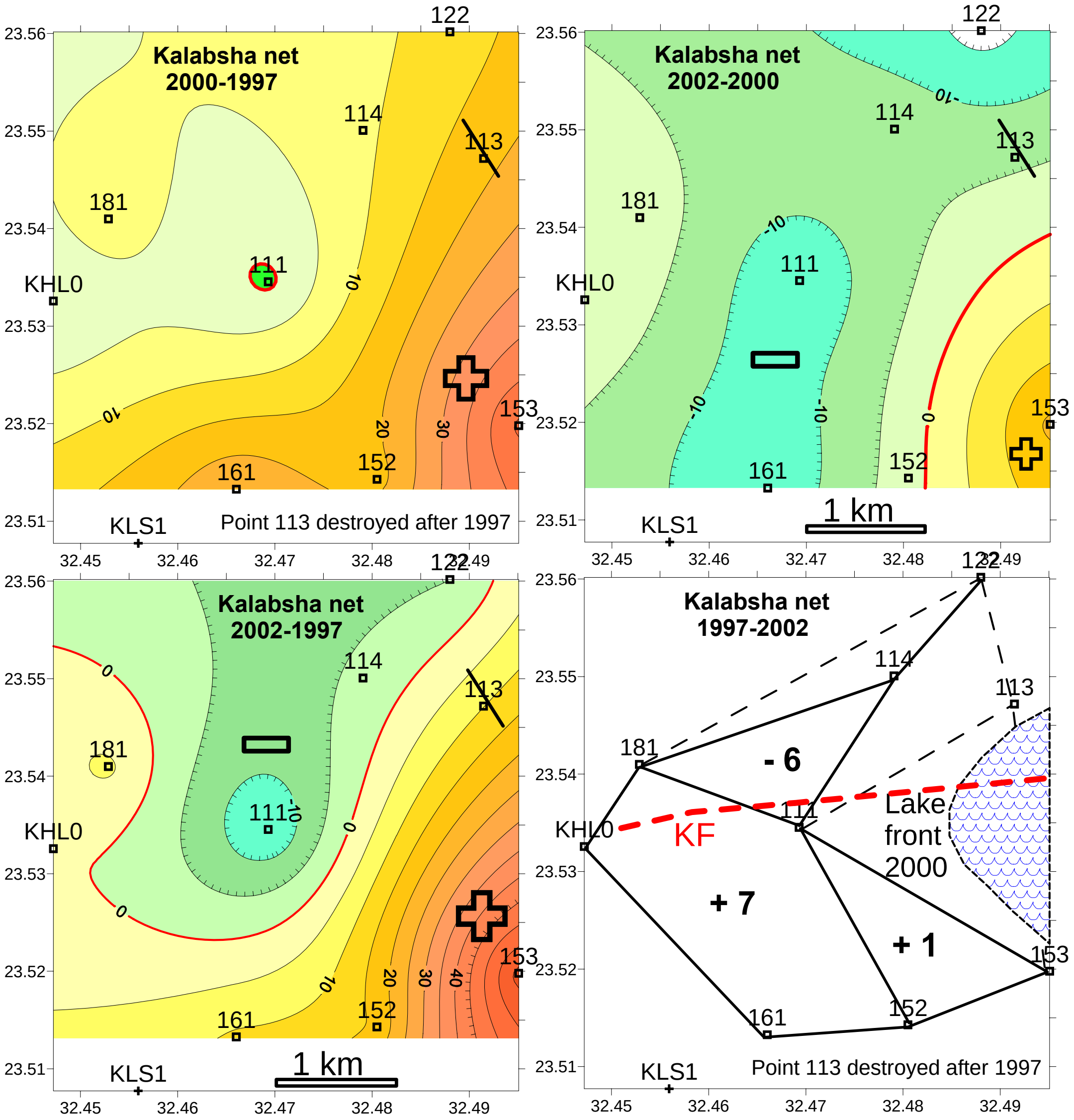


Fig. 5.6. Significant temporal gravity change (top left) was observed between 1997 and 2000 at station 153 (SE corner), the closest to the Lake - probably consequence of up to 2 metres increase of water level (water loading effect, groundwater saturation and table rise). Certain continuation of gravity change at station 153 was observed even in 2002 (top right) - indication of further infiltration or increased pressure (?), while the rest of the Kalabsha area exhibits minor decrease of gravity (drawback of groundwater). This can be caused by different infiltration conditions south of the Kalabsha fault. The total gravity change1997 – 2002 is presented at bottom left. Gravity change contour interval 5 µGal. Approximate extent of the Lake is given in bottom right for 2000. Here also the gravity network closures are presented for campaign 2000. KF – Kalabsha fault.

Mrlina et al. (PAPER 4) studied only the first period of 1997-2000. They considered the loading effect, comprising the stress change (compression) in the rock massif, which may produce a density difference and consequently a change of the observed gravity. After the last campaign in 2002 I found that during 2000-2002 most of the area exhibited negative gravity change of low amplitudes (less than 15 µGal), caused by groundwater decay backwards to the Lake, with the exception of Station 153. The area around this station seemed to experience the ongoing increase of the gravity signal with positive amplitude of +15 µGal.

If we calculate the total gravity change 1997-2002, most of the area shows low gravity change of ±15 µGal. Central and northern parts exhibit rather low negative change. The striking anomaly of temporal gravity change is related to Station 153, as the total amplitude reaches over 60 µGal for the whole period of the study.

Note: It is necessary to stress that the observed gravity changes cannot be explained by height changes, as the available data indicate vertical movements of only a few millimetres, as described above.

In order to explain such gravity signals, 2.5D gravity modelling was performed along a profile running parallel to Stations 161-152-153 and further to the Lake coastline. Two versions of such a model are demonstrated in Fig. 5.7. No very accurate result can be obtained with respect to only three gravity stations existing along the profile. However, the two models represent two different explanations of gravity signals. Both of them comprise the flat layer of the increased Lake level (thickness 2 m).

- Model A – Infiltration zone: This model implies the water infiltration into a dry zone in the forehead of the Lake, considering that in the "low" season (spring) there is no water on the surface in this area (x=4000-5000 in Fig. 5.7.). As well, there was no water in the previous years before 1998, see Fig. 2 in Paper 4, while in 2000 (in the model) the level was about 180 m (MSL). It means that the floods in 1998-1999 delivered water that could saturate the Nubian sandstone formation. The shape of this infiltration edge is, of course, speculative, but fits well the observed data.

- Model B – Increase of groundwater level: This model just simply assumes the general increase of groundwater level due to the surface Lake water maxima in the studied periods. The shape of the groundwater anomalous layer would probably decline smoothly westwards (here simplified by a rectangle).

The depth of groundwater is estimated from distant sources (wells). It is less important than the relative change of its level.

In Fig. 5.7. it is clear that both models can provide reasonable amplitude of gravity change to fit observed data at Station 153. If we assume that there are more stations located between 153 and the Lake coastline, we could observe much stronger signals. Few stations were calculated on the Lake surface, as if measured "by ship". In this area, the 2-m thick water layer plays a very significant role, as expected. As for Station 152, Model B with increased groundwater is more suitable. Until we can constrain these models by independent sources of information, they are both speculative. It is most likely that a combination of both models would bring us closer to reality.

Groundwater rise can be initiated not only by downward saturation of surface water, but also by the water loading effect, when vertical stress (compression) may lead to the decrease of pore space in the rock massif, and consequently to such a rise of groundwater level.

The density differences were estimated from my set of Nubia sandstone samples measured in a laboratory. Considering the average evaluated porosity of 20 %, the density difference of dry and water-saturated sandstone is 0.20 g/cm^3 which is very significant value.

The Nubian formation is also a pronounced hydrocarbon reservoir in Egypt, including the Gulf of Suez and Red Sea fields.

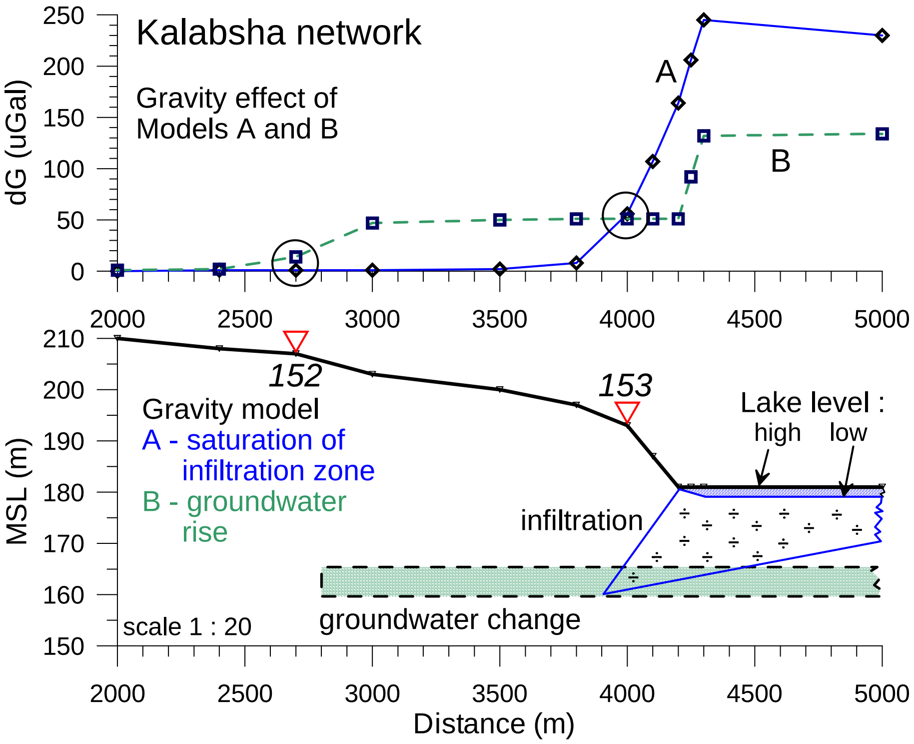


Fig. 5.7. Profile along stations 161 (not in figure) – 152 - 153 down to the Lake water level at the end of 2000 (WSW-ENE). Two models were calculated. Beside 2 m of increased surface water level with 1.00 g/cm3 density of water, Model A suggests infiltration into porous Nubia sandstone. Model B represents simplified rise of groundwater level, the depth of which is only estimated from distant sources.

There may be an evoking question – why we observed more significant gravity change S of the fault zone, rather than in the fault zone itself (Stations 111 and KHL0)? It can be explained by more permanent saturation of the fault zone due to its lower altitude position and strongly fractured character. In that case there is no reason for striking gravity changes. On the contrary, inside the southern block the long-term increase of the Lake water level (1988 – 1999) could cause significant infiltration and groundwater level rise inside the porous Nubia sandstone formation. The water loading effect can also contribute to the gravity changes with regard to reducing pore space and pushing groundwater upwards.

In **conclusion**, we can consider surface and ground water of the Aswan Lake to be a source of gravity changes. Significant seasonal and long-term variations of the Lake water level can trigger not only earthquakes, but also pore pressure changes, rock massif saturation and groundwater level fluctuation. All these phenomena may directly or indirectly produce observable gravity signals, as at the 153 site. This study indicates that the movement of fluids in such rocks can be detected by 4D gravity (time-lapse gravity). In the case of a more detailed observation network, the model of groundwater movements can be improved. We plan such changes of the network in our further investigation in order to better understand groundwater movement and related processes.

5.3. Gravity monitoring of geomechanical processes in geoengineering (PAPER 5)

As presented in PAPER 5, there are multiple possible sources of temporal gravity changes that can be caused by ongoing geomechanical processes. Near subsurface (units and tens of metres) is often composed of strongly weathered rocks, covered by young unconsolidated sediments. Such formations are vulnerable to any natural or man-made load, such as groundwater penetration, presence of voids, mining, drilling, digging, or just whatever else, including increased load from traffic.

Water is definitely one of the most significant problems in engineering geology; in some cases it represents even a high risk factor. As it is not simple to determine hydrogeological systems in engineering areas, indirect techniques have to be tested and applied to characterize groundwater level depth and oscillations, water flow as a consequence of engineering works, or even salt water penetration into fresh water aquifers. As an example, Yaramanci (2000) presented a test of geoelectrical measurements applied to the study of decompressed and water-saturated zones in a salt mine, aimed to serve as a nuclear waste deposit. They also performed monitoring of water content changes in the salt rock massif. However, common geoelectric measurements may not often be suitable due to high industrial noise, including 50 – 60 Hz frequencies, and the presence of metallic materials. Moreover, geoelectrical methods for groundwater investigations are based on cable spreads that may be inapplicable in many cases.

Here the advantage of a discrete-point character of gravity measurements can be taken. This technique does not depend on cables and requires just singular stable sites that can be distributed in an irregular grid, if profiles layout is impossible. On the other hand, complicated terrain conditions on steep slopes, engineering excavations, road or railroad bodies, etc., may require a detailed determination of terrain effects on measured gravity. For such situations it is necessary to develop a local terrain model from all available data, including additional geodetic measurements. This is not a problem for 4D gravity, as usually there are no such immediate changes of the surface; however, if this is the case, it is necessary to upgrade the terrain model and recalculate the terrain corrections.

I performed high number of microgravity measurements targeted at geoengineering problems, especially related to void detection and sinkhole propagation (Mrlina, 1999), as well as related to groundwater. Some of these projects were, in fact, 4D microgravity ones. As presented in PAPER 5, the main objectives to deal with can be the following:

- Groundwater variations
- Underground void propagation to surface
- Landslides evolution
- Stress changes in mines

I will add some details and examples on the first two subjects.

Gravity monitoring of an open-pit mine waste dump

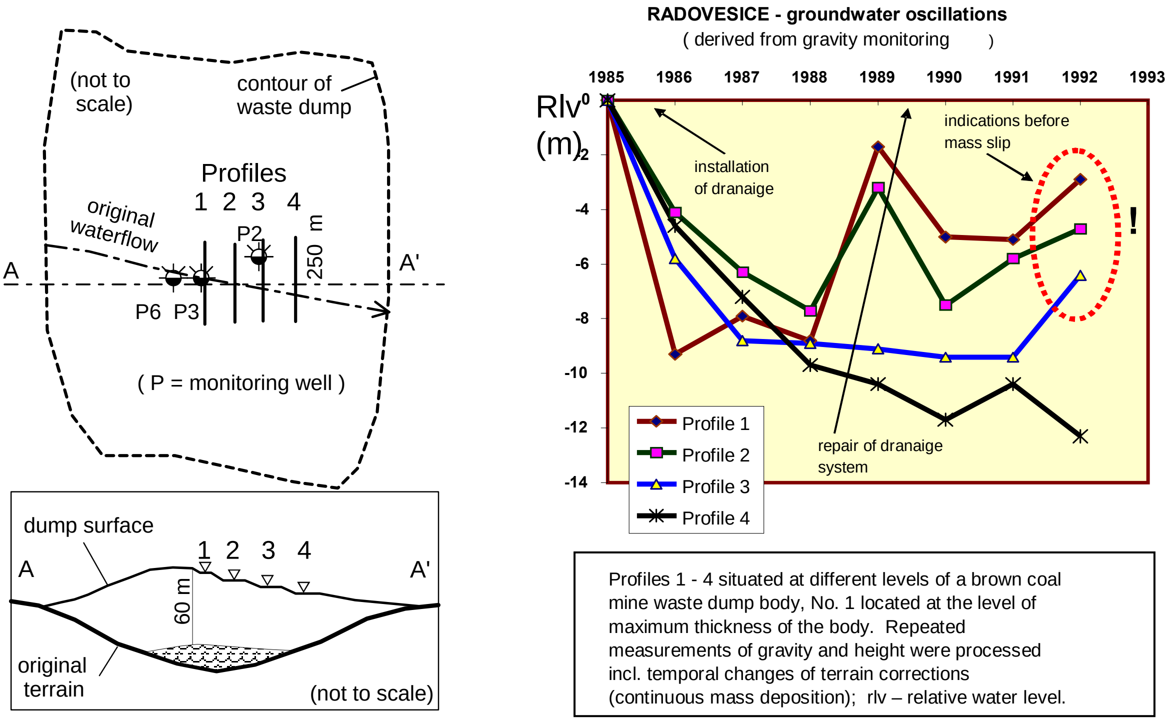
We performed repeated microgravity measurements in the sensitive environment of a coal mine waste dump Radovesice, NW Bohemia, for groundwater monitoring. In this case, simultaneous control of elevation was essential, and therefore we focused on time change of Complete Bouguer Gravity Anomalies (CBA), including changes in terrain corrections, whilst applying real near-subsurface rock density.

The waste dump of an open pit coal mine serves as a deposit site for all the overburden rock material that is scraped out in order to open the coal seam. Depending on the size of the mine, such dump may become a huge body that requires enormous effort to be made on the strategy for its further development, but especially for related environmental and potential risk aspects. Often the deposited material consists of various clay and sand mixtures with an extremely low level of compaction and strength. Such an artificial “mountain” has to be controlled for its stability.

In our selected location in NW Bohemia, the dump body height reached over 100 m in maximum, while 50 – 70 m was an average thickness of the whole body. The material was mainly Miocene claystone (75%) and sandstone (25%). At the beginning of engineering operations and material deposition, an underground gallery was excavated in order to establish a drainage system to collect groundwater from the dump body located in a valley, originally with a small brook.

We introduced the gravity monitoring technique into the existing monitoring system (geodesy, boreholes). Four parallel profiles were established on four steps (levels) of the dump body, each at different elevation (see Fig. 5.8.). The length was about 250 m with 5 m interval between stations, which makes a total of 200 observation stations. The principal target of the project was to test the possibility of groundwater control inside the body of the waste dump (Dobeš, 1987, Mrlina and Dobeš, 1990).

Annual campaigns of 4D gravity were performed since 1985 till 1992 using a good resolution Scintrex CG-2 No. 173 gravimeter, well calibrated on the relevant section of a calibration line. At the time, there was no better gravimeter in the country. The accuracy of 10 – 15 µGal was achieved thanks to double or triple observation rounds for all the stations. Technical levelling provided elevation data accuracy better than 1 cm. Both gravity and levelling measurements were tied to two reference stations outside the dump body.



Profiles 1 - 4 situated at different levels of a brown coal mine waste dump body, No. 1 located at the level of maximum thickness of the body. Repeated measurements of gravity and height were processed incl. temporal changes of terrain corrections (continuous mass deposition); rlv – relative water level.

Fig. 5.8. Groundwater monitoring on a waste dump of an open-pit coal mine.
Left – position of 4 gravity profiles and monitoring boreholes (up), and a schematic cross-section through the dump (bottom).
Right – graphs of groundwater level fluctuations derived from repeated gravity surveys and the correlation of gravity data with monitoring boreholes data (upgraded Fig. 3 from PAPER 5). Red ellipse indicates the forthcoming dump failure.

The density difference between dry and saturated material was determined by two independent procedures. Laboratory measurements of rock samples and the indirect determination from gravity observations on a steep slope of the dump (Dobeš, 1987) brought very similar result: 1.67 g/cm^3 for the dry rock and 1.99 – 2.02 g/cm^3 for the saturated one. The difference of 0.32 g/cm^3 was used for further interpretations. Based on the analysis of density data, observed gravity changes and monitoring records from wells, we concluded that 1 m change of water level inside the dump body is reflected by 12 μGal of temporal gravity change. This may be a specific value for the studied case, as in other sites the hydrological system and saturated zone may be of different parameters (PAPER 1). It means that the gravity accuracy of 10 – 15 μGal corresponds approximately to the accuracy of ±1 m of the groundwater level.

In this case, temporal gravity changes were calculated from the difference of CBA with respect to existing variations of the dump surface. Elevation changes on the profiles were caused mainly by material displacement and re-deposition due to fast erosion. As well, regarding the progress of deposition of the new stripped overburden material from the mine, terrain corrections had to be recalculated. A density of 1.70 g/cm^3 was used for both corrections. While the elevation-related corrections were very small or negligible, the terrain correction annual difference exceeded even 50 μGal in some cases. Therefore our own 2.5 x 2.5 m elevation model of the nearest zones (0 – 70 m) had been permanently upgraded. The evaluated gravity changes were calibrated at the sites of two monitoring wells (P2 and P3 in Fig 5.8) in order to relate gravity changes to water level variation. The results were expressed directly as graphs of groundwater level change for each profile, as presented in Figure 5.8.

The following stages of groundwater level variations were identified from the 4D gravity data:

- Starting point in 1985 after full employment of the drainage system – decrease of groundwater level in 1986.
- Normal conditions until 1988.
- Sharp rise of groundwater at the central part of the body (profiles 1 and 2) in 1989 indicated partial collapse of the drainage system – it was proved by technical inspection and followed by reconstruction of the system.
- Decrease of groundwater to normal level in 1990-1991.
- Indication of groundwater level rise on 3 profiles in 1992 was a precursor of the dump body anomalous saturation, and a failure a few months later. Highly saturated layers of soft unconsolidated dump material, mainly clay, caused an extensive slip of the body downhill through the valley (PAPER 5).

The presented case history from a waste dump is, in geological terms, very similar to the case of a landslide. The engineering principle is the loss of resistance to gravity (weight) stress of the overburden masses on topographic slopes when the rock (clay, shale, marl, etc.) is oversaturated by groundwater. Gravity monitoring in such conditions was reported e.g. by Ullrich and Brueckl (2004) from a steep slope in the Alps in Austria, where gravitational creep was in progress. The time-lapse gravity signals up to 40 μGal were observed within 9 monitoring campaigns in 2000-2003. Bláha et al. (1998) presented a number of examples of gravimetric investigations of landslides, most of them being connected to groundwater problems. In our case, despite using an older type of gravimeter, the groundwater level change of two and more meters was observable, as explained above. The quantitative relation of approx. 25 μGal / 2 m was derived from gravity and borehole data.

In **conclusion** I wish to highlight that repeated precise gravity measurements can indicate groundwater level or water saturation changes with time in near subsurface. Such processes may lead to increased risk of instability of geological formations in anomalous stress conditions, especially on slopes. Last, but not least, active surface or karstic hydrological systems, as well as water flow in and above mines, may cause soft rock removal and give origin to subsidence and surface collapse (Whittaker and Reddish, 1989). The progress of rock disintegration in such cases can be subject to 4D gravity as well.

Gravity monitoring of water-gas contact

Very different application of water monitoring is represented by the monitoring of water-gas contact movement during gas exploitation. I gave the first simple demonstration of such process in PAPER 5. As mentioned in Chapter 3.2., I performed some more modelling on this subject (Mrlina, 2007a,b), and Fig 5.9. presents another such case. In Fig. 5 of PAPER 5 the depth of the reservoir layer was 2500 m (thickness 20 m, porosity 10 %) and the differential gravity signal ***dg(t)*** from such water movement was only 8 µGal in maximum. In the latter case the depth of 500 m was selected, and porosity increased to 15 % which resulted in 23 µGal amplitude. I can conclude that the applicability of 4D gravity is in this case limited to exceptional favourable conditions.
In fact, the investigation in Aswan (Chapter 5.2.) is a good example of such conditions where the target geophysical change (water filling pore space) occurs in relatively shallow depth.

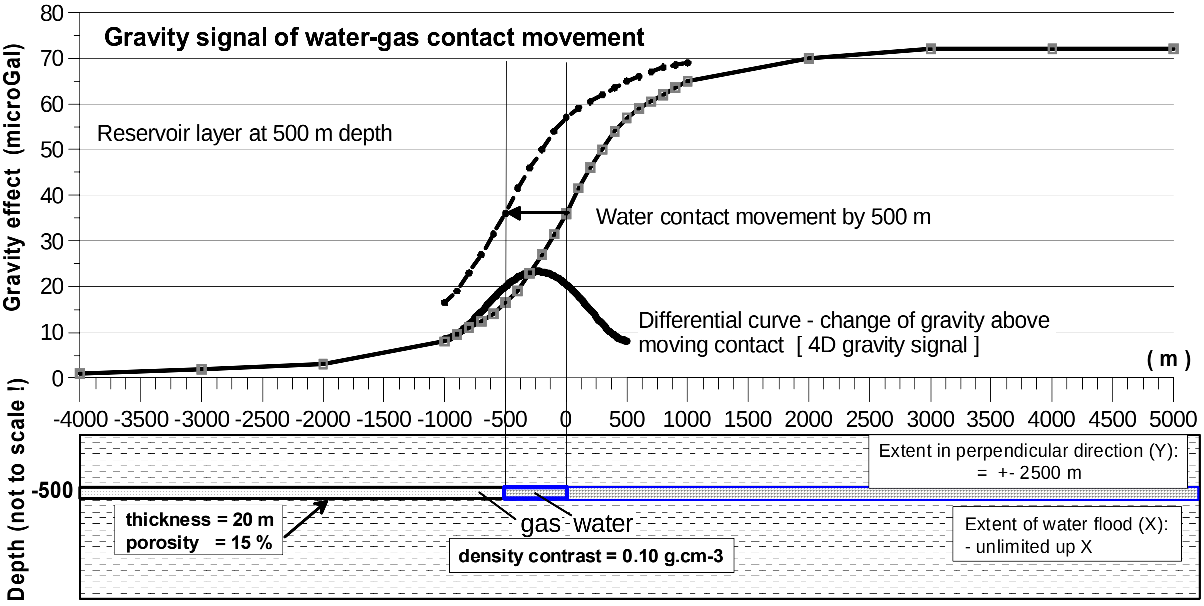


Fig. 5.9. Modelling of gravity change related to water infiltration process in a semi-horizontal porous formation. The two dotted curves show the gravity effect of the water-gas (water-air) at original position and at shifted position (water movement from right to left). Smooth thick line represents the temporal gravity change related to water front progress (Mrlina, 2007a).

Gravity monitoring of potential surface failure related to voids

As mentioned above, water (both surface and groundwater) causes rock disintegration. This can be also the case of such process above an underground void (natural cavities, or man-made spaces). Beside water, also stress changes and rock strength decline give origin to so called “arch effect”. This process disintegrates the rock depending on its lithology, fracturing and weathering. As result, this rock mass is falling to the bottom of the void. Again,

depending on local conditions, such disintegration process can result, beside surface subsidence, either just in filling the void by this material, or in the surface collapse at the final stage of development (Whittaker and Reddish, 1989).
I experienced such case in the Příbram Uranium mining district. Figure 1 in PAPER 5 shows two stages of a survey:

1) Usual microgravity survey revealed number of negative anomalies that we considered as indications of voids (Mrlina and Dobeš, 1990) - the line with triangles.
2) Repeated gravity survey showed temporal gravity changes (red column graph) that well correlated with indications of voids. The central anomaly over 50 μGal exhibited almost 20 μGal of gravity change after about 15 months. We considered this to be the effect of ongoing rock disintegration in relatively shallow roof of the void. In Fig. 1 of PAPER 5 there is a schematic idea of the first 2 stages of the "void/disintegration/collapse" process.

In this case the repeated survey was performed as an investigation test. On the contrary, another survey aimed at void identification I performed at the Zelný trh square, Brno, Czech Republic. This survey revealed indications of voids that were probably related to the historical galleries and cellars in the city centre. Almost 2 years later, a surface collapse occurred at one of the given locations. I repeated the survey and the data showed interesting indications of mass displacements (subsurface consists of unconsolidated sands and clays). The original gallery (negative anomaly in 1996) was probably filled by product of rock disintegration process that resulted in the collapse. As there was no void any more, the gravity changed in 1998 into relatively positive anomaly right above the collapse. However, at the sides of the collapse gravity changed into negative, which could be explained by some more mass moved into the void from sides, leaving new caverns behind. Similar mass displacement could happen at the right section of the profile presented in Fig. 5.10. Eventually, the filled historical gallery was restored as shown in the same figure – photo at bottom-right.
This case history demonstrates the profit of using 4D gravity, as the new mass redistribution had to be determined with respect to high risk for inhabitants and traffic.

I wish to present one more example of similar use of 4D gravity. I participated in an experimental 4D microgravity survey on the TGV railroad in France where an unknown void (military cellar from WWI) caused a significant trouble to the TGV express train rail body. The first target was to locate such voids. At certain stage, one of the anomalous sites was selected for treatment by filling through a borehole. Then, the repeated gravity survey was expected to show no any anomaly at the site. However, certain negative anomaly was still observed, see Fig. 5.11. This was explained by not complete filling of the cellar due to possible leakage into another void, and/or by lower density of the filling due to weak compaction of the material inside the cellar.

What is important to highlight is that in case of disintegration of the void roof we may rather observe the gravity effect of the disintegrated overburden than the void itself, as it may be too deep to be directly detected. The positive impact of such a case is a good chance of locating the area with high probability of a void existence. The negative impact is that we cannot distinguish what is the ratio between the gravity effect of the void itself and the effect of the disintegrated overburden. Therefore, it is difficult to estimate the depth of the void which is, on the other hand, often the main question of engineering geologists.

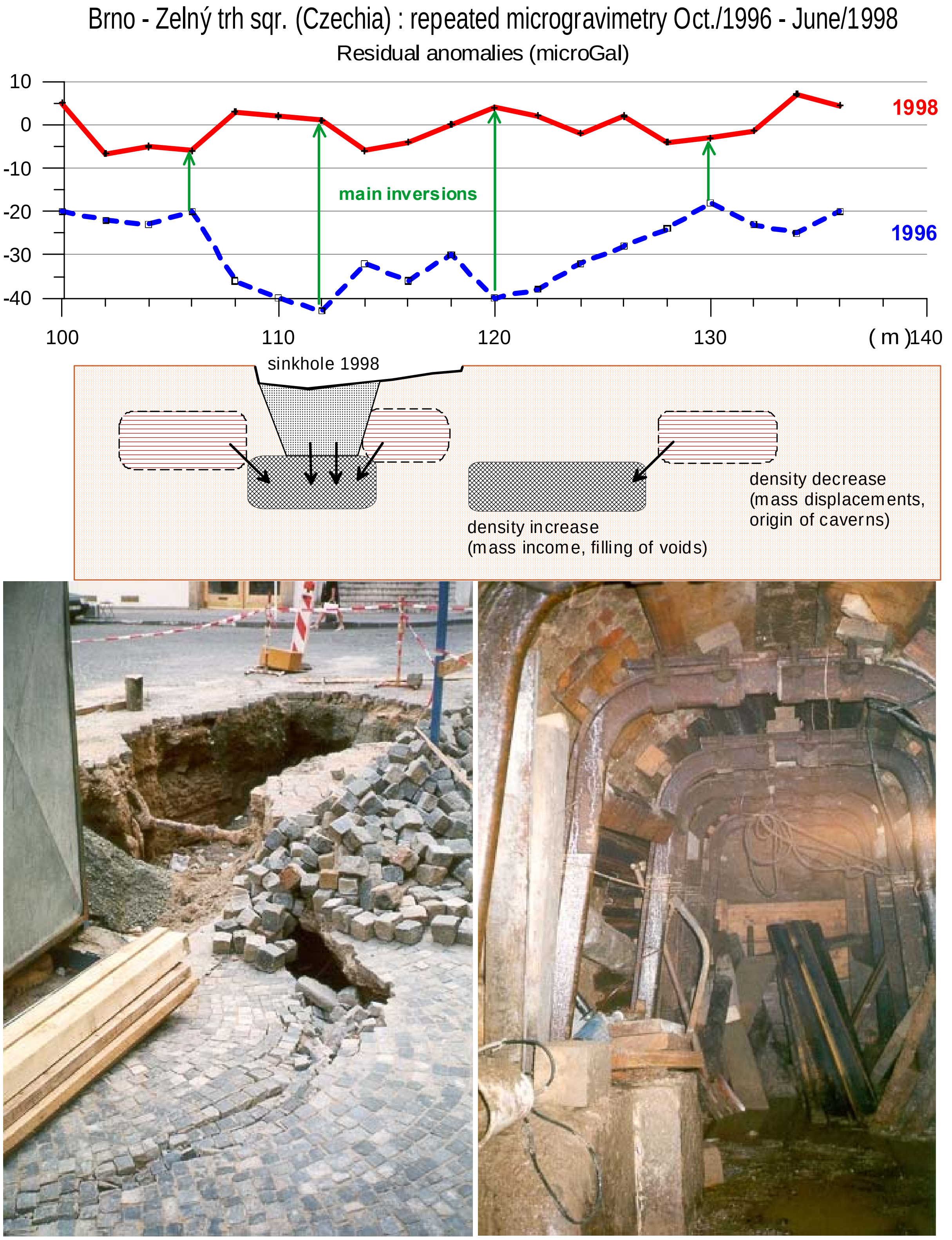


Fig. 5.10. Surface collapse occurred at the location of a gravity low of 1996. Repeated survey shows gravity inversion that was related to mass displacements, as suggested in the cross-section. The blue and red curves were intentionally offset. (Photo *J.Mrlina*)

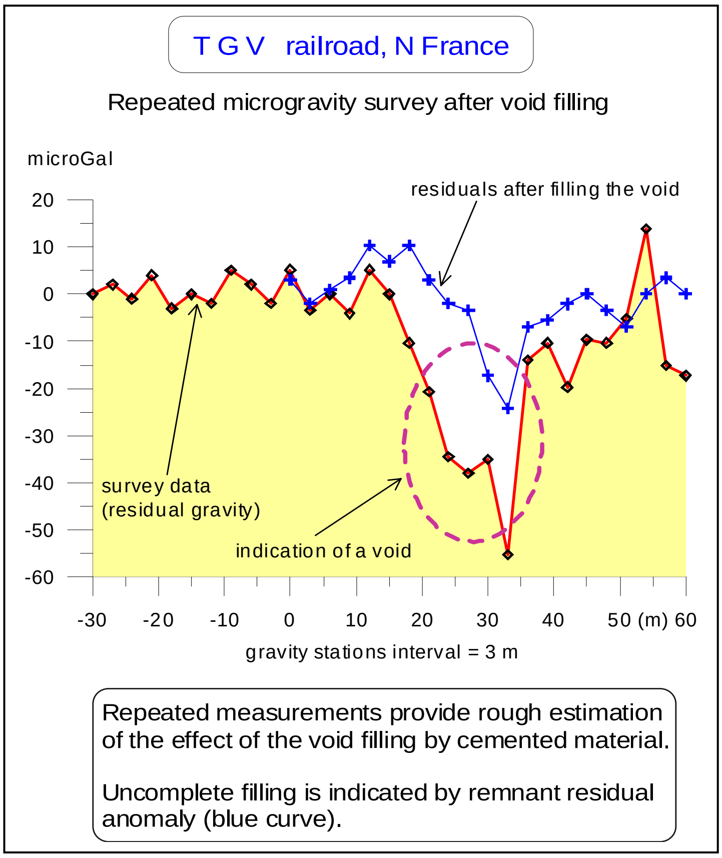


Fig. 5.11. Microgravity survey and repeated measurements. The red curve shows residual gravity anomalies indicating a significant void between points 20 to 40 m. The blue residual curve represents gravity change after the disclosed underground void was filled by material.
It shows that the filling process was not completed.

I conclude that the presented case histories proved 4D microgravity to be an efficient tool for mass changes monitoring in the near subsurface. The range of applications is wide and depends on how significant density change was developed by geomechanical processes. The control of groundwater is essential throughout the observation periods as it may affect the target gravity signals. In some cases, groundwater itself becomes the target of investigation.

6. Discussion

The Thesis was targeted on the whole cycle of gravity changes determination and evaluation, starting with some theory, instruments, corrections, disturbing effects and ending up with observed phenomena in various geological conditions (as indicated in Chapter 2.).

It is clear that high precision gravity measurement is an essential condition for 4D gravity. Therefore, great attention was paid to the gravimeter itself. The participation in the 'world comparison and calibration campaigns' in Sevres (Vitushkin et al., 2002), mentioned in Chapter 4.1., revealed some differences among gravimeters, even some of them were excluded from final data processing. This demonstrates crucial significance of the instrument's correct and exact performance. In fact, we have to include the gravity operator as well, as substantial experience is a must for performing 4D gravity.

I concluded that most of the disturbing effects from the instrument itself (drift, etc.) and from the environment (air-pressure, etc.) can be eliminated and corrected. However, groundwater is often not considered which may result in significant impact on the data analysis. Moreover, groundwater belongs not only to disturbing phenomena, it can also be a target of gravity monitoring.

The main target of the Thesis was to demonstrate really observed gravity changes. The first case history was focused on West Bohemia. I showed that the observed temporal non-tidal gravity changes exceeded significantly the level of confidence of the data (e.g. during the Autumn 2000 earthquake swarm). The amplitudes reached even over 50 µGal, almost 8 times higher than 95% confidence value of 7 µGal. Such level was deduced from the average of 5 µGal accuracy of any observation campaigns. This was compared with similar investigations worldwide, e.g. Ferguson et al. (2007). The important point to be highlighted is the fact that the sense of the changes corresponds with what resulted from totally independent studies – GPS displacements and fault planes solutions of earthquakes. The example given in Fig. 5.1., Chapter 5.1., reflects the correlation of the compression derived from gravity changes on the eastern side of the Nový Kostel focal zone, with the northward displacement vector of GPS (PAPER 3) and left lateral sense of motion on the fault plane from the earthquakes analysis (Fischer and Horálek, 2003). Further study will be oriented to more exact stress field modelling from all these data.

I wish to point out that in West Bohemia the regional tectonic stress may be combined with stress effect of fluids related to active magmatism, as proposed by Bräuer et al. (2007), as well as by Mrlina et al. (submitted 2008) who delineated an unknown volcanic structure that is considered to be the first known Quaternary explosive maar within the Bohemia Massif. It is located about 25 km southwards of the main epicentral zone of Nový Kostel.

Similar gravity signals related to the stress field (earthquakes) I observed in the Gulf of Corinth in 2001 (Mrlina, 2002, 2004). I combined my former measurements in 1997-2001 with those I performed within the frame of the EC Project "Corinth Rift Laboratory" in 2002-2005. To the SE of Aigion on the southern coast of the Gulf of Corinth, the gravity signal changed during the 2001 earthquake swarm of low energy (up to M=3.2). The preceding negative gravity changes (1997 – 2000) on the southern coast (relative to the north coast) developed into an indication of local compression in the swarm area (positive gravity change 2000 – 2001), see Fig. 6.1. Such stress development was modelled e.g. by Mitsakaki et al. (2007) for the Aigion 1995 earthquake.

Still, we have to consider that these two examples do not prove that the technique will be successful at any site. It depends on local conditions - especially how the stress field affects the bulk density on the rock massif, as well as what is the stress impact on groundwater movement and pore pressure.

The second case history from Aswan can be considered as a transition case. The site is a tectonically active area with relatively high seismicity, but at the same time water in the Lake and groundwater play very significant role. This was also a case where two gravimeters provided very different accuracy ranging from 4 – 6, and 12 - 16 µGal, respectively. Recently I revised the impact of tectonic stress on observed gravity changes, and the models of two different groundwater movement scenarios were developed as more likely source of gravity changes close to the Aswan Lake.

Based on results from all the three areas I concluded that in any tectonically active region at least four phenomena have to be carefully considered - tectonic stress, magmatism, groundwater and vertical movements.

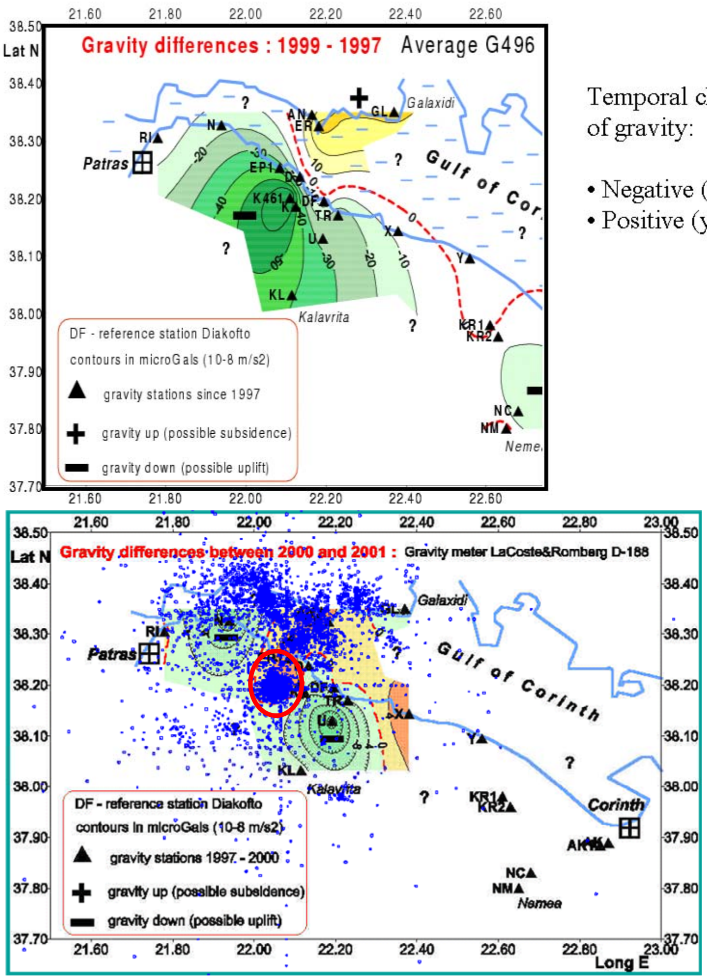


Fig. 6.1. Gravity monitoring in the Gulf of Corinth, Greece. Usual character of significant negative – positive evolution of gravity changes in the 1990s (up) changed in 2001 in the period of a weak earthquake swarm (bottom). Main focal zone (red ellipse) showed relative positive gravity change of about 25 µGal due to compression before the swarm. The brown colour under the blue dots (earthquakes) indicates positive gravity change 2000 – 2001.

Geomechanical and hydrological processes in the subsurface often cause serious problems in geoengineering, even risk for personnel and technology. Among others, surface collapse, landslide hazard, geomechanical stress in deep mines. The examples given in the Thesis show that the gravity changes related to such phenomena are at the same range of amplitudes as in case of the geodynamic ones, in x.10 µGal. On the other hand, the spatial extent of observable gravity changes is very limited, in x.10^0 to x.10^4 m^2, while the tectonic stress may produce gravity changes in the extent of x.10^4 to x.10^6 m^2, in extreme cases even x.10^8 m^2, as shown in Fig. 4.4.

7. Conclusions

In my Thesis I concentrated on the investigation of temporal gravity changes from various aspects – the instrumentation requirements, compensation of disturbing effects, processing procedures, evaluation of data accuracy and examples of application. The presented case histories were focused at very different targets in the geological sense: stress field changes in tectonically active areas, groundwater and other fluids (gas) in various geological settings, and last but not least, geoengineering risk sites. Such wide range of targets was selected intentionally, as all these applications have something in common – high precision gravity data, with similar range of amplitudes at tens of microGal level.

I showed that

- variations of tectonic stress can be indicated by gravity changes of $x.10^1$ μGal even in areas with low magnitude earthquakes, as in West Bohemia.
- groundwater level change can be detected at various depth, even in deep reservoirs, but the resolution drops with increasing depth and decreasing density contrast.
- hazardous geomechanical processes in geoengineering can be monitored if significant change of density develops in the subsurface – this can be rock disintegration above underground voids, tension in landslide bodies, stress change in deep mines and groundwater fluctuations.

I can conclude that it does not matter that much what geological or geomechanical process we want to monitor, but what density contrast is produced by that processes, and what rock volume is involved.

I recommend starting any 4D gravity project with pear feasibility study in order to estimate the amplitudes and spatial extent of the expected gravity changes. Based on such study relevant field and processing procedures have to be applied. In any case, I suggest checking the local groundwater conditions and if necessary, independent monitoring of possible groundwater variations, as it represents one of the principal environmental impacts on observed gravity.

The environmental effects can be, in general, eliminated by various corrections. However, there are more principal limitations of the technique – great depth and small size of the target geological body (or ‘volume’), as well as small density change originated during the period of observations.

The presented principals of 4D gravity, as well as number of case histories prove that 4D gravity is an efficient tool for the monitoring of geodynamic and geomechanical processes in the Earth’s crust. Land gravity data acquired by relative or absolute land gravimeters cannot be currently replaced by any other gravity method - marine, airborne or satellite. The main reason, beside logistics and cost, is the data accuracy. The 4D gravity applications require 1 - 2 μGal resolution of gravimeters with 2 - 7 μGal repeatability. Such accuracy provides necessary level of confidence of evaluated temporal changes of gravity between observation campaigns. As well, often no other geophysical technique can be applied due to low resolution, different principles or site conditions.

I believe the targets of the Thesis were achieved, as

- with the given instrumentation, and observation/processing procedures the necessary accuracy of 4D gravity data can be obtained, at the level of about 7 μGal,
- the impact of various instrumental and environmental effects can be controlled and reduced,
- the causative processes and phenomena affecting temporal gravity changes were discussed, as well as the limitations of the technique,
- the presented case histories prove the existence of temporal gravity changes related to geodynamic, hydrological and geomechanical processes.

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