INDIRECT STRESS MEASUREMENT BY STATIC VERTICAL PENDULUM

Pavel Kalenda[1], Libor Neumann[2], Ivo Wandrol[1,3]

Abstract: Static vertical pendulums or other deformometry apparatus were used for indirect measurement of stress in the upper crust. The first static vertical pendulums were installed in Prokop mine in Příbram and in cave No. 13C in Moravian karsts since 2007. One pendulum was installed in a productive potassium mine in Lubeník (Slovakia) in 2008.

The two years experience of measurement shows that it is possible to find the main direction of stress in the surroundings of the pendulum and its development in time. The noise level and anomalous deformation development shows the value of relative stress in the surroundings of the pendulum. The correlation of deformation between distant stations shows that stress variations are not of local origin, but the stress field has regional character and is similar practically in the whole lithosphere plate.

The great changes in stress orientation and in stress state were observed before the biggest earthquakes on the Eurasian lithosphere plate. Two years of our experience resulted in successful prediction of Kurile earthquake on November 24, 2008 (M=7,3).

1. Description of static vertical pendulum clinometer

Micro-inclination and deformation monitoring using this instrument is based on optical contactless sequential shooting of a pattern placed on a vertical pendulum (Neumann 2005, 2007). After using a close-up lens with optical magnification (20 to 100x) in a high resolution camera (320x240 to 800x600 pixels) and under the condition of reading the sensitivity of 1 pixel, one can measure a relative position pattern – camera with a sensitivity of about 100 – 1000 nm. With a frequency of sequential shooting 0.1 – 1 Hz, one can detect hourly mean positions from 10 to 100 nm. The positions can be always recalculated to inclination of a plumb line. Cables 1 – 3 m long allow to reach an inclination sensitivity of 100 - 1000 nRad for actual positions and 10 – 100 nRad for hourly mean positions. Longer hangers, if used, appropriately allow increasing sensitivity in measurements of both instantaneous and mean values regarding positions and angular increments.

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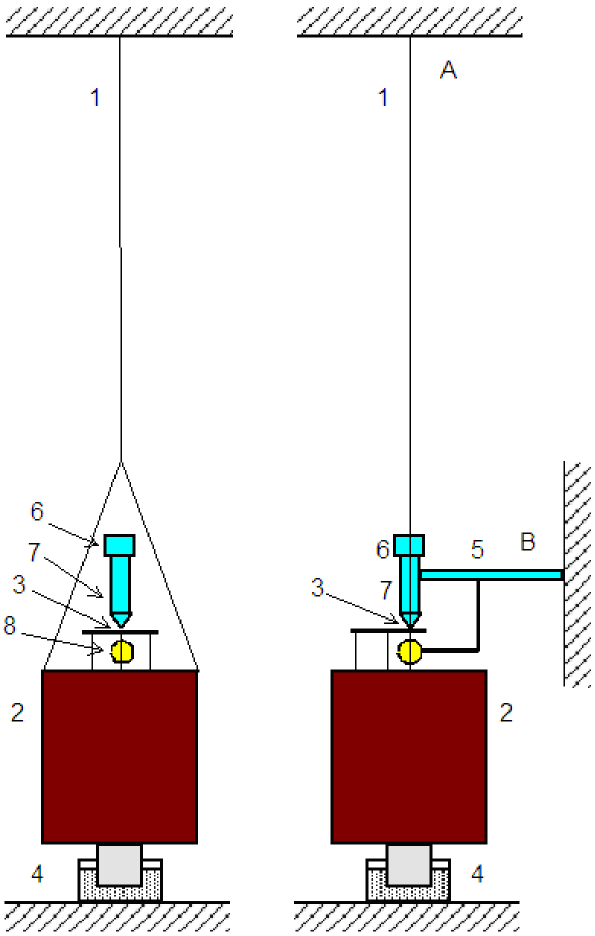
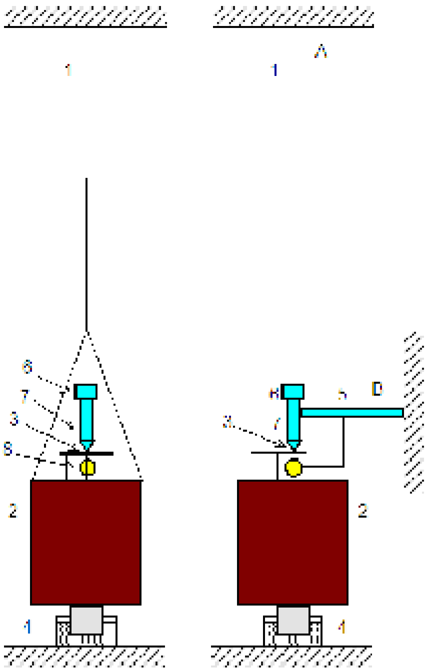


Fig.1 Scheme of static vertical pendulum clinometer



Such a contactless measurement is advantageous as it excludes errors due to friction and one can have any time data to calculate the absolute difference between the actual position and any previous one. In such a way one can find secular deformation trends in endless time periods, long anomalous deformation paths of weeks and months duration, as well as short-time changes in days.

A vertical pendulum is highly sensitive to all kind of interference, which is disadvantageous. It will react to traffic, walking people, wind, drought, changes in humidity and temperature. Therefore it needs an insulated chamber or place without access of visitors. We found optimal places in the old inclined gallery Prokop in Příbram abandoned mines, with chambers and branches, where only highly scientific instrumentation is in operation at present (Skalský 1963, Skalský and Pícha 1965), and only operators are allowed to enter. A suitable environment will be found in cave No.13C in Moravian karsts, which is closed to the public.

2. Results of long-term measurements

All results of measurement obtained from surface and subterranean instalment show identical deformations of objects on the surface and of mass in the depths.

After installation of the pendulum lasts a period then there are relaxed various stresses of the pendulum's cable and the holders of the cable of the pendulum and camera. This deformation development can be described by the equation

$$d = d_o \exp(-k(t-t_o)) \quad , \qquad /1/$$

where d_o is representing decompensated deformation, which was caused by changes of stress in the surrounding of the pendulum's hanger and by change of strain of the pendulum's material (see Fig.2). The constant k is determinated by elastic properties of hanger material and of rock in the surroundings of points A and B. The constant t_o is the time of manipulation with the pendulum when the stress state in the surrounding of suspensions of the camera and cable was changed. Such stress relaxation is clearly visible on Fig. 2 after May 17, 2007, when the pendulum was re-installed. The measurement of deformation is not disturbed by this additional stress relaxation of the pendulum after a couple of weeks or months and measured deformation is fully dependent on changes of external stress in the rock mass between points A and B. The length of measuring a base between points A and B and their geometry in the chamber determines what reaction of massif on the external stress field will be. If the length of the measuring base will be longer than the results of deformation will be less sensitive to the geometry in the surrounding of points A and B.

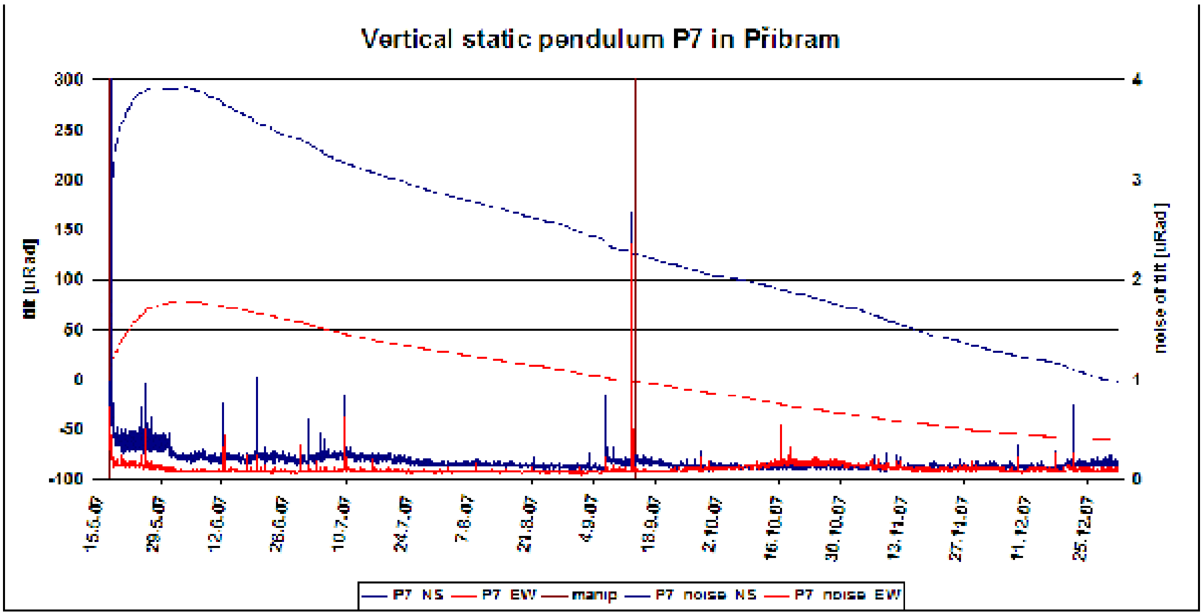


Fig. 2 The tilt and noise of tilt development on station P7 in Příbram (vertical lines mark the time of small manipulation with pendulum, i.e. focalisation of optics)

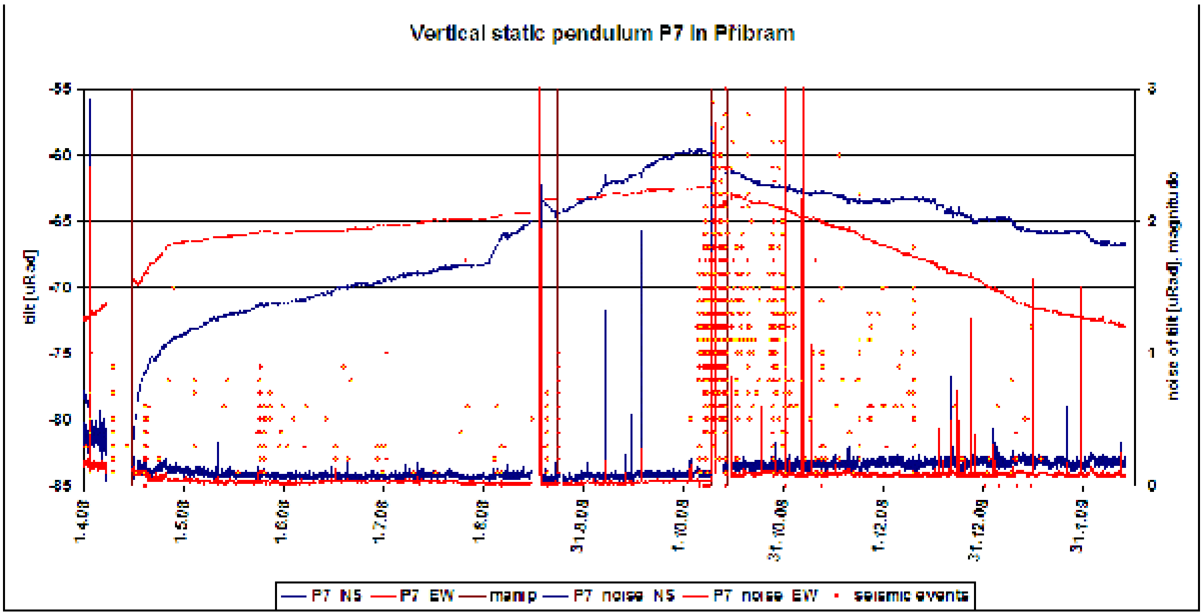


Fig. 3 The tilt and noise of tilt development on station P7 in Příbram and seismicity in Nový Kostel seismic swarm area, registered by Webnet (Horálek, Fischer 2008).

It is possible to define the periods, when the tilt development was changed radically on the mid-term scale. For example, pendulum P7 in Příbram changed its tilt development around August 3 and October 1, 2008 (see Fig. 3). The next big changes of tilt development were observed at the turn of 2008 and 2009.

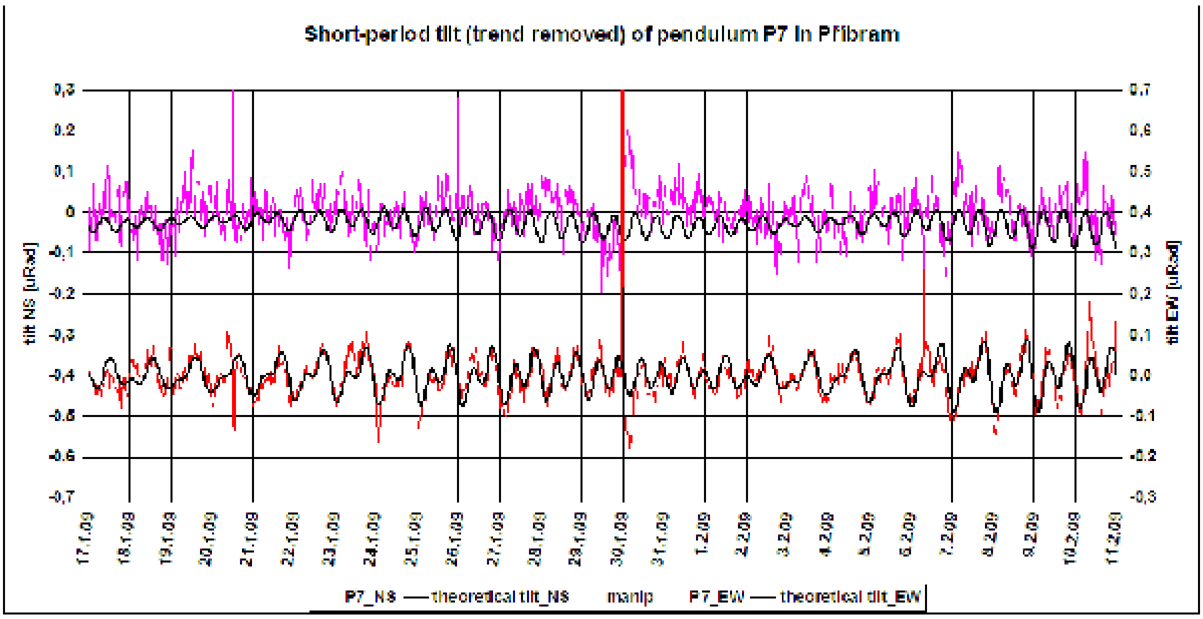


Fig. 4 Short-period tilt (trend removed) of pendulum P7 in Příbram.

On a short-time scale, we can observe semidiurnal variations of tilt, caused by earth tides (see Fig.4). The amplitude of tilt varies in time and it is different on both directions (NS and EW) compared each other or compared with theoretical values of tilt according to the semielastic model of the Earth's lithosphere by Wahr-Dehant-Zschau (Skalský 1991). The diurnal periods of tilt is clearly visible on the pendulum P1 at Příbram, which is installed only 1-2 m below the surface (see Fig.5a, b). Such diurnal waves are caused mainly by exposition of the Earth’s surface (Neumann 2007). In the afternoon, when the surface temperature is the highest, the deformation of the rock mass in the surrounding of the pendulum becomes irreversible (see Fig. 5b). Such diurnal waves were observed on pendulum P7 too, although this pendulum is installed in the distance 200 m of pendulum P1 and in the ground 90 m below the surface (see Fig. 6). The amplitudes of diurnal waves on pendulum P7 are much smaller than on pendulum P1.

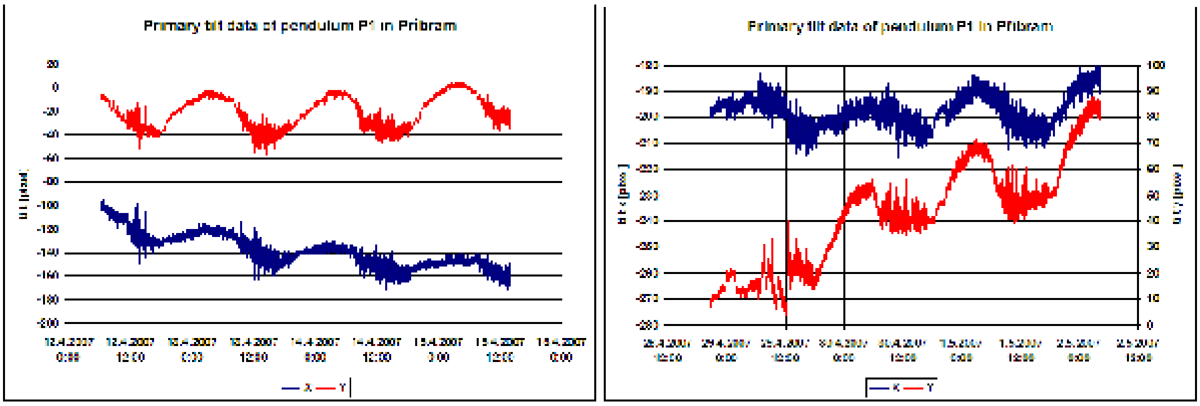


Fig. 5 The diurnal variation of tilt on pendulum P1 in Příbram

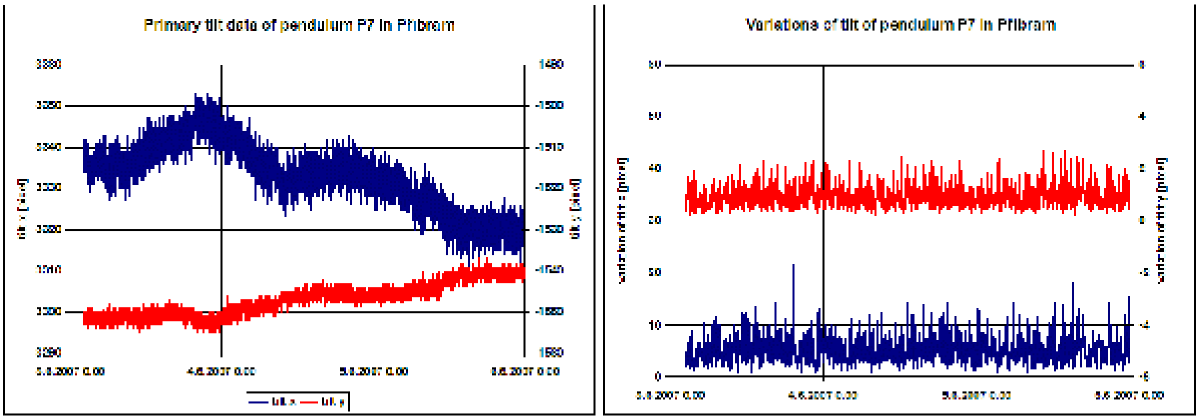


Fig. 6 The diurnal variation of tilt on pendulum P7 in Příbram

The stress transfer from the surface to the depths is enabled by thermoelastic wave, described by Hvožďara et al. (1988) on the strain measurement in Vyhne (Slovakia) (Brimich 1996).

When the primary data, measured with sampling period of 10s, are analysed, the various forms of irreversible deformations in the surrounding of the pendulum are visible. The most often irreversible deformation is creep (see Fig. 7), silent earthquakes (see Fig. 8a) or microearthquakes (see Fig.8b).

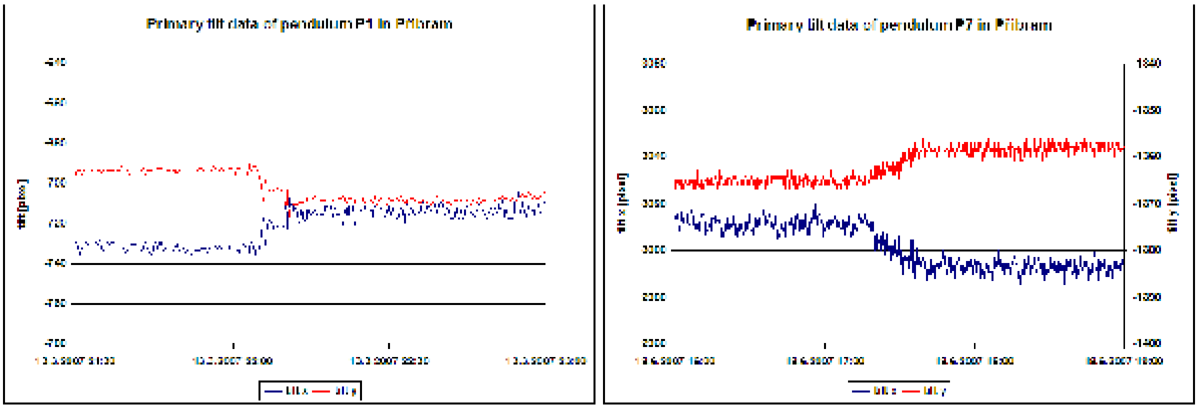


Fig 7 Creep, observed on pendulums P1 and P7 in Příbram

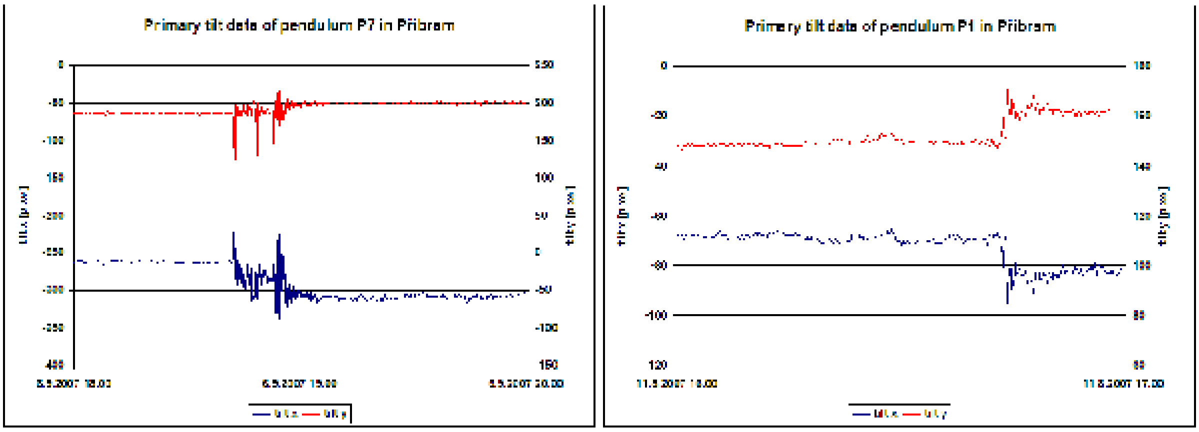


Fig 8 Silent earthquake and microearthquake, observed on pendulums P1 and P7

The movements, generated by local, regional or teleseismic earthquakes were observed on all pendulums. Sometimes, coseismic deformations were observed, which were caused mainly by surface waves of big earthquakes, i.e. in the case of the Sumatra earthquake on September 12, 2007 (M=8.5) (see Fig. 9).

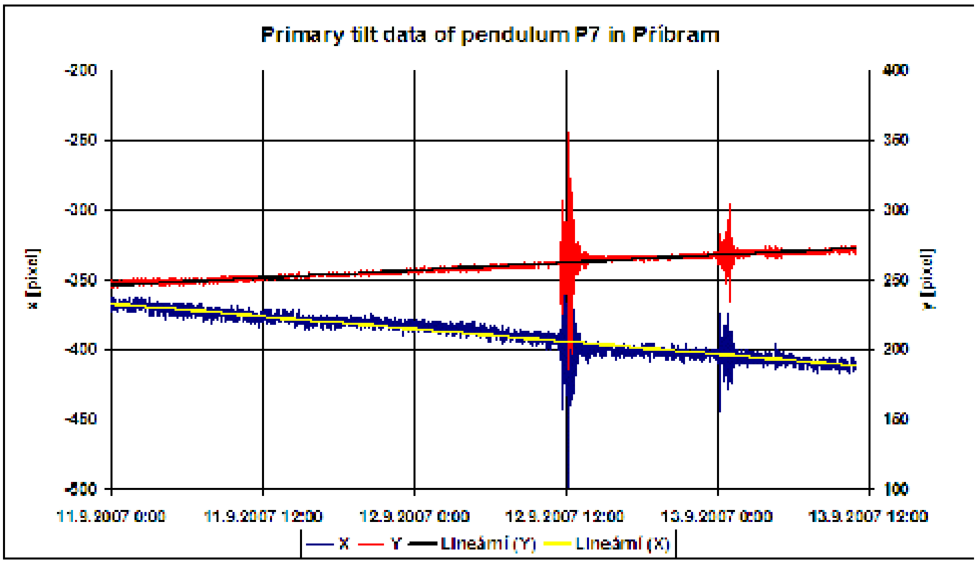


Fig. 9 Coseismic slip registered during Indonesian earthquake on 12.September 2007

3. Estimation of stress and direction of its main component

The estimation of the stress tensor in the surrounding of the pendulum is not as easy as it looks, because it is not clear what deformation is caused by increasing of stress and what deformation is caused by decreasing of stress and massif relaxation. Because the blocks of Earth core can be regarded as a beam with one fixed end in the mantle and one free end on the Earth's surface (see Fig. 10), such blocks will be inclined to the north when the force ***F*** increases and its direction is from south to the north. On the other hand, if the force ***F*** decreases and its direction are oriented against in northern direction, the blocks will incline to the south according to Hook´s law

$$\sigma_{ij} = \sum_{kl} c_{ijkl} \cdot \varepsilon_{kl}. \qquad /2/$$

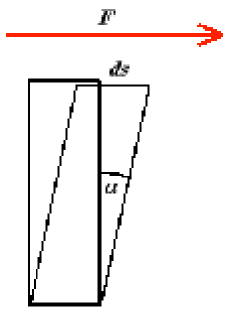
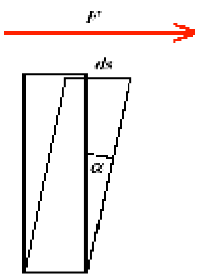


Fig.10 The scheme of deformation of blocks of earth core



In the real environment of Earth's core, the ideal beams with one fixed end are not present and each blocks of Earth's core react individually to increasing stress by individual deformation, rotation and movement, which are defined by local geometry of block's contact with other blocks, by stress transfer between blocks and physical parameters of rock mass and faults between blocks. It results into the apparently chaotic and opposite movements of blocks with various directions and amplitudes (Stemberk et al. 2003, Briestenský et al. 2007a, Briestenský and Stemberk 2007b).

How to decide, what deformation matches the stress increasing and what deformation matches relax time and decreasing of the stress? It is possible to decide it by the help of irreversible deformation. When the stress in the rock mass increases, the Hook's law holds until the strength limit. When the stress is greater than the strength limit of the softest parts of rock mass, the creep of the massif occurs, the seismic noise increases and the deformation becomes irreversible. There are the rose diagrams on Fig. 11 of directions of tilt, which were measured during one hour long intervals between point A of the suspension of pendulum and point B of the suspension of the camera. The prevailing directions, measured on pendulum P1 are in directions NNW, SSE, WNW and ESE (see Fig. 11a). If only the biggest movements are summarised, the prevailing directions are only to SSE (see Fig. 11b). The general direction of pendulum P7 was to the south (see Fig. 11c), which is the same as during the biggest movements (see Fig. 11d). Generally speaking, the direction to the south (SSW – SSE) is the direction of the main stress component in Příbram during the observed period and the force has its orientation from north to south.

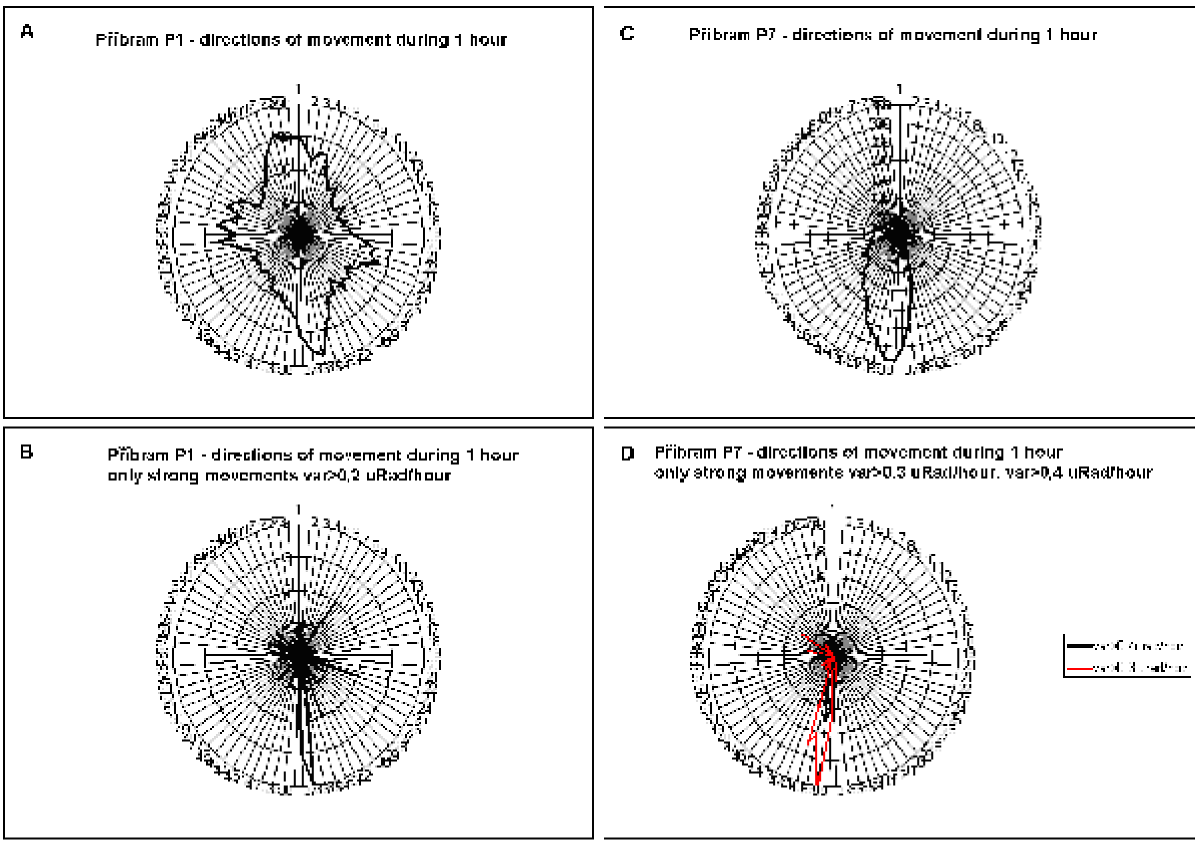


Fig. 11 Directions of movement of a pendulum during one hour

The second way, how to determine the period of the increased stress in the area under study, is with the help of monitoring of microseismicity. The microseismicity generates seismic noise, which can be measured by variations of differences between actual positions of pendulum and the central (average) position, i.e. „noise“ of pendulum (see Figs. 5 – 9). The anomalous development of the tilt of pendulum P7 in Příbram to the west and south is on Fig. 12. The normal development during the year 2007 was defined by interpolation of tilt changes by a polynom of 3-rd order. It is clearly visible that the high „noise“, especially in the NS direction, was observed in June 2007. At that same time, the anomalous tilt of the pendulum to the west and south was observed. The biggest tilt anomaly in September 2007 was accompanied by high „noise“ that started on September 7 after the Taiwan earthquake (Mw=6.2). The maximum of anomalous tilt of the pendulum was around September 12, when two strong earthquakes took Sumatera (Mw=8.5 and Mw=7.9). The third period of increasing stress was at the end of the year 2007 and in the beginning of the year 2008. Two of three anomalous periods in the year 2007 correlate well with the strongest seismic events on the Eurasian lithosphere plate (Sumatra, Andreanoff island). On the other hand, the strongest seismic events, which were observed on the other lithosphere plates (Peru mb=8, Chile mb=7.7, Windward mb=7.3), took place at the same time as small „noise“ of the pendulum, small stress in the area under study and massif relaxation. Generally speaking, the periods of increasing stress can be defined by higher „noise“ of the pendulum and the direction of the main stress component can be estimated by prevailing directions of the pendulum´s movement. As it can be seen on the Figs. 11 and 12, the orientation of the main stress component varies in time.

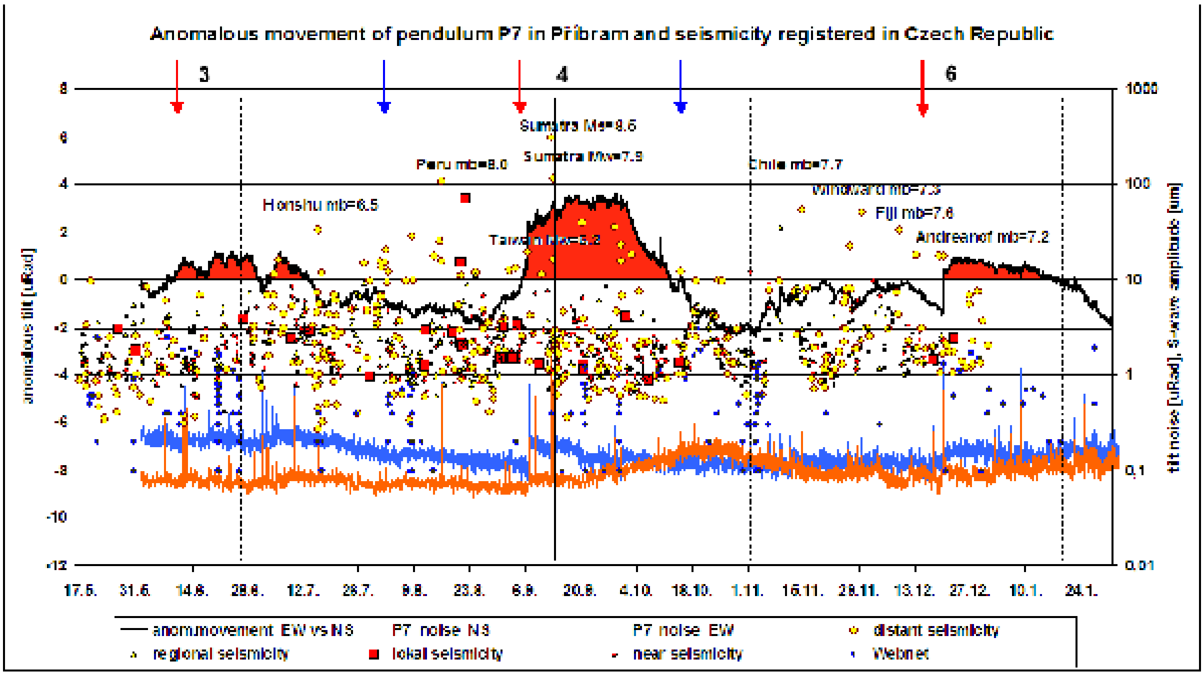


Fig.12 Anomalous tilt of pendulum P7 in Příbram and seismicity, registerd by the Czech seismic network (Zedník 2007, ANSS 2007), seismicity in Nový Kostel swarm area (Horálek and Fischer 2007) and the local seismicity in Příbram (Málek et al. 2007).

4. Discussion

The annual tilt variations were observed on the horizontal pendulum in the Grotta Gigante, Italy for many years (Breitenberg and Zadro 1999, Braitenberg et al. 2006, 2007). They explained annual tilt variations by precipitation variations during a year.

Hvožďara et al. (1988) explained the annual variations of tilt (or strain) by the annual thermoelastic wave, which is generated in the subsurface layers by thermal waves (penetrating the depths c. 15 - 30 m below the surface), but which can penetrate the deepest depths as an elastic wave. The high „noise“ of all pendulums, strainmetr in Vyhne (Brimich 2006) and seismic noise and microseismicity (Zátopek 1949) during autumn and winter corresponds well with annual thermoelastic wave.

Our observations show that the increasing tilt to the south and higher „noise“ on pendulums in Příbram during winter corresponds well with higher stress. On the other hand, the extent of active faults and vertical movements are observed during summer (Stemberk et al. 2009).

The diurnal variations of tilt are similar to annual variations of tilt and they are generated by diurnal thermoelastic waves, which depend on the temperature variations of the rocks on the surface, which depend mainly on the solar expositions of the surface and quality of surface cover (rock, sediment, soil). Such diurnal thermoelastic waves were observed in depths of 90 m below the surface on the pendulum P7 (see Fig. 6) and even at depth of 1300 m on the tidal station in the old mine of Anna in Příbram (Melchior and Skalský 1969), although the diurnal thermal wave can penetrate only to depths of about 15 – 30 cm. The amplitude of diurnal thermoelastic waves was 4 – 11x greater than the theoretical amplitude of tidal wave S1 (Melchior and Skalský 1969). The phase of diurnal thermoelastic wave in the ground was the same, as the phase of thermal wave on the surface, i.e. with the maximum in the afternoon between 1 p.m. and 3 p.m. local time (see Fig. 5).

The highest diurnal variations of tilt were observed before the strongest earthquakes (Sichuan, Kuril Islands) especially in the N-S direction. The anomalous diurnal variations during the periods from May 7 to May 16, 2008 and from May 24 to May 31, 2008 can be seen on Fig. 13. The biggest anomalous tilt of pendulum P7, as well as the biggest „noise“ variations was not observed in the afternoon (which is typical for local diurnal thermoelastic waves), but after midnight. It can be explained by thermoelastic waves, which are generated in the hypocentral area of future earthquake in the afternoon at local time (13:30 LT).

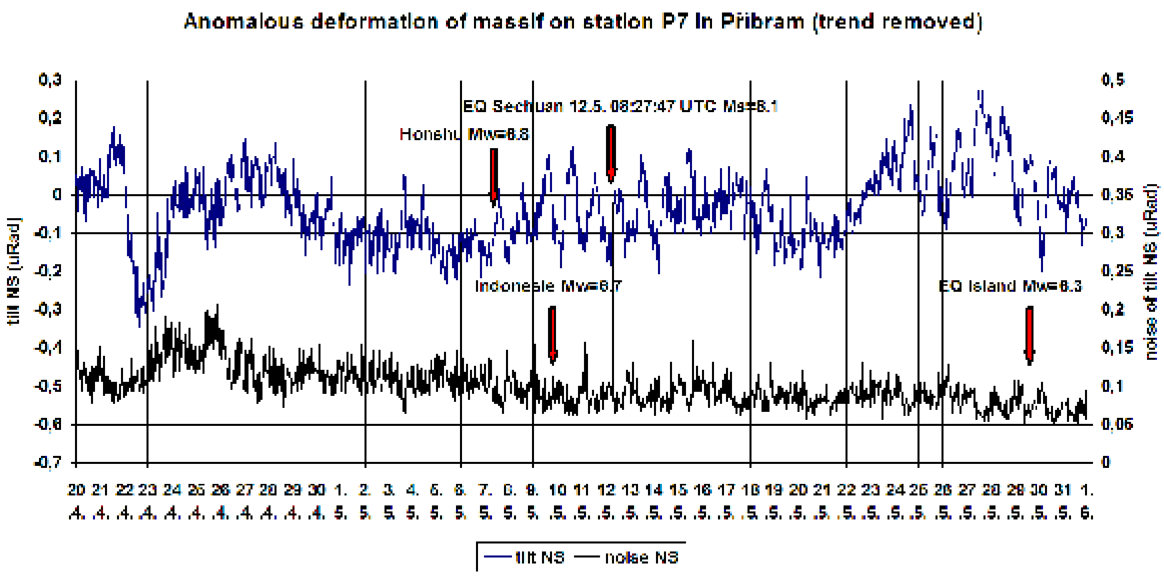


Fig. 13 Anomalous tilt of massif before the Sechuan earthquake 12.5.2008 (Ms=8,1)

The similar situation like on May 2008 started on October 30, 2008 when the diurnal thermoelastic waves were observed on both pendulums P7 in Příbram and in the cave No.13C in Moravian karsts (see Fig. 14). The maxims of „noise“ were observed before midnight, which could be generated by the breaking of the asperity on the other side of the Earth by local thermoelastic wave. The possible place of the asperity was localised in the area of Kamchatka and Kurile Islands, where the contact of North America, Pacific and Eurasian plates is. The magnitude of the future earthquake was estimated by the analogy with Sichuan earthquake 7+. The time of the future earthquake was predicted into a period of 28 days starting on October 30, 2008, because both influences – tides and thermoelastic waves – were took into account. Our prediction fulfilled on November 24, 2008, when deep earthquake hit the area between Kurile Island and Kamchatka with magnitude of 7.3. The random probability of such prediction, based on the data between 1970 and 2000, was only 6.4%, so we can state that our prediction was not random on the level of a significance of 90%. Such correct prediction confirmed the correct recognoscation of a thermoelastic wave that was generated on the asperity in the hypocentre of the Kurile Islands earthquake. The nucleation phase of this earthquake was triggered not only by thermoelastic wave, but also by a strong earthquake near Sulawesi on November 16, which led to the medium earthquake sequence in the Arctic Ocean between November 17 and November 19, 2008 (see Fig. 14).

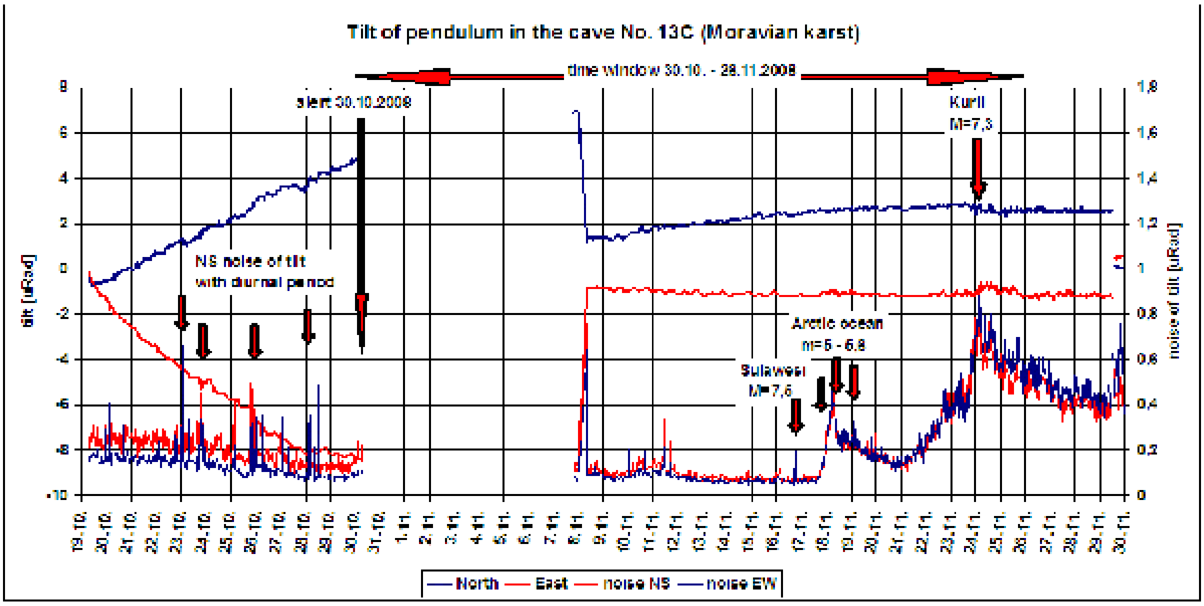


Fig. 14 The tilt of the pendulum in cave No.13C in Moravian karsts before predicted Kuril Islands earthquake 24.11.2008 (M=7,3) (ANSS 2008)

5. Conclusion

Static vertical pendulums or other deformometry apparatus were used for indirect measurement of stress in the upper crust. The first static vertical pendulums were installed in the old Prokop mine in Příbram and in cave No. 13C in Moravian karsts since 2007. One pendulum was installed in a productive potassium mine in Lubeník (Slovakia) in 2008.

More than the two years experience of measurement shows that it is possible to find the main direction of stress in the surroundings of the pendulum and its development in time. The noise level and anomalous deformation development shows the value of relative stress in the surroundings of the pendulum. The correlation of deformation between distant stations shows that stress variations are not of local origin, but the stress field has regional character and is similar practically in the whole lithosphere plate.

The great changes in stress orientation and in stress state were observed before the biggest earthquakes on Eurasian lithosphere plate. Two years of our experience resulted in the successful prediction of Kurile Islands earthquake on November 24, 2008 (M=7,3).

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