TILT VARIATIONS AT SHALLOW DEPTH: IMPLICATIONS FOR THE INSTALLATION OF A LASER GYROSCOPE AT THE GEODETIC OBSERVATORY WETTZELL

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Introduction

Observation pillars near the earth's surface are always subject to local ground deformations which mainly result from thermoelastic and hydrologic induced stresses. The importance of such effects rises with increasing precision of the instruments. The construction of the world's most precise laser gyroscope at the Geodetic Observatory Wettzell requires utmost orientation stability of the observation pillar. A detailed site investigation and records of natural tilts at different depths as well as environmental parameters were performed in order to assess the magnitude and origin of tilt variations and to develop strategies to minimize them under the given geological, hydrological, and financial conditions.

Site investigation

The Geodetic Observatory Wettzell is located in the Bavarian Forest 610 m above sea level on a flat saddle between two hilltops. The investigated area is a meadow with a slight slope of 4-6° towards west. A total of 6 boreholes reveal a strongly varying degree of weathering of the bedrock consisting of metamorphic crystalline rock (gneiss). The uppermost 2 m mainly consist of sandy loam, which is the result of the total decomposition of the bedrock. Below 2 m an increasing number of boulders of different size (up to 1-2 m) occur, which are remnants of the weathering process. The transition of weathered rock to solid rock is smooth and at varying depth; solid rock is present below 7-14 m. But even the solid rock is crossed with joints and fractures, where weathering might have produced zones of low strength and good permeability.

As a consequence of the geological conditions, the hydrological situation of the underground is very inhomogeneous. The sandy loam close to the surface is a pore aquifer with low permeability. The zone of weathered and partly weathered rock consists of pore aquifer zones with medium permeability and zones of no permeability in between (rock boulders). The fractured solid rock can be characterised as a cleft aquifer with strongly varying permeability. The records of 4 different groundwater gages match the complex hydrological situation. Although being no more than 100 m apart, every gage shows somewhat different behaviour. Three gages show groundwater levels of about 3-7 m below the surface, one gage show a very different level of 9-12 m. The maximum level difference is between 2.3 and 3.8 m in all 4 gages.

Tilt records

Tilt variations were recorded using two Applied Geomechanics type 722A borehole tiltmeters in a geodetic survey pillar close to the surface and in boreholes at 6 m and 13 m depth, and using an Askania pendulum at 30 m depth.

The survey pillar (Fig. 1) shows tilts after rainfall or snow melting up to 20 µrad. A strong and rapid tilt of the pillar up to 40 µrad may occur when the soil is freezing and thawing (e.g. January 2001). There is a linear drift of about 80 µrad/y towards WNW, but no seasonal wave can be observed.

At a depth of 6 m (Fig. 2), where is the transition between the unsaturated zone and the groundwater, the most prominent tilt signal is a seasonal wave with a double amplitude of 40 µrad. An thermal effect of the instrument does not seem to play a major role, because the tilt signal and the temperature are not exactly in phase. The short term tilt variations are due to rain and show amplitudes up to a few µrad per event. The highest value of 7 µrad occured after heavy rain on dry soil in October 1998. There is nor a clear temporal neither a quantitative correlation between tilt and rainfall or groundwater level. Time, direction, and amount of tilt after rain depends on the actual condition of the soil like humidity and temperature. In the winter when the soil is wet, even small amounts of rain or snow melt quickly migrate downwards and reach the tiltmeter level to produce soil deformations. But in the spring and summer, when the soil is dry and the vegetation needs a lot of water, the water migrates to deeper levels only after intense rain.

The instrument at 13 m depth, that is below the groundwater table, shows a weaker reaction after hydrological events, but there is a certain correlation with the groundwater level. A coefficient of roughly 10 nrad/cm can be deduced.

The Askania pendulum at 30 m depth (Fig. 3) shows a hydrologically induced seasonal signal of about 0.4 µrad, a seasonal thermoelastic wave of less than 0.2 µrad, and a linear drift of about 0.8 µrad towards NNW. The dominant hydrological signal occurs in late winter and spring when rain and snow melt penetrate deep soil layers. This signal correlates with the groundwater record at gage BK1, where the groundwater level is deeper than at the other gages. Short term hydrological tilts in the order of 0.1-0.2 µrad rather tend to correlate with gage BK3. This behaviour underlines the complexity of the hydrological system. But it is clear that beside the earth tides, the strongest signal at this depth is of hydrological origin.

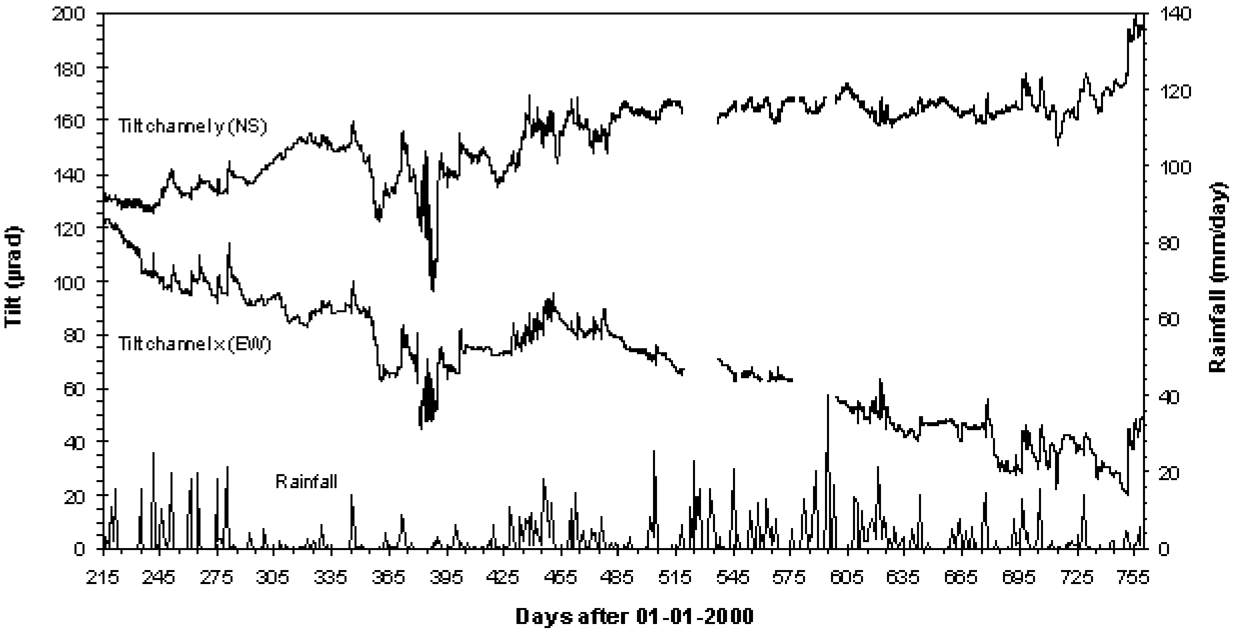

Figure 1: AGI borehole tiltmeter in a geodetic survey pillar; record over 540 days.

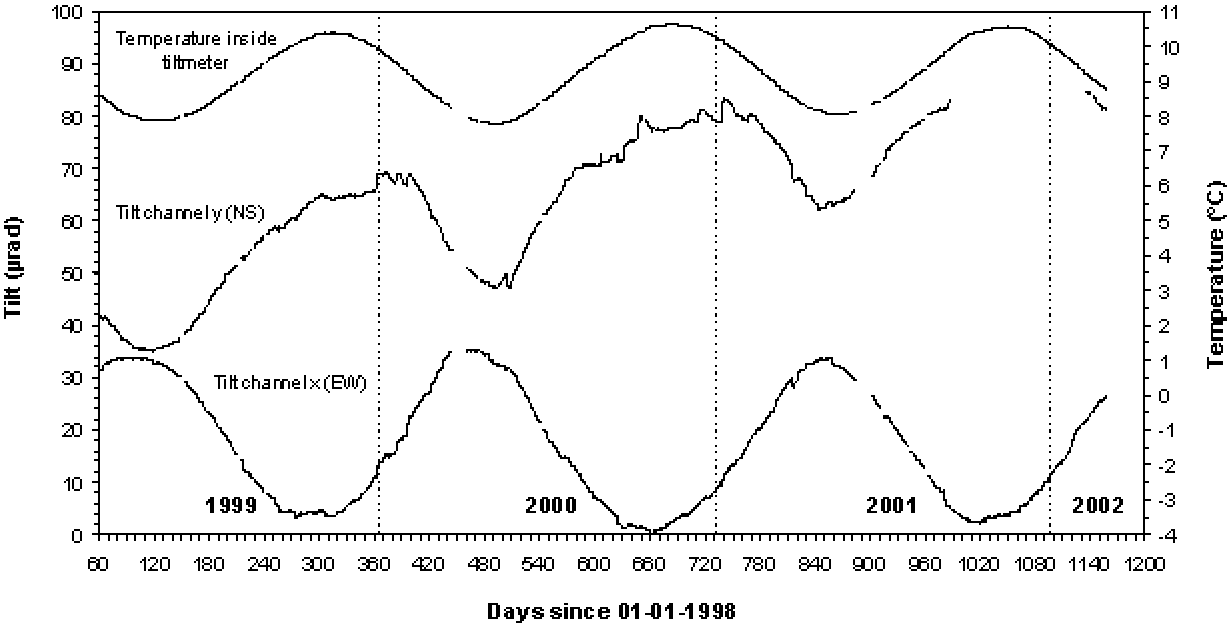

Figure 2: AGI borehole tiltmeter in 6 m depth; record over 3 years.

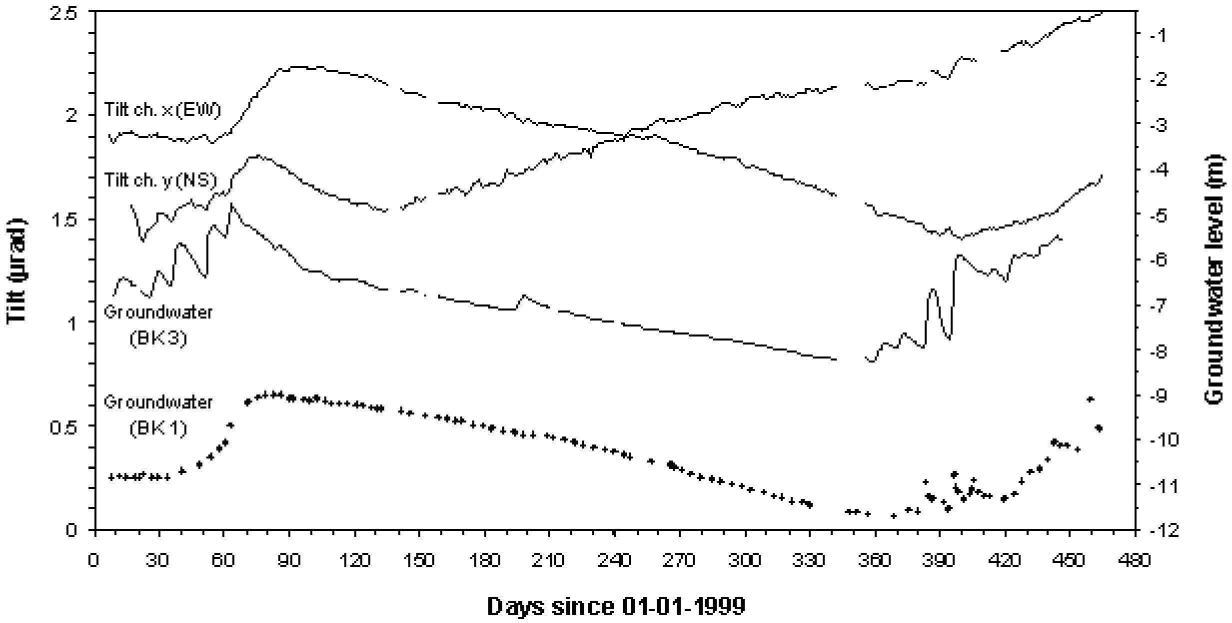

Figure 3: Askania pendulum in 30 m depth, earth tides removed; record over 460 days.

Results

Tilt records close to the earth's surface are mainly affected by thermoelastic and hydrologically induced, local soil deformations. The propagation of a thermal wave into the underground can be described by the formula for one-dimensional heat conduction:

$$T(z,t) = A\ \exp(-z\,\text{Ö}w / (\text{Ö}2\,a))\ \ \sin(w\,t - z\,\text{Ö}w / (\text{Ö}2\,a))$$

where A is the amplitude at the surface, z is the depth, w is the frequency and a is the thermal diffusivity. The amplitudes decrease exponentially with depth and Öw, that diurnal thermal waves are detectable only in the upper 2 m. The annual thermal wave reaches in Wettzell double amplitudes of 2.8 °C at 6 m and 0.1 °C at 17 m depth. The temperature field is assumed to be stratified parallel to surface, that lateral inhomogeneities or an uneven surface are required to produce vertical tilts. The absence of seasonal tilts near the surface thus indicates that lateral inhomogeneities are small in the uppermost soil layer. However, there are strong seasonal tilts in 6 m depth being the consequence of major lateral strength contrasts between solid rock (boulders) and weathered rock (soil). In 30 m depth the thermoelastic seasonal tilts are very weak, which can be due to very small temperature amplitudes or small inhomogeneities in the solid rock.

Hydrological tilts occur immediately after rainfall or snow melt close to the surface. Near the groundwater table, tilts may be temporally correlated with either rain or groundwater. The seasonally varying direction indicates that thermoelastic strains due to heat transfer by downward migrating water seems to play a certain role. Below the groundwater table, tilts tend to correlate with changes of the groundwater level. These variations in hydrostatic pressure give rise to deformations even in 30 m depth.

The results entered into the design of the pillar and the observation lab, which depth was limited by the groundwater table. A drainage system below the lab keeps the groundwater level constant. The pillar is founded 5.5 m below the lab on solid rock and is shielded from deformations at shallower depth by a system of concrete rings. A thick thermal isolation and a mound on top keep the temperature in the lab constant at a 1/100 °C-level. A surface water seal prevents seeping water to migrate to deeper levels. High resolution platform tiltmeters being installed on top of the laser gyroscope prove the stability of the construction. However, after heavy rain a movement of the pillar of some hundred nanoradian can be observed.

Conclusions

The comparison of tilt measurements at different depths with environmental data reveal that thermoelastic deformations strongly decrease with depth and highly depend on the presence of lateral inhomogeneities. The influence of such deformations can be strongly reduced by increasing the depth of foundation and by thermal isolation. Hydrological tilts occur at every depth where meteorological water is present. They might be reduced by a deep, stable foundation and proper water draining, but cannot be prevented. Monitoring of tilt variations with high resolution tiltmeters placed on top of the laser gyroscope is required.