Point stability at shallow depths: experience from tilt measurements in the Lower Rhine Embayment, Germany, and implications for high-resolution GPS and gravity recordings

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SUMMARY
From 1996 to 1999, we have studied ground tilts at depths of between 2 m and 5 m at three sites in the Lower Rhine Embayment (LRE), western Germany. The LRE is a tectonically active extensional sedimentary basin roughly 50 km × 100 km. The purpose of the tilt measurements was (a) to provide insight into the magnitude, nature and variability of background tilts and (b) to assess possible limitations of high-resolution GPS campaigns and microgravity surveys due to natural ground deformation. The tilt readings, sensed by biaxial borehole tiltmeters of baselength 0.85 m, cover a frequency range from 10⁻⁸ Hz to 10⁻² Hz (periods from minutes to years). Assuming that the tilt signals represent ground displacements on a scale typically not larger than several times the tiltmeters’ baselength, and that tilt signals at shallow depth could in a simple geometric way be related to changes in surface elevation and gravity, we try to estimate the magnitude level of point movements and corresponding Bouguer gravity effects that is generally not surpassed. The largest tilt signals observed were some ±50 μrad yr⁻¹. If they were observable over a ground section of extension, e.g. 10 m, the converted rates may correspond to about ±0.5 mm per 10 m yr⁻¹ in vertical ground displacement, and ±0.1 μgal yr⁻¹ in Bouguer gravity effect, respectively. Large signals are mostly related to seasonal effects, probably linked to thermomechanical strain. Other causes of ground deformation identified include seepage effects after rainfalls (order of ±10 μrad) and diurnal strains due to thermal heating and/or fluctuations in the water consumption of nearby trees (order of ±1 μrad). Episodic step-like tilt anomalies with amplitudes up to 22 μrad at one of the observation sites might reflect creep events associated to a nearby active fault. Except for short-term ground deformation caused by the passage of seismic waves from distant earthquakes, amplitudes of non-identified tilt signals in the studied frequency range seem not to exceed ±2 μrad. As the larger tilt signals are close to the precision achieved with modern GPS systems and superconducting gravimeters when converted into height and gravity changes, further enhancement in resolution of these techniques may require simultaneous recording of local ground deformation at the observation sites.

Key words: deformation, geodesy, geodynamics, GPS, gravity, Lower Rhine Embayment.

1 INTRODUCTION
The precision of GPS measurements has reached a level where the coordinates of geodetic reference points can be obtained with millimetre resolution (Prescott 1996; Görres & Campbell 1998). Natural fluctuations in point stability due to local ground deformation of various causes are one of the factors that may limit further increase in resolution and application of this technique to monitor displacements on the submillimetre scale. Similarly, gravity observations with resolution of a few μgal (tens of nm s⁻²) have become possible in the field (Torge 1989; Van Gelderen et al. 1999), and attain 10 ngal resolution in recordings of mechanical earth tide gravimeters or superconducting instruments (Wenzel 1997), but interpretation of residual signals is hampered by a lack of understanding of the
complexity of local ground dynamics. Foundations of geodetic observation points are typically laid at 1–4 m depth. Studies of ground deformation at these depths can reveal insight into the types and characteristics of natural background variations and the underlying physical processes.

Tilt measurements are particularly apt at such investigations, because they are rather easy to operate at remarkably good resolution. However, various investigators have found that local ground tilts are stronger by one to two orders of magnitude at depths of several metres than at depths of several tens of metres (Tanaka 1969; Wood & King 1977; Savage et al. 1979; Meertens 1980; Wyatt 1982; Lewkowitz 1985; Kümpel et al. 1986). Moreover, in a case study, low coherence of signals from shallow borehole tiltmeters has been demonstrated for installations in granitic material in a semiarid environment by Wyatt & Berger (1980). This phenomenon appears to be due mainly to a decrease of hydro-meteorological impacts with depth and enhancement of tilt signals through strain-tilt coupling at non-planar stress free boundaries, particularly at the earth surface (Harrison 1976; Harrison & Herbst 1977; Wyatt 1989). Consequently, long-term tilt signals observed at shallow depths should generally not be taken as evidence for tectonic movements (Wyatt et al. 1988). Researchers interested, e.g. in the weak deformation signals of the solid earth tide therefore avoid installation of their instruments near the surface. According to reports by others (see above) the larger tilt signals expected at rather shallow depths can be observed with instruments of resolution 0.1 μrad ≥20 msca (i.e. roughly the bulk tidal tilt amplitude).

From 1996 till 1999, we operated continuously monitoring tiltmeters at three sites in the Lower Rhine Embayment (LRE), Germany (Fig. 1). The LRE is an extensional sedimentary basin roughly 50 km x 100 km in western Germany that is receiving particular attention from several research groups forming the Collaborative Research Centre ‘Interactions between and modelling of continental geosystems’ at Bonn University (SFB350 of Deutsche Forschungsgemeinschaft). The topography in the LRE is flat except for gentle offsets along several major NW–SE-trending normal faults, dipping towards either SW or NE (Wrede & Hilden 1988). These cut through the overlying unconsolidated sediments of thickness up to about 1 km and appear to extend to depths of at least 15 km. The faults are indicators of extensional tectonics in the LRE which are believed to have started in the Cenozoic and are still ongoing (Wrede & Hilden 1988; Van den Berg et al. 1994; Klostermann et al. 1998). Moderate seismic activity with normal dip slip displacements dominating characterizes the present situation (Ahorn 1983; Pelzing 1994; Grünthal et al. 1998). Drainage of aquifers for open-pit lignite mining has lead to significant subsidence in some areas (Fröhlich & Müller 1986).

As part of the Research Centre’s activities, high resolution GPS and microgravity campaigns are repeated every year (GPS; Campbell et al. 1994; Görres 1996; Görres & Campbell 1998) or every several weeks (gravity; Keysers & Kümpel 2000; Keysers 2001) to learn about neotectonic movements and possible related mass transfers in the LRE on the hundred kilometre and kilometre scales. The objectives of the tilt measurements were to find out about the magnitude, generic nature and variability of background signals and the various processes that dominate local ground dynamics in this context. In the time spans between the GPS and gravity campaigns, the tilt measurements, to a certain extent, were also aimed at keeping record of major creep events or co/postseismic displacements, should they occur.

We report data from tilt recordings that were obtained between 1996 and 1999. The data allow us to assess some general constraints for GPS and gravity surveys due to ground dynamics in the LRE, and possibly beyond this region. The findings may be useful for users of high resolution GPS techniques and microgravity campaigns who are interested to obtain insight in factors limiting the accuracy of their measurements. We do not present model calculations to validate the physical causes that have lead to the observed tilt phenomena. Rather, reasoning of the physics behind the tilt effects is based on plausibility assessments reckoning in direct observational data—with temporal coincidence or coherence of signal constituents of different parameters, physical and hydrogeological understanding, and numerous earlier investigations reported in the literature. Some early results of this study have been published by Lehmann et al. (1998).

2 INSTRUMENTS AND SITE LOCATIONS

Three biaxial tiltmeters of nominal resolution 0.1 μrad over a dynamic range of ±800 μrad and non-linearity up to 0.2 per cent were available for the study (Model 722 A, Applied Geomechanics Inc. 1991). The sensors are quartz tubes with gas bubbles in electrolytic fluid (see also Agnew 1986); readings are given in units of voltage and reflect resistivities which depend on the position of the bubble in the quartz tube. Two of these sensors are mounted in perpendicular directions on a cylindrical stainless steel case. A temperature sensor (thermistor) is mounted between them. The steel case is housed in the lower end of a cylindrical steel body, which is the tiltmeter housing of length 0.85 m and diameter 0.054 m. The instruments are designed for installation in boreholes at typically 2 m to 8 m depth; the diameter of a borehole is advised to be 0.15 m to 0.20 m.
Coupling to the ground is achieved by filling and tampering quartz sand around the tiltmeter body during installation, known as the sanding-in method (Agnew 1986).

Calibration studies in a laboratory carried out by Mentes et al. (1996) and more recent experiments of our own have revealed that a linear scale factor in units μrad/volt describes the response of the instrument to tilts over the full dynamic range with precision better than 6 per cent, on average. The built-in thermistor provides temperature readings of the tilt sensors’ immediate vicinity that can be used to correct signal trends caused by thermal influence (Holzhausen 1997). The single biggest source for such influence is expansion and contraction of the sensor liquid, shrinking or swelling the gas bubble and changing the amount of liquid in contact with the sensor electrodes. Effects from thermal changes in the conductivity of the electrolytic liquid are entirely removed by taking output voltage as a percentage of input. Thermomechanical deformation of the instrument, already minimized due to the mechanical outlay, is partially compensated by the tiltmeter’s electronic circuitry. Residual thermal effects can largely be accounted for by application of two temperature coefficients (Applied Geocircuitry). The sandy, unconfined aquifer reaches down to 14.7 m. The ground water table typically varies between 2.0 m and 3.2 m depth. The top layer is 1.5 m thick and consists of loam and silt and is covered by a few decimetres of soil.

Site WS is on a farmland, at about 1 km from another GPS station and the second microgravity network in the LRE (Fig. 2b). The site is located 5 km southwest of the Erft Fault which extends over about 40 km and separates the Erft Block from the Cologne Block (see Fig. 1). Due to long-term, massive drainage related to the open-pit lignite mining, the ground water table here is lowered to about 210 m below the surface whereas on the Cologne Block, the water table is only at 10 m to 20 m depth (Erftverband 1996). This indicates that the Erft Fault is an effective hydraulic barrier. GPS campaigns by Görres & Campbell (1998) reveal height changes of 22 mm yr⁻¹ across this section of the Erft Fault, with subsidence occurring on the Erft Block. Significant fluctuations in relative gravity values, evident from the microgravity data of Keysers (2001), appear to be of seasonal rather than of long-term character. The tiltmeter here is installed at a depth of 3.0 m (bottom end). The underground consists of sandy sediments except for a thin soil layer.

Site BV is located amidst farmland in the south of the LRE and has been chosen mostly to study shallow hydrological effects that may induce ground deformations. The tiltmeter borehole is at 13 m from a groundwater observation well of the Erftverband, Bergheim and a single chestnut tree; all located in the corner of a triple junction of low traffic roads. A meteorological station with sensors for air pressure and rainfall has been installed at a protected place 700 m away. The ground water table is at only 0.8 m to 2.0 m below the surface, but is still mostly confined. Drilling was difficult at a depth of about 0.5 m, where a highly compacted stratum was encountered. A ground penetrating radar survey and inspection of an older map later revealed that in former times the west-east trending road (Fig. 2c) went through this test site, possibly presenting a distinct heterogeneity at shallow depth. The tiltmeter was placed at 2.4 m below surface (bottom end).

Fig. 3 is a sketch of the instrumental set-up showing the variety of different sensors we use. The AGI Model 722 A tiltmeter is set in a bed of tampered quartz sand, inside a PVC casing of diameter 0.2 m. The casing is locked and hydraulically sealed at its lower end. Power supply through rechargeable batteries and a multichannel digital recorder are housed in a box that is buried in the ground. Soil temperature is sensed at 0.05 m depth (WS only). Air pressure and rainfall data are, in fact, recorded at nearby places (JL, BV). Fluctuations in depth of the ground water table of the most shallow aquifer, sampled by a pressure transducer in a well, and ground water temperature are recorded by autonomous sensors (JL, BV). Depths of well levels are checked twice a month using a manual reading device.

3 RAW DATA

The full data set that is analysed in this paper is presented in Fig. 4. Individual recordings are coded as in Fig. 3,
with indices denoting the sites. Sampling intervals are 5 min (non-meteorological data of JL and all data of BV) or 10 min. Since we are primarily interested in variations of ground tilt, all parameters including soil temperature at WS, but not other temperature data and rainfall, are given in relative values. To facilitate comparison of signals from different sites, scales of corresponding parameters in Fig. 4 are identical.

Fig. 4(a) shows all the series recorded at site JL. Data gaps in the tiltmeter and ground water data result from instrumental failures (either sensors, recorders, or power supply). The rather high microseismic noise visible in the 1997 data of the tilt signals TX JL and TY JL is caused by the mining activities in the Hambach lignite pit at 4 km distance. It has largely been suppressed through application of the built-in low-pass filter of the tiltmeters after October 1997. The filter has a corner frequency of 0.133 Hz (Applied Geomechanics Inc. 1991). The large spikes on September 26 1997, in both tilt components, reflect the passage of seismic waves of the Ms 5.9 earthquake in Umbria, Central Italy (epicentral distance about 970 km). The sampling rate of 5 min does not allow resolution of the peak amplitudes, but appearance of this event in the tilt recordings testifies that the tiltmeter was coupled to the ground. The earthquake is also visible in the tilt data of sites WS and BV (Fig. 4b,c). Other spike-like signals in the tilt recordings can not simply be attributed to seismic events. They mostly occurred at one site at a time only. The true causes are unclear, but could, for example be due to mechanical disturbances close to the tiltmeter's borehole (e.g. loading from a heavy vehicle), lightning effects from a thunderstorm, or undersampled wave trains from minor, low distant earthquakes or blasting operations.

Fig. 4(b) displays the signals obtained at site WS. Again, to suppress microseismic noise probably also resulting from the
Hambach pit at 16 km distance, the instrument’s low-pass filter has been applied in October 1997. The soil temperature ST_WS was sensed at 0.05 m below surface by a thermistor together with an uncalibrated amplifier and so is given in units of the amplifier’s output signal. What appears to be noise in this recording is mostly diurnal variations in ground temperature. Fig. 4(c) has the recordings of site BV. As for microseismicity, this site was the most quiet one. Application of the low-pass filter from October 1997 onwards did not visibly affect the signal variance. After a failure of the tiltmeter following flooding of the location in November 1998, the tiltmeter was replaced by an instrument of the same type, with orientation perpendicular to that of the previous installation. Tilt signals in Fig. 4(c) are plotted with unchanged azimuth to the North direction and x-, y-channels as indicated. Orientation in Fig. 2(c) is as from November 1998 onwards.

4 VARIOUS TYPES OF TILT SIGNALS

Clearly, besides the microseismicity and the spike-like anomalies, there are further non-random signal constituents in the tilt recordings. Based on their time characteristics, they include seasonal and other long-term trends, rainfall induced tilts, diurnal variations, and episodic step-like tilt events. The latter three types are less evident from Fig. 4 and require scale amplification to become better visible. We focus on these constituents in subsequent sections.

4.1 Seasonal and other long-term trends

At all sites, the dominant tilt variations are of seasonal character (Fig. 4). Peak excursions from mean tilt positions tend to occur around February/March/April and August/September/October. Dominance of seasonal tilts has also been observed by Bonaccorso et al. (1999) and Sleeman et al. (2000) who have used the same type of installation at 2–7.6 m depth on Volcano Island, Italy, and at 5 m and 8 m depths at two locations in the Netherlands, respectively. Fig. 5 shows displacements of the top ends relative to the bottom ends of the tiltmeters in units of tilt angle, providing views of the azimuthal character of the ground dynamics. Largest tilt movements at JL and BV seem to be orientated in NW–SE direction, yet more in the W–E direction at WS. Total recorded amplitudes of seasonal signal parts are roughly 45 μrad (JL), 35 μrad (WS), and 80 μrad (BV). Taking into account possible thermal influence on the sensors as given by the manufacturer, these values are uncertain by 3.5 μrad for JL, 10 μrad for WS, and 12 μrad for BV.

The most likely remaining causes for seasonal tilts are thermoelastic deformations in the ground and hydrological effects. From Fig. 4 it can be seen that seasonal trends exist in all the well level recordings, in ground water and soil temperature curves and in data of instrument temperature. Although the tilt series of site BV exhibit some correlation with the well level fluctuations we think the seasonal tilts are unlikely to be caused by hydrological effects (as for example, due to changes in local pore pressure gradients). The main reason is that we would expect short-term fluctuations of the ground water table, which are the dominating events in the well level curves, to be more pronounced in the tilt data (Figs 4a and c). Also, the seasonal trends at WS could hardly be explained by ground water influence, given that the depth of the water table is 210 m here.

The soil and instrument temperatures are well correlated at site WS, indicating that changes in instrument temperature are a consequence of seasonal heating and cooling of the shallow subsurface. The best correlation is seen between curves TT_HL and TX_HL (June 1997 until Dec. 1998), TT_WS and TY_WS (July 1997 until Feb. 1998), and TT_AV with TY_AV/TX_AV (March 1996 until Dec. 1999). The change in tiltmeter orientation in November 1998 at site BV did not change the character of the seasonal trends with reference to the North direction. Whereas at JL and WS, the influences in TX and TY appear to be of similar strength but opposite sign for both tiltmeters—with positive correlation between signals TT_HL and TX_HL and negative correlation between TT_WS and TX_WS—the data at site BV reveal a strong positive correlation between TT_AV and TY_AV/TX_AV, and a weak negative correlation for TT_AV with TX_AV/TY_AV, which argues in favour of dominance of site effects.

Super-annual trends are evident in the tilt data of sites JL and BV, but not in that of WS (Figs 4a, b and c). The magnitudes are about 30 μrad yr⁻¹ at JL and up to 40 μrad yr⁻¹ at BV, but these values are poorly constrained because of the limited overall lengths of the observations. We can not draw any conclusion regarding the spatial wavelength of these signals and thus abstain from speculations whether the trends could have anything to do with regional tectonics.

4.2 Rainfall-induced tilt

Rainfall has been suggested to cause ground deformation either by surface loading, induced changes in ground temperature and thus thermoelastic strain, swelling of soil and clay particles due to moisture variation in the vadose zone, or by elastic or poroelastic strains due to pore pressure changes in the ground.
Figure 4. Raw data series of sites JL (a), WS (b), and BV (c) with individual signals as denoted in Fig. 3. At site BV a different tiltmeter has been installed in November 1998, with orientation perpendicular to that of the previously installed one. Tilt signals are plotted with unchanged azimuth towards North, orientation as in Fig. 2(c). Spike-like excursions shortly after the $M_b$ 5.9 earthquake of 1997, September 26 in Central Italy, at roughly 950 km epicentral distance in all tilt recordings indicate the good coupling of the tiltmeters to the ground.

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The tilt recordings from the LRE indicate rainfall related tilts at sites JL and BV, but not at WS. Fig. 6 displays several cases from site BV, in particular the variability in the tilt response to rainfall due to different factors such as duration of the precipitation, pre-rainfall moisture conditions in the vadose zone and seasonal changes in evapotranspiration. Typically, significant rainfalls are followed by changes in ground tilt that coincide with changes in both the local ground water table and ground water temperature. In summer and autumn infiltrating rain water is mostly warmer than the groundwater in place (Fig. 6a,d) and cooler in winter and spring. During winter time, thaw events may have similar effects like heavy rainfalls.

At site BV, a rainfall generally provokes a ground tilt to the SSW, regardless of the sign of the induced change in ground water temperature. Therefore, tilt as a consequence of a change in ground (water) temperature can be ruled out. Lateral changes in loading deformation can be shown to be too small to explain the tilt signals (Kümpel 1982a). The lack of rainfall induced effects at site WS, where the ground water table is deep, argues against the soil swelling mechanism. Thus lateral pore pressure changes in shallow aquifers are the most likely process leading to this type of signal. The effectiveness of lateral pore pressure changes in the water saturated regime to cause significant ground deformation has been demonstrated by Kümpel (1989, 1997), Kümpel et al. (1996), Vasco et al. (2000) and Lehmann (2001) in configurations of pumped wells and borehole tiltmeters. Laterally inhomogeneous feeding of the most shallow aquifer from infiltrating rain water can be explained by gradients in effective permeability in the vadose zone or by heterogeneous evapotranspiration due to variable vegetation at the surface, for example. In the period range of days we have not found a significant impact from air pressure fluctuations on ground tilt.

A quantitative estimate of the magnitude of rainfall induced tilt can be obtained from Fig. 7. Herein, several such effects when identified as separate peaks, are plotted for sites JL and BV. Highest regression coefficients taken from these data are 0.14 μrad mm⁻¹ for JL and 0.25 μrad mm⁻¹ for BV. The values are in accordance with reports by others, who have observed rainfall induced tilt responses from 0.06 μrad mm⁻¹ up to 0.6 μrad mm⁻¹ for depths from 1 m to 10 m at different locations (Tanaka 1969; Meertens 1980; Wyatt & Berger 1980) including even sites on hill slopes (Wosnitza 1997; Rebscher et al. 2000). As rainfall events exceeding 100 mm are very rare in the LRE, our data suggests 25 μrad to be an upper bound for tilt amplitudes induced by rainfalls in this area.

### 4.3 Diurnal tilt variations

Air temperature in most regions shows significant diurnal fluctuations leading to respective variations in soil temperature and barometric pressure. Diurnal signals also exist as air pressure changes on the global scale and as direct insulation of the surface. We have recorded diurnal tilt signals with amplitudes high above that of the solid earth tide. Similar observations were made by, e.g. Kümpel et al. (1996), Rebscher (1996), Wosnitza (1997), and Sleeman et al. (2000), using the same type of instruments, at different sites. Regarding the physical

Figure 5. Traces of tilt signals observed at JL (a), WS (b), and BV (c), representing differential displacements of the tiltmeters’ top ends to their bottom ends. Numbers along the curves denote end of respective month. For better clarity, traces of subsequent years have been offset by amount as indicated. Insets show course of seasonal trends (not to scale). Suppression of high frequency noise after application of low-pass filter is clearly visible for signals of sites JL and WS.
mechanism involved, these authors suggest either lateral changes in thermoelastic deformation due to irregular thermal heating of the surface (see also Harrison & Herbst 1977), or subsurface pore pressure fluctuations in the water saturated zone caused by diurnal peaks in the water consumption of vegetation. The phenomenon is often more evident during sunny days and can vanish or be invisible at certain periods as well.

Fig. 8 shows, as examples, two weeks of tilt data from sites BV and WS with more or less pronounced diurnal fluctuations, namely in summer 1996 (Fig. 8a), autumn 1997 (Fig. 8c), and
in winter 1997 (Fig. 8b,d). Maximum peak-to-peak amplitudes of the diurnal signals in the composed tilt data are 2 μrad at BV and 4 μrad at WS. Recordings from the first week in Fig. 8(a) and the second week in Figs 8(b and d) show weak diurnal variations, if at all. The soil temperature recorded at WS presents the same diurnal character as the tilt data (Fig. 8c,d). No diurnal variations are resolved in the tiltmeter temperatures (both sites), nor in the groundwater temperature (site BV). Accordingly, signal contributions from thermal influences on the tiltmeter sensors should be of secondary importance.

Amplitude spectra of all the tilt and soil temperature signals plotted in Fig. 8 are given in Fig. 9. Apart from the strictly diurnal peaks emerging consistently in all the diagrams, there is also clear evidence of semidiurnal peaks, except perhaps for TYWS in Fig. 9(d). Semi-diurnal fluctuations probably indicate non-harmonic diurnal forcing, which is not surprising, because the excitation function is not a pure sinusoid. In proportion to each other, the diurnal fluctuations in signals TXWS and TYBV are almost of same strength (Figs 8a and b), unlike the seasonal fluctuations at this site (Fig. 4c), whereas at WS seasonal and diurnal signals in TXWS and TYWS agree fairly well in their characteristics (Figs 4b and 8c and d). From analysis of the diurnal tilt signals, we can not rule out either of the mechanisms mentioned above. Since rather large diurnal signals are observed at WS, where only some bushes are present and the groundwater level is deep, thermoelastic deformation of the ground appears to be the overwhelming effect here. At site BV, water consumption of the chestnut tree might still produce significant diurnal pore pressure gradients in the shallow water table and thus noticeable tilt signals.

4.4 Episodic step-like tilt events

The tilt signals shown in Fig. 4 reveal some prominent step-like anomalies that are not associated with rainfall or earthquakes. Although we are not sure of the causes of all the anomalies, we have no reason to believe that they are due to instrumental problems, mechanical or electronic, instabilities in tiltmeter-ground coupling, or external anthropogenic disturbance. By far the largest such anomalies have occurred at site WS. Three examples are presented in Fig. 10 (the events of Figs 10a and b can also be identified in Fig. 4b). The first anomaly lasted for about 40 min and had a total amplitude of 22 μrad with inverse signs for TX and TY. A somewhat smaller event happened a week later, with 10 μrad amplitude and an orientation mostly in TY in the opposite direction to previously, and again 5 days later, with 5 μrad amplitude and now positive signs in both tilt components. Other irregularities seem to have occurred in subsequent weeks.

Fig. 10(b) shows a step-like anomaly of amplitude 12.5 μrad that happened from between 15:00 and 16:00 hrs on New Year’s Day in 1997, in opposite direction to the largest event in Fig. 10(a). The rather strong variations of diurnal period, seen on the preceding days, are probably thermally induced which is backed by STWS data. The upper few centimetres of the soil were frozen during these days, which could have resulted in direct quasi-periodic stress on the casing of the tiltmeter borehole. Other significant tilt alterations visible in Fig. 10(b) might also be caused by soil freezing or thaw effects. Fig. 10(c) displays a much more gradual step-like tilt anomaly of amplitude 4 μrad, occurring over a time span of slightly more than a day. Similar events seem to have occurred 23 days earlier and 18 days later (less pronounced in TYWS).

Despite there being no direct evidence from other observational parameters, such as recordings from tiltmeters installed nearby, we think that displacements associated with fault movements along the Erft Fault system at about 5 km distance, perhaps stimulated by instabilities from the massive mining induced drainage, could have caused these strong tilt anomalies.
The tectonic component of the Erft Fault activity is characterized by a long-term movement rate of order 0.1 mm yr\(^{-1}\) for the Pleistocene and of about 1 mm yr\(^{-1}\) for the Lower Pleistocene, inferred from geological observations at the fault (Ahorner 1968). The mode of tectonic fault movements in the LRE, coseismic or non-seismic, such as creep, or a combination of both, has recently been a subject of discussion (e.g. Meghraoui et al. 2000). Tectonically induced creep events in tilt data have repeatedly been observed near major faults in California (Johnston et al. 1976; McHugh & Johnston 1976; Mortensen et al. 1977; Wesson 1988 and references therein). From observations obtained in a local geodetic GPS-array on a

Figure 8. Evidence of diurnal tilt fluctuations at sites BV (summer 1996 and winter 1997; a and b) and WS (autumn and winter 1997; c and d). Signals from top to bottom are: air pressure (AP), tilt variations in x and y orientations as in Fig. 2(b,c) (TX, TY), tiltmeter temperature (TT); and ground water temperature (GWT), change in height of the well water table (WL), rainfall (RF) for (a) and (b), or soil temperature (ST) for (c) and (d). Tilt signals have been deprived for linear trends. Figure parts (b) and (d) show data for the same period.

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kilometre scale in the same area, Campbell et al. (in preparation) report vertical and horizontal displacement rates of centimetres per year. If extrapolated to a reference length between some 100 m and 1 km, the strongest tilt signal of roughly 20 μrad (Fig. 10a) corresponds to a relative displacement of 2–20 mm, an order of magnitude which would be compatible with the geodetic findings. Except for short-term ground deformation caused by the passage of seismic waves from distant earthquakes, amplitudes of non-identified tilt signals in the frequency range $10^{-8} - 10^{-2}$ Hz seem not to exceed ±2 μrad, which testifies to the stability of the tiltmeter instruments and their installations.

5 TRANSFER TO CHANGES IN ELEVATION AND GRAVITY

Except for the latter type of tilt phenomena, the ground deformation signals described in this paper appear to be typical for unconsolidated sedimentary material in the depth range from the surface to 5 m, and for periods from hours to years. The magnitudes of meteorologically and hydrologically induced strains at these depths exceed that of the solid earth tide by a factor 10–100 (e.g. Tanaka 1969; Harrison & Herbst 1977; Wyatt & Berger 1980; Kümpel 1982b; Wyatt et al. 1982). Further enhancement in resolution of surface geodetic techniques like GPS, levelling and gravity surveys may therefore be hampered by such natural ground movements.

In principle, ground tilting and changes in elevation or gravity are independent quantities which can not be evaluated by monitoring one or the other. Yet, they are often correlated because ground tilts at shallow depths are usually associated with rotational ground movements including vertical displacements, which themselves are linked to changes in gravity. In fact, as the various types of ground deformation discussed above are not restricted to a single component of the deformation tensor, a tilt signal that is seen as inclination of a vertical reference does, at least partly, also exist as tilting of a horizontal reference, and vice versa. Displacements are generally not exclusively constrained in either the vertical or a specific horizontal direction. Tilt observations could thus be useful to assess the order of magnitude of variations in height and gravity changes, if some gross assumptions are being made.

Physically, tilt signals sensed by tiltmeters are superpositions of four main effects; (1) shear deformation in the ground; (2) rotational movements; (3) dynamic effects due to ground

Figure 9. Amplitude spectra of tilt signals from site BV (a and b) and site WS, together with spectra of soil temperature (c and d) for periods shown in Fig. 8. Spectra were obtained by FFT with Hanning window for data sampled at 5 min intervals (a and b) and 10 min intervals (c and d), respectively.
accelerations that lead to inertial movements of the sensor liquid in the tiltmeter; and (4) changes in the direction of the plumb line due to Newtonian attraction from mass displacements in the surroundings. Close to the stress-free surface, vertical shear strains can not exist; instead rotational movements may occur. Horizontal shear strains will only result in tilts (for tiltmeters using the plumb line as reference orientation) if lateral mechanical heterogeneities exist near the tiltmeter. Dynamic tilt effects can be ignored if analyses are restricted to signal periods high above the eigenperiod of the tiltmeter. This is the case with all the signals considered in this paper, except for those resulting from microseismic noise and seismic waves. Tilt effects due to Newtonian attractions of substantial mass displacements are generally several times lower than directly induced ground deformations, as can be deduced from Green functions of loads on the Earth’s surface (Farrell 1972; Jentzsch 1997). In many cases, rotational ground movements with non-zero vertical displacements are therefore the dominating signal constituents contained in the recordings from shallow depths.

Much uncertainty exists about the wavelength of a deformation signal. The effective base length $l$ of the tiltmeter installation imposes a fundamental limit on what can be detected (Agnew 1986). If the wavelength of a deformational signal is $l$, the measured response will be proportional to $\sin(2\pi l/l)(2\pi ll/\lambda)$, which is close to 1 for small ratios $l/l$, but goes to zero for $l\ll l$. Signals with wavelengths less than $l$ are largely filtered out, so are in practice ignored although they do exist. For signals that do appear in the recordings it is unclear whether their wavelengths are of the size of the instrument’s baselength or arbitrarily longer. Only clusters of a greater number of tilometers or of instruments with a variety of baselengths allow assessments of the true wavelengths.

Taking all this into account, we can still attempt to estimate from tilt observations the order of magnitude of possibly related height and gravity changes. At least, such assessments can be considered as scenarios for potentially occurring effects due to ground dynamics. Fig. 11 is a diagram combining the relevant quantities. It displays the relation $T = \arctan(\Delta h/l_0)$ between tilt angle $T$, horizontal baselength $l_0$ and vertical displacement $\Delta h$. For small angles, as is the case here, $T = \Delta h/l_0$. The borehole tiltmeters we are using sense ratios $\Delta h/l_0$, so horizontal displacements over a vertical baseline ($l_0 = 0.85$ m). The two ratios will generally be different but approach each other the more rotational movements dominate over vertical shear strains. The parameters along the oblique lines are $\Delta h$ and its conversion into a change in Bouguer gravity (i.e. $-308.6 \mu\text{gal} \ m^{-1} + 2\pi G \rho \Delta h$; $G =$ gravity constant) assuming a subsurface density $\rho$ of 2590 $\text{kg} \ \text{m}^{-3}$. When a change in elevation is converted into free air gravity, a height increase of 1 m would typically correspond to a decrease in gravity by 308.6 $\mu\text{gal}$ (3086 $\text{nm} \ \text{s}^{-2}$).

Referring to $\Delta h$, when comparing tilt signals and height changes involves several drastic simplifications: $\Delta h$ is not necessarily the maximum height change that is associated with a tilt signal of strength $T$, nor is it the minimum that could be seen by a GPS system. On the one hand, any translational component in the ground displacement vector is not detected by the tilt instrument, including vertical shifts, and unless $l$ is much larger than $l$, the recorded tilt signal amplitude is smaller than the true one. On the other hand, a GPS antenna may be placed in the centre of a rotational movement, i.e. at a place where no local height change occurs. Apart from the involvement of mass attraction, conversion of height changes into gravity variation is more straightforward.

Fig. 11 also shows the magnitude of the tilt signals presented in this study. As the outer annular space of the borehole casings has been cemented, the effective baselengths may be somewhat larger than 0.85 m. The sizes of observed signals range between 0.1 $\mu$rad which is the tiltmeters’ resolution and roughly 100 $\mu$rad. Except perhaps for the supposed creep events and the superannual trends, we have no reason to believe that the wavelengths of the tilt signals could be larger than several times...
the tiltmeters’ baselength. GPS observations in the LRE are revealing height changes from millimetre to centimetre size per year, at station spacing from kilometre to some tens of kilometres (Campbell et al., in preparation). For comparison, they are also included in Fig. 11, as are the gravity changes recorded by Keysers & Kümpel (2000) and Keysers (2001) on the kilometre scale with resolution 10 mgal and seasonal variations up to 40 mgal.

Whereas the maximum rates in yearly height changes seen by the GPS measurements are obviously too small to induce gravity signals that could be discovered by repeated field gravity surveys, they are, in principle, consistent with tilt variations on a regional scale. However, investigations by others have shown that signals from shallow borehole tiltmeters are widely different from those of geodetic levelling over baselines of tens to hundreds of meters, i.e. that tilt rates can not be extrapolated from short to much larger baselines (Agnew 1986). Another uncertainty when comparing such signals results from different accuracies over the time scales of the observations: In our case, long-term stability for GPS data has been confirmed over 7 years; the scale factor for the gravity readings has repeatedly been calibrated throughout the observation period of 2 years; yet direct control of the long-term stability of the tiltmeters and their installations is lacking.

Beyond the experiences with the data from the LRE, Fig. 11 can be used for assessing the order of magnitude of deformational ground noise affecting the resolution of GPS and gravity measurements. If the tilt signals we have observed reflect typical ground displacements at shallow depths, and could be extrapolated to wavelengths up to, e.g. 10 times the tiltmeters baselength, GPS measurements may be distorted on the 1 mm level by local meteorological or hydrological influence. Gravity readings, similarly, are affected on the 200 ngal level, which is not critical for mechanical field gravimeters but could be so for continuously operating earth tide or superconducting instruments (Wenzel 1997). To be more specific, rainfall induced effects could amount to ±0.1 mm per 10 m baseline in point elevation, or ±20 ngal in Bouguer gravity; diurnal strains due to thermal heating (and/or fluctuations in the water consumption of nearby trees) may imply signals of size ±0.01 mm per 10 m, or ±2 ngal, respectively. Enhancement of the resolution of such techniques may thus require recording of quasi-static deformation at shallow depths, allowing better identification and possibly correction of influential effects.

6 CONCLUSIONS

Several years of tilt recordings at three sites in the LRE have revealed distinct types of non-random signals reflecting natural ground deformation at shallow depths (2 m to 5 m). The various types of signals include long-term trends, seasonal fluctuations, rainfall induced tilts, diurnal tilt variations, and episodic step-like events. Maximum amplitudes observed for these types of ground tilting are 40 μrad yr⁻¹, 80 (peak to peak),
6, 4 and 22 μrad, respectively. As the nominal resolution of the tiltmeters we are using is 0.1 μrad, the signals are highly significant. By comparison with parallel recordings of soil and groundwater temperatures, depth to groundwater level, rainfall and changes in barometric pressure, and taking into account the different hydrological situations at the three sites, we conclude that the physical processes most likely provoking these signals are thermoelastic strains (seasonal and diurnal tilts), lateral gradients in pore water pressure (rainfall induced), and creep associated to a major active fault at near distance (episodic events). Reasoning of the physical mechanisms involved is based on plausibility assessments taking into account direct observational data, with temporal coincidence or coherence of signal constituents of different quantities, physical and hydrogeological understanding, and investigations reported by others.

The observations have been carried out to gain better insight into magnitudes, nature, and variability of background tilts, and to estimate limitations in resolution of vertical point position and microgravity surveys. Although ground tilt, elevation, and gravity are independent quantities they are usually correlated on the scale of microradians, submillimetres, and nanogals because deformation signals and associated ground displacements are not restricted to exclusive directions in space. Detailed observation of one of these parameters thus reveals qualitative information of the other two. This justifies to discuss the relevance of a signal seen in any of these quantities as a factor that limits observational accuracy of another one. Assuming a simple geometric relation between tilt and vertical displacement, and the observed tilt signals to be representative for baselines up to, e.g. 10 times the tiltmeters’ baseline, the data suggest that largest tilt signals could correspond to height changes of ±0.5 mm per 10 m yr⁻¹, or variations in Bouguer gravity of ±0.1 μgal yr⁻¹, respectively. This is close to the resolution achieved with modern GPS systems and mechanical earth tide or superconducting gravimeters installed at an observatory. Further enhancement in resolution of these techniques may require simultaneous recording of local ground deformation at the observation sites to obtain insight in influencing meteorological and hydrological effects.

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