Performance of a Deep Borehole Tiltmeter

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with 4 figures and 1 table

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Abstract: HARRISON, LEVINE and MEERTENS (1983) have described deep borehole tiltmeters that have been installed at two sites near Boulder, Colorado. One site is at the edge of foothills with closely spaced holes 6 m, 16 m and 33 m deep. The other site is 24 km to the east, in flat plains, where five holes have been drilled 33 m deep each and spaced from 30 m to 120 m apart. Using an observation series of 28 days, earth tides are being observed with a signal to noise ratio of almost 40 dB and with an apparent secular tilt of about 0.1 microradian. Data from the instruments are being used to construct the tidal admittance and to study the coherence among the instruments. The semidiurnal tidal admittance shows very good agreement with theory. Consecutive monthly admittances show a standard deviation of approximately 6 % and no secular trend. The instruments show no nonlinear behavior.

Keywords: borehole tiltmeter, tidal admittance, secular tilt, tilt tides.

1. Introduction

The measurement of crustal tilt can provide information on the elastic constants of the Earth and the response of the Earth to stresses of tectonic origin. It can also be used to study strains in areas of seismic or other activities.

We have deployed several tiltmeters at two locations near Boulder, Colorado. The first location is at the western edge of the NBS Department of Commerce site in Boulder, and the second is located approximately 24 km east of Boulder near Erie, Colorado.

Two tiltmeters were installed at the Boulder site, a pair of vertical pendulums in a 16 m borehole and a pair of horizontal pendulums in a 33 m borehole. The boreholes at the Erie site are all 33 m deep. We have been experimenting with several different instruments there including a vertical pendulum with feedback and a straight-line level.

In this paper we present the analysis of tilt data from the Boulder site, where instruments have been in continuous operation for more than nine months.

2. Preliminary data reduction

Most of the experimental problems in installing and operating the tiltmeters were solved by September 1980, and our analyses have been confined to data acquired after October 1980.

The first step in the data reduction was to remove the obvious errors produced by instrumental failures. The amount of data lost due to these causes was quite small and confined to approximately eight relatively short intervals that occurred on the average of about once per month. This total does not include a larger number of outages lasting only a few hours, which were filled by interpolation. Since the longer outages were relatively rare events, we decided to omit those periods from the analysis. The data were low-pass filtered and then decimated to one sample per hour.

The filters were symmetrical lead-lag filters constructed by applying a cosine-taper windowing function to the idealized low-pass filter response function. They were constructed to have unity gain from dc to approximately -80 dB cycles/hour. These filters have a half-width of eleven terms, and they are well suited to tidal analysis since they introduce no phase dispersion into the filtered data. The filters produce a time delay of an integral number of sample points. The amplitude response in the pass-band is smooth, so that calculated power spectra usually do not need to be corrected for the filter transmission function. The decimation to one sample per hour reduced the number of data points by an order of magnitude and made the subsequent task much easier. Since we are interested in low frequencies, no information was lost by this process.

The next step was to examine the power spectra of the data. Figure 1 shows the spectrum of the data from one of our horizontal pendulums running at the NBS site. Several points became immediately apparent:

i) The spectrum may be used to set a lower bound on the nonlinearity of the system. The largest single peak in the spectrum occurs at 1.93 cycles per day (the M_2 tide); any nonlinearity in the system is therefore generated at peak at 3.86 cycles per day. Since this is a relatively quiet part of the spectrum, excess power is a sensitive test for a nonlinear response function. However, any nonlinear response of this kind is too small to be measured. If the response of an instrument is R when the applied tilt is T, then

$$R = k(T + qT^2)$$

where k is the gain of the tiltmeter and $q < 0.005$.

ii) The power between the diurnal and semidiurnal peaks (i.e. near 1.5 cycles per day) is a reasonable estimate of the ultimate precision attainable in any tidal analysis. It is unlikely that power in this frequency band can be removed by fitting the tilt data with any simple function of the usual locally measured variables, e.g. local temperature, since the wavenumber spectrum is unknown in general. Using the observed spectrum, we find that the signal-to-noise ratio measured in this way is about 37 dB, so that we should be able to determine the tidal amplitudes with an uncertainty due to random low-frequency noise of about 1 %. The actual variance is larger than this (see 3.). We have not been able to totally eliminate other diurnal and semidiurnal effects, the most important of which is probably temperature.

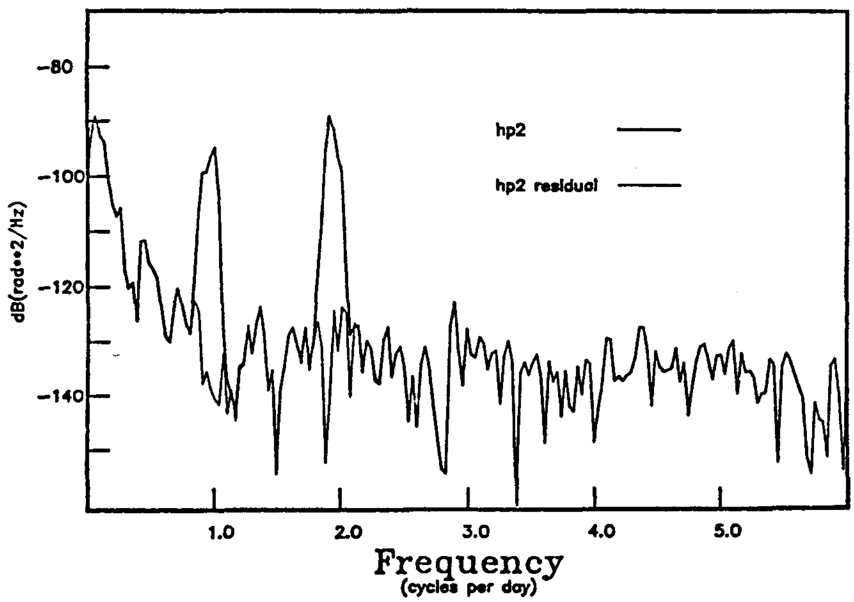

Fig. 1. Power spectra of the tilt data obtained using a horizontal pendulum at the NBS site in a hole 33 meters deep. The curve marked "residual" is the spectrum of the residual time series obtained by removing a least-squares fit of the tides to the data.

3. Tidal analysis

To compute the tidal admittance, we have compared the tilt tide with theory. Our previous experience (LEVINE, 1978; LEVINE &

HARRISON, 1976) has suggested that the ocean load may be quite different for the semidiurnal and diurnal components, and that the fitting program must allow for at least four degrees of freedom, i.e. two amplitudes and two phases. We have not been able to get a good estimate of the long-period admittance, however, because the data set would have to be broken into several shorter intervals to get estimates of the admittance in each frequency band, and our data set is not long enough.

To estimate the admittance, we have used an expansion of the potential in spherical harmonics (MUNK & CARTWRIGHT, 1966). The dominant contribution to the earth tide signal comes from the first non-vanishing term in the expansion, which has degree 2. There are three second degree functions; the first is a long-period term, the second term is nominally diurnal, and the third term is nominally semidiurnal. The third degree term, which is the dominant source of the the three cycle per day tide, is about 1 % of the second degree term at the latitude of the tilt installation and may be ignored when estimating the diurnal and semidiurnal admittances.

This method of analysis has many advantages over the Fourier decomposition methods , e.g. an expansion of the theoretical tides using the Cartwright-Taylor-Edden (1973,1971) potentials. It allows the admittance to be different for the long-period, diurnal and semidiurnal components, that is physically reasonable since both the ocean load and the correction for local topography are likely to be different among these widely disparate frequencies. At the same time, it does not allow different admittances for the components within one of these broad bands. But the method can be used to allow structure within a band by incorporating leads and lags in the fitting process, although we have not used leads and lags with any great success in our previous work. It is a physically reasonable first hypothesis that since an appreciable structure within a band must be caused by a high-Q resonant structure, such structures are unlikely. The same level of resolution can be achieved in the Fourier decomposition methods by summing the various diurnal components into one time series. However, the full Cartwright-Taylor-Edden potential contains several hundred terms and makes computation cumbersome. Consequently, the full-blown Fourier decomposition is only justified if one has physical reason to believe that the tidal admittance is in fact modified by a high-Q resonance, e.g. in our previous efforts to estimate the modification of the diurnal admittance due to the well-known core resonance as discussed in LEVINE (1978).

The actual calculation of the tidal admittance using our method proceeds in two parts:

i) The potential is calculated for each time at which a tilt tide value has been measured. The potential consists of five terms for each time. The five terms correspond to the amplitude of the n=2, m=0 term, the real and imaginary parts of the n=2, m=2 term (where n is the degree and m is the order of the spherical harmonic). Each term is multipled by its respective normalized spherical harmonic.

ii) Once the potential file has been created, a second task is to compute the least-squares coefficients between each time series component and the tilt data. One potential file can be used to fit all of the data sets from a single site. The least-squares parameters obtained in this way are a function only of the azimuth of the tiltmeter and the effective Love numbers at the site, so that these numbers can be converted to absolute admittances. As a check on this procedure, the entire process is repeated with a theoretical time series. We have chosen to use a series of data of 28 days to exploit the natural lunar-month periodicity of the tidal signal, and then we make nine estimates of the admittance using our data. The most stable admittance should be that for the semidiurnal components, since the dominant frequency is far removed from the usual perturbations due to thermal effects. Table 1 shows the results of our estimates of the admittance.

Table 1. Semi-diurnal admittance calculated from tilt data obtained using a horizontal pendulum at our NBS site in Boulder, Colorado. Each admittance is calculated using a time series 28 days long.

BLOCK NUMBER	TIME PERIOD	AMPLITUDE	PHASE(deg.)
1	Oct. 1980	1.06	-0.49
2	Nov. 1980	0.92	-7.60
3	Dec. 1980	1.01	-3.90
4	Jan. 1981	0.94	-4.50
5	Feb. 1981	1.03	-6.40
6	Mar. 1981	1.01	-3.10
7	Apr. 1981	0.92	-7.50
8	May 1981	0.99	-4.50
9	June 1981	0.98	-4.79
Avg.		0.984	-4.8
Std. Dev.		0.06	2.5

The admittances were calculated using data from one of our horizontal pendulums oriented at 232 degrees measured clockwise from north in a 33 m deep borehole at the NBS site, which is located at 39.992 N, 105.269 W.

The tidal admittance is surprisingly close to unity (a time series that corresponded exactly to theoretical expectations would have an admittance of unity and a phase of zero). This calculation contains no adjustable constants. These admittance calculations make no correction for ocean loads, local topography or cavity effects, inclusion of which may change our absolute admittances by a few percent. Nevertheless, the agreement is encouraging.

In the present context, the stability of the admittance is at least as important as its absolute value, since the stability is a direct check on the stability of the instrumental calibration. Although our preliminary analysis led us to expect random fluctuations in the admittance on the order of 1 %, the observed fluctuations are approximately six times larger, implying that the noise spectrum is not white, and that there is some residual sensitivity to extraneous effects, presumably of temperature. The amplitude of the extraneous signal necessary to account for the observed fluctuation in the admittance is on the order of five nano-radians. The instruments are located on the side of a rather steep hill, which slopes toward the southeast, so that the instrument side of the hill is exposed to the sun during most of the day. In view of the large surface temperature cycle (20^{o}C difference between day and night is not unusual), it is not unreasonable to assume that this is a real tilt of the hill. Our long period analysis, however, has suggested that these thermal effects are instrumental rather than real, and that our main effort is to find out which part of the instrumental system is responsible. The following conclusions are appropriate:

i) There is no secular change either in the calibration of the tiltmeter or in the elastic properties of the installation. Although the admittance is noisier than expected on the basis of the white noise model calculations, the admittance shows no secular trend.

ii) The instrument and the site show no observable nonlinear behavior. The strongest piece of evidence for this is the absence of any excess power at 3.86 cycles per day.

iii) The agreement between theory and experiment is surprisingly good. Although the site is poor in many ways, the

the observed admittances do not differ from what one would expect on the basis of classical tidal theory.

4. Analysis of long-period effects

The second part of our analysis has involved a study of the secular tilt records. We have no theoretical prediction of what these data should look like, so our analysis has been confined to observing whether there are any unreasonably large tilt episodes, and what are the effects of local temperature and rainfall.
We have used the data from two instruments located at the NBS site in Boulder in our investigations, a pair of vertical pendulums located in a borehole 16 m deep, and a pair of horizontal pendulums located in a borehole 33 m deep. The holes are spaced a few meters apart and located on the side of a hill at the eastern edge of Green Mountain. We would expect data from such a site to be modified by the topographic anomaly and the crustal inhomogeneity to produce secular tilts. Our previous work using a laser strainmeter in the Poorman Mine nearby showed secular strains on the order of one micro-strain per year and annual tilts at the micro-radian level are therefore not unreasonable. Tilt episodes showing a time derivative much higher than that implied by the overall annual rate or tilts much larger than a few micro-radians are suspect.

Figure 2 shows the data from the four tilt sensors. There are no tilt episodes in any of the records (compare Figure 4, WYATT & BERGER, 1980). This negative result is encouraging, because it reconfirms the hypothesis that carefully designed instruments (be they strainmeters or tiltmeters) yield records that are consistent with simple elastic models of a site. We attribute the smoother records obtained to better installation, as our instruments are deeper and more rigidly attached to the surrounding material than those at other sites (compare Figure 3, WYATT & BERGER, 1980). However, the tilt records we have obtained have been contaminated by other effects, as shown in the plot of the cumulative rainfall at the bottom of the figure. Vertical pendulums are sensitive to rainfall, while the horizontal pendulums are not sensitive to rainfall. We attribute this to the fact that the vertical pendulums are only 16 m below the surface. This effect can be seen in the subset of the data plotted in Figure 3.

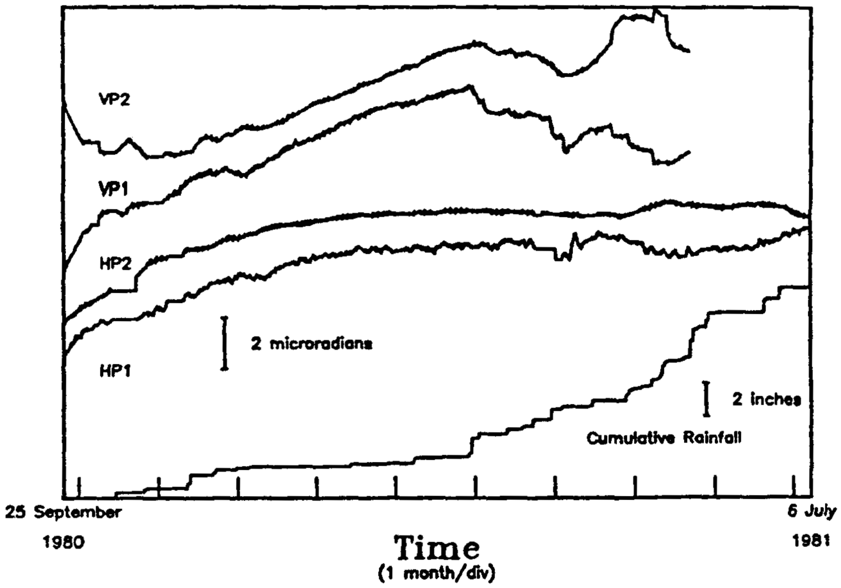

Fig. 2. Data from four tiltmeters at the NBS site. The traces marked VP1 and VP2 are data obtained using vertical pendulums in a hole 16 meters deep. The traces marked HP1 and HP2 are data obtained using horizontal pendulums in a hole 33 meters deep. The bottom trace shows cumulative rainfall taken from weather records. The vertical pendulums were moved to Erie late in May, 1981.

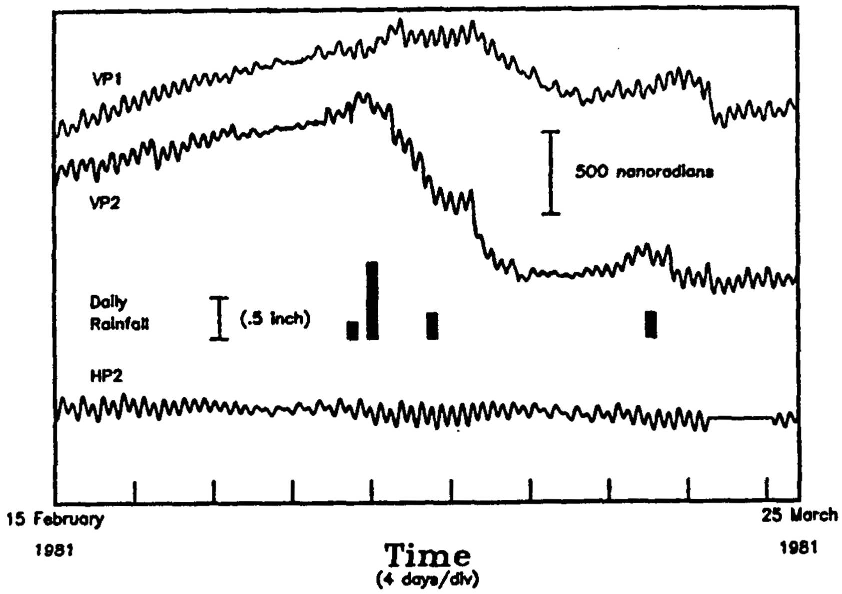

Fig. 3. A comparison of the sensitivities of different instruments to rainfall. The traces marked VP1 and VP2 are data from two vertical pendulums in a hole 16 meters deep. The trace marked HP2 is data from a horizontal pendulum in a hole 33 meters deep. Rainfall is shown by the black bars near the center of the figure.

It is not clear whether the overall drift is real. The two vertical pendulums show highly correlated long-term drifts, and the same is true for the horizontal pendulums. If these signals represent real tilts, they imply that both tiltmeters are tilting along axes almost exactly midway between the two sensors. However, it is more likely that the two sensors in each capsule are responding to some external event, although what this is is unclear.

Figure 4 shows a section of the same data sets plotted with the local temperature. The situation here is quite confusing. Channel one of each instrument is sensitive to temperature, and channel two is not. It is unlikely that these signals represent real tilts, since channel one of the vertical pendulum has been installed with its sensitive axis along an azimuth of 218 degrees (measured clockwise from north) while channel one of the horizontal pendulum has its sensitive axis along an azimuth of 142 degrees. These two azimuths are almost orthogonal. Both channels are nominally identical in all respects. We have not come up with a model for this effect. An examination of the temperature sensitivity of the system is our highest priority task at the moment.

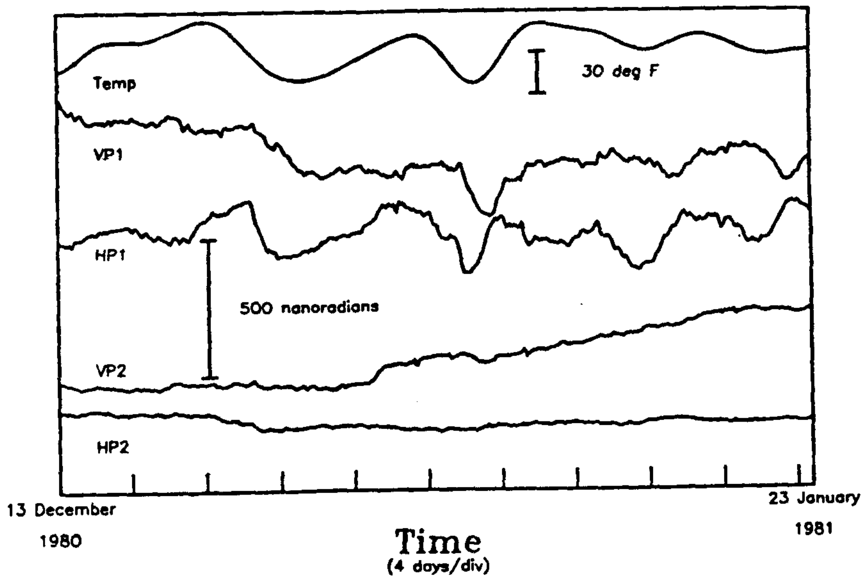

Fig. 4. Tidal residuals from four tiltmeters at the NBS site. The traces marked VP1 and VP2 are data from two vertical pendulums in a hole 16 meters deep. The traces marked HP1 and HP2 are data from two horizontal pendulums in a hole 33 meters deep. The top trace shows lowpassed surface temperature.

Our long-period results are summarized as follow:

i) An instrument placed in a hole 16 m deep is definitely sensitive to rainfall. There is no question that instruments must be deeper than this. Our evidence to date has suggested that 33 m is deep enough.

ii) Even in an instrument 33 m deep, there is a small residual temperature dependence on one channel that remains unexplained. Note that the second, nominally identical channel shows no such effect. It is possible that this signal is generated by a true thermally induced tilt, but we regard this possibility as unlikely. Otherwise, it would have required that the instruments have one sensitive axis exactly aligned along the direction of the thermal tilt and that the thermal tilt be in a different direction at the two depths. Some as yet undiscovered asymmetry in the instrument is probably responsible.

ACKNOWLEDGEMENTS

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DISCUSSION

Q: Do you have an idea of the depth of the ground watertable as well as of the effective pore volume just above the ground watertable? (Kümpel)

A: The ground watertable depth is a few meters below the ground level. We do not know, however, the effective pore volume. The instruments are located in Pierre shale. (Levine)