Design of a Deep Borehole Tiltmeter

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with 2 figures

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Abstract: A deep borehole tiltmeter has been developed which can be operated below the near surface layers to reduce the influence of meteorological effects. This is relatively inexpensive to build and to install. A 15 cm diameter borehole is cased with steel irrigation pipe and has a stainless steel instrument compartment 10 cm in internal diameter at the bottom of the hole. The tiltmeter is contained in a 2 m stainless capsule held against the sides of the hole with flat springs. The tilt sensors are mounted on a platform which can be leveled by means of motors controlled from the surface, allowing for hole deviations of up to five degrees from the vertical. A number of different tilt sensors have been used on such platforms. Simple pendulums and horizontal pendulums have so far yielded the best results. A depth of 33 m is normally used, although this is not a critical aspect of the design, because the electronics are inside the instrument capsule. The instruments are capable of operating unattended for long periods of time at tidal sensitivity; results of our tidal measurements can be found as well in these proceedings.

Keywords: borehole tiltmeter, secular tilt, tilt tides, vertical pendulum.

1. Introduction

At the time of the Eighth International Symposium on Earth Tides in Bonn, it was clear to many of us that there are important advantages to making earth tide tilt observations with borehole tiltmeters, and that many applications--such as the investigation of elastic inhomogeneities in the crust or earthquake prediction--would require deploying a considerable number of these instruments. We therefore set out to develop a borehole tiltmeter which would be relatively cheap to build and install; this not only meant building an inexpensive tiltmeter but it also meant using a small diameter hole and not going any deeper than necessary.

2. Borehole design

The holes we use are nominally 15 cm in diameter and 33 m deep. After the hole is drilled, a steel casing 135 mm in diameter with a 6 mm wall is pressed into the hole. The casing is shipped to the

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site in lengths of six meters, where it is welded into a continuous watertight pipe as it is lowered down the hole. The casing is sealed in place by means of cement poured into the bottom of the hole before the casing is inserted, and around the sides of the casing after it is in place.

The steel casing terminates at the bottom in a stainless steel section that is 2.3 meters long and which is used to hold the tiltmeter capsule. The bottom section is 11.5 cm in outside diameter, and it has a wall thickness of 6 mm. The top of this section has a transition section to the standard carbon steel pipe which constitutes the rest of the casing.

The bottom section is closed at its lower end by a plate welded on in the shop. A hemispherical knob is welded to the inside of the bottom plate to support the weight of the tiltmeter capsule.

3. Instrument capsule

The instrument capsule is a 1.8 meter long stainless steel tube which is closed at the bottom and has a pair of contact points and a flat spring welded on near its top and a second pair with a second flat spring near its bottom. The top of the capsule is sealed with a cap attached by screws and that contains an O-ring. The cap has a water-tight opening for the electrical cable to pass through, hooks for attaching the lifting cable, and a post for attaching the orienting rods.

The capsule was designed to minimize tilt-strain coupling due to cavity effects. HARRISON (1976) has shown that there is no cavity effect if the side of the borehole is used as a reference axis for the tiltmeter, and only a small effect if the center of the bottom of the hole is used as one reference point. The capsule is raised and lowered by hand in a few minutes using a stainless steel lifting cable attached to the top cap.

The length of the capsule also improves the coupling between the tiltmeter and the Earth by increasing the effective lever arm from a few centimeters (the length of the tiltmeter) to approximately two meters (the length of the capusle).

Figure 1 shows the capsule installed at the bottom of the borehole.

4. Capsule orientation

To compare the tilts recorded by different instruments or to compare the tidal tilt with theory, it is necessary to know the orientation of the tiltmeter. Magnetic sensors inside the capsule which sense the direction of the Earth's magnetic field cannot be used in this instance since the casing is magnetic. The capsule itself is not visible from the surface, so that we cannot determine the orientation by sighting on the capsule from the top of the hole.

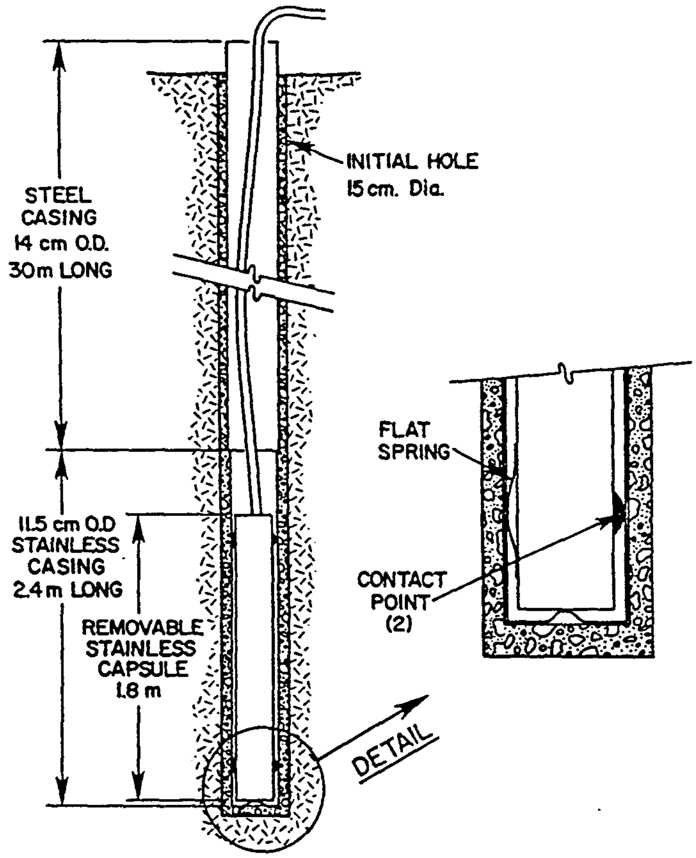

Fig. 1. A schematic diagram of the tiltmeter capsule installed at the bottom of a borehole 33 meters deep.

We have developed a system involving a series of light rods to determine the orientation of the capsule at the bottom of the hole. A post is welded to the top cap of the tiltmeter capsule with a flat side oriented so that the normal to the flat side is along the axis of one of the tiltmeters. Additional sections of rod are attached as the capsule is lowered. The first section attaches to the post on the capsule using a trapped ball and a detent to provide an easily removable coupling; subsequent sections bolt together with small screws. Each section is notched so that it can only be attached in one orientation. After the orientation of the top notch is determined using a transit and a compass, the entire series of rods is removed from the capsule by simply lifting gently to disconnect the bottom rod from the tiltmeter capsule.

This method has been used to determine the azimuth of instruments at the bottom of holes 33 meters deep with an uncertainty of about 1°. It is difficult to extend this technique to holes much deeper than 33 meters since the weight of the rods becomes appreciable, and the capsule becomes very difficult to handle.

5. Leveling platform

The leveling platform mounts inside the tiltmeter capsule and is used to support and level the tilt sensors. It is supported on a three-point kinematic mount. Two of the supports are screws connected to small motors. These motors are driven from the surface and are used to re-zero the instrument. The leveling platform has a range of approximately five degrees in any direction, so that the instrument must be vertical to within five degrees to start with. This limited re-zeroing capability imposes some constraint on the drillers, but the required tolerance can be met in 33 meter deep holes.

Figure 2 shows the tiltmeters and the leveling platform.

6. Tilt sensors

All of our instruments use mechanical tilt sensors. The sensors are pendulums mounted on fine wire suspensions, manufactured by Larry Burris of Instech, Inc. We have experimented with three types of sensors: simple pendulums 5 cm in length, small horizontal pendulums with a one-second free period, and a rather complex "straight line level" with a free period of three seconds. Our best results to datehave come from the horizontal pendulums, and we expect to use this type of sensor in our future instruments.

In all of the sensors the pendulum is placed between two fixed plates separated by about 1 mm to form two arms of a capacitance bridge. The other two arms are formed by two fixed impedances, traditionally the center-tapped secondary of a carefully balanced transformer. Two precision resistors are used to complete the bridge. If the two outer plates are driven out-of-phase by a 21 kHz ac signal, the signal at the center plate has a magnitude proportional to the deflection of the center plate from the electrical midpoint of the system (i.e. from the postion at which the potential in the gap is the same as the mean of the outer plate driving voltages), and a phase (relative to the driving signal) giving the direction of the deviation.

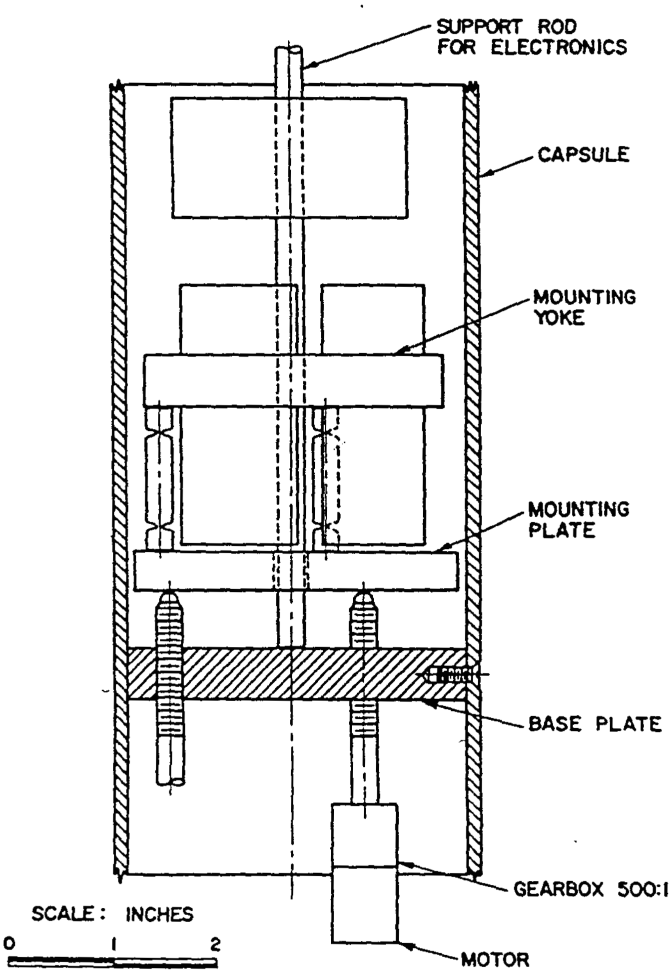

Fig. 2. Scale view of the tilt sensors mounted on the leveling platform inside of the capsule. The electronics package is above the tilt sensors inside the capsule and is not shown. Also not shown is the thermal insulation.

7. Tiltmeter electronics

Since both the amplitude and phase of the signal at the center plate carry information, we use a phase-sensitive detector to derive a voltage proportional to the tilt. The reference for the phase detector is obtained from the drive signal to the outer plates. The signal input to the phase-sensitive detector is driven by a preamplifier having a gain of several thousand. The actual gain of the instrument is set by running the tilt sensor on a test table and adjusting the gain to yield an overall sensitivity at the output of nominally 2 volts/micro-radian.

The electronic boards are designed and built by Jerry Larson of Maryland Instrumentation.

An equally difficult problem is the sensitivity of the system to fluctuations in the parasitic capacitances in the circuit (especially in the components that drive the outer plates) and between the connecting wires and ground. The capacitance between the center plate and either end plate is of order 3 pf, and a full-scale tilt, of order 5 micro-radians, results in a change of only about one part per million in this capacitance. Thus the entire system must have stray capacitances whose values change by less than a small fraction of a picofarad, and in practice, this requirement is far more stringent than the need for high electrical gain. We have addressed this requirement by keeping the system as small as possible and by placing the entire electronics package in the temperature-stabilized environment at the bottom of the hole.

The drive voltage for the outer plates is obtained from a small step-up transformer. The secondary of the transformer drives a pair of matched resistors to ground; in the circuit, the bridge is formed between the two capacitances of the tilt sensor and the two precision resistors, and the balance may be trimmed by inserting a small potentiometer if desired. Although we have not found this to be desirable, it has been necessary to adjust the relative phase of the two outputs so that the two plates are driven exactly out of phase. Unless this is done quite carefully, the signal at the input state does not go to zero even at the electrical center due to the appreciable quadrature voltage. The quadrature voltage may be large enough to saturate the input stage, if the system is sufficiently out of balance, thereby limiting the sensitivity of the system. The trimming capacitors required to cancel the quadrature voltage are on the order of a few picofarads so that lead dress is critical. The entire circuit is enclosed in a shielded box to minimize changes in the stray capacitances. Nevertheless, it is possible that some of our long-term tilts and some of the residual sensitivity to temperature changes are caused by changes in the values of some of these components with a resulting change in the balance point of the capacitance bridge.

8. Digitizing systems

Every hole has its own digitizer. The most important advantage of the digitizer is that it eliminates the need for transmitting analog tilt information on the surface where it is subject to noise pickup. It also increases the isolation between holes and prevents large ground loops between widely-spaced instruments. The digitizer in each hole is made up of an analog multiplexor, an analog-to-digitizer converter, and a control section which is made up of approximately 25 integrated circuits.

The digitizer communicates with the recording system via two optically isolated coaxial cables using a bit-serial transmission system. The transmission system is the same as ordinary RS-232C except that the voltage levels are standard TTL levels rather than the bi-polar levels used in the RS-232C protocol. By optically isolating the cables, the instrument is decoupled from the ground at the recording system which may be located several hundred meters away.

The Boulder site is connected by a dedicated telephone line to a PDP 11/34 computer on the University of Colorado campus. This computer interrogates the data loggers every 6 minutes and stores the values on disk. At the Erie site (24 km from Boulder), the data loggers are interrogated by a local microprocessor which stores up to six hours of data. The data are transmitted to Boulder over a radio link once per hour.

9. Power supply

The power consumption of the electronics package described above together with the digitizing system is approximately 7 watts. This is somewhat more than can be conveniently supplied by batteries. All of our existing sites have commercial power nearby. The power supply will be a restriction on site selection for the foreseeable future.

The data logger boards and the DC-DC converter that supplies power to the tiltmeters suspend in a plastic capsule about 5 m into the borehole from the surface. The DC-DC converter allows us to define a completely independent ground system for the tiltmeters, thus isolating them from surface electrical noise.

10. Summary

We have developed a borehole tiltmeter that is capable of operating for long periods of time at tidal sensitivity. In addition to the tiltmeter and its associated electronics, we have constructed appropriate ancillary hardware to acquire and analyze data from many widely separated instruments.

We currently have six of these instruments in operation. Results to date are described in a companion paper in this volume.

ACKNOWLEDGEMENTS

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