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Earth tides and their place in geophysics (summary)

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The experimental study of tidal phenomena in the solid Earth has been pursued for a century and, in particular, the last 15 years since the I.G.Y. has seen a spectacular growth in activity. The geophysical significance of the work has remained limited however, and it is necessary to study possible reasons for these shortcomings.

Work in the U.K. on tilt and gravity variations has helped to identify some of the relevant problems associated with the philosophy of instrumentation and its deployment, calibration, experimental repeatability, and analytical procedures. Here the importance of the oceanic influence is clear, whereas elsewhere it has not always been accorded sufficient attention.

The future of the discipline may lie in a decline in interest in body effects and a greater concentration upon the mantle, the crust and their inhomogeneities in which experimental and theoretical studies proceed in parallel.

Introduction

Measurements of tidal changes of tilt and gravity in the solid Earth have been made for many years now with the original objective the determination of the tilt attenuation factor, $1+k-h$, and the gravimetric factor, $1+h-\frac{3}{2}k$. On the basis of two equations and two unknowns it was hoped to investigate the rheology of the Earth. The case was convincing in that the forcing function, the tide-generating potential, was already precisely known and consequently presented a circumstance uncommon in geophysics. We have now experienced a significant application of effort to the discipline at more than 300 observing stations, but the facts are that the output is confusing and disappointing. The optimism of 50 years ago has been shown to be misplaced, since the geophysical interpretation of the results has been limited.

More recently there have appeared theoretical Earth models based on evidence provided by the seismic, geotectonic and geological disciplines. It is ironic that in spite of differences in their assumptions as to the structure of the Earth, nevertheless the models are able to produce global values of the Love numbers within a range of only 2 to 3 %. At this juncture it is therefore necessary to ask ourselves pertinent questions concerning the problems which have delayed the advance of the Earth tide discipline towards its primary goal. It is also necessary to learn from the experience gained and to consider whether it is possible that our particular brand of instrumentation and expertise might be better applied to a different range of problems.

Observational anomalies

The problems can best be assessed by an examination of the published results for the harmonic tidal constituent M_2 which, being associated with lunar time scales, should be the constituent least disturbed by meteorological influences. The bulk of the evidence comes from Europe (Melchior 1966, 1970) and the U.S.S.R. (Ostrovsky & Matveev 1970) where, despite intensive activity during the last 15 years, the general conclusion is that there exist large unexplained anomalies of ± 40 % in north–south tilt, ± 15 % in east–west tilt and ± 8 % in gravity

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variations. The phases of M_2 tilt typically exhibit discrepancies of ± 10°, although gravity is again more consistent with anomalies of, say, ± 2°.

Little progress has been made towards explaining these anomalous results, particularly the highly susceptible north–south tilt. Such detailed discrepancies cannot be explained by the interaction of marine tides in view of the distance of most of the observing stations from the coast. Neither does solar heating provide an obvious answer. Indeed a basic uncertainty remains as to the scale of the problem. Some workers have interpreted results in terms of major structural blocks or regional inhomogeneities (Tomaschek 1952; Nishimura 1950; Melchior 1967). A recent suggestion of considerable interest (Bower 1971) concerns the possible influences on the measurements due to tidal effects in aquifers. At the other extreme the microscale problem of interfacing instruments with a rock surface have been studied (Lennon & Vaníček 1970).

Assessment of instrumentation

With the experimental evidence showing large discrepancies it is natural that instrumental performance should receive close scrutiny and more particularly that the reliability of calibration should be investigated.

The difficulties of absolute calibration of gravity meters are well known and usually involve some linear interpolation from the milligal to microgal range. The problem of the calibration of horizontal pendulums has led to the development of the crapaudine dilatable (Melchior 1966) and also to a more detailed study of the equations of motion (Vaníček & Lennon 1972). At present, for both gravity meters and tiltmeters, the best assessment of performance can be obtained from comparative exercises between different instruments and different instrumental types preferably with different calibration systems.

The dispersion in the measured phases can also be investigated by comparative exercises. This is a particular problem for the horizontal pendulum since the phase depends critically on an accurate determination of the varying azimuth of the pendulum beam (Skalský & Pícha 1969). Clearly such phenomena divert interest towards the water-tube tiltmeter, the development of servo-nulling devices, perhaps based upon the crapaudine (Vogel 1970), and to the vertical pendulums, such as the Graf–Askania device.

The work at Bidston suggests that an uncritical acceptance of current instruments can be expected to achieve an accuracy of ± 4 %, but with greater attention to procedures, particularly calibration procedures, ± 1 % might be feasible. It seems therefore the instrumentation presently available is with care capable of a satisfactory performance and we must look elsewhere for an explanation of the range of the experimental results.

Coherency investigation

After failing to find an explanation of the anomalies in terms of instrumental performance, it is natural to turn to an examination of the installation procedures and perturbations due to the site. Clearly, this is a very difficult area to examine and most of the questions which arise can only be answered by a long and detailed experimental programme. In the case of a tiltmeter, for example, what is the optimum method of installation and the optimum base length such that the recorded tilt is typical of the regional signal? Most Earth tide stations are in mines which are often excavated along geological discontinuities. More generally, perhaps, the cavity in which tidal measurements are taken represents a discontinuity in the Earth's crust which may perturb the measurements in some way. The use of niches and pillars and their position relative to one another and within the chamber may be of importance. Recent developments of excavating special shafts or boreholes (Beaumont, Hyndman & Keen 1970; Ostrovsky & Matveev 1970; Flach & Rosenbach 1971) are of importance in this context since they represent new ways of sampling the tidal signal.

The only way to a solution of these problems is by an intensive experimental investigation involving many different instruments, recording at different azimuths where appropriate, and at different points within the same station. Only in this way can there be built up a picture of the scale of coherency of the tidal signal within a particular station. From this stage one can progress to nearby installations to examine the coherency of the regional signal. This is the philosophy of the experiments now being conducted at Llanrwst, North Wales. Also at the Bidston instrument test bed, comparative exercises have been performed involving nine tiltmeters of five fundamentally different types and three gravity meters of two fundamentally different types so that some insight can be gained into signal variations in time and space both real and instrumental. These experiments have in fact led to a deeper understanding of some of the problems discussed. The vault measures 15 m east–west by 2.5 m north–south but even on this micro-scale differences of tilt are observed according to position within the vault. The recorded M_2 tilt in the east–west azimuth and the M_2 phases in both azimuths are consistent even for instruments of vastly different design. In the north–south azimuth, however, differences of the order of 20 % in M_2 tilt are consistently observed between one end of the vault and the other.

Similar experiences have been noted at geophysical stations, in particular at Kondara, U.S.S.R. and at Sclaigneaux. We may be dealing here with the station cavity problem but one thing is clear, namely, the danger of using a single pair of tiltmeters at a station and from them drawing conclusions concerning regional geophysics. This may well be the cause of many of the anomalous results.

Future developments

The renowned gravity profile across the U.S.A. by Kuo, Jachens, White & Ewing (1970) shows that with care consistent and useful results are now obtainable from a tidal gravity survey and such work is in progress in the U.K. For tiltmeters, however, an intensive coherency examination is required before progressing to the wider regional concept and work along these lines must be encouraged for, in the long term, it may be in tilt that the greatest potential exists.

More fundamentally, the question which must be asked is should not experimental work attend more closely to variations in space, to heterogeneity problems and indirect effects in their own right since it is in this area, rather than the global concept, that the experimental techniques developed hitherto have shown themselves to be sensitive. Only one major drawback exists, namely that in this new regional discipline the experimentalist must acknowledge that the new forcing function, which produces his signal, for example the marine tides, is not precisely known. Experience has however taught him that this fact has to be faced in any case.

Indeed it is in this area that theoretical models have made rapid progress in the last few years especially in the development of multi-layered loading models to describe the effects in the range 0 to 30° from the load. Bower (1970, 1971) and Pertsev (1970) have developed models based on the work of Slichter & Caputo (1960) and Longman (1963). More recent advances have been made by Farrell (1972) and Beaumont & Lambert (1972). These models demonstrate the sensitivity of the measurements to crustal and upper mantle structure and, moreover, the finite-element model of Beaumont & Lambert can be developed further to include lateral inhomogeneities. In this respect the value of the improvement of tilt measurements must be emphasized since for a marine site the tilt loading signal represents a far greater proportion of the total measured signal than does the corresponding loading signal in other tidal measurements.

The preliminary comparisons of the M_2 tilt and gravity observations in the U.K. with the loading models of Bower are most encouraging. It appears that there has now been reached a stage of active interaction between theory and experiment. The models can identify the most interesting areas for experimental exercises and, in the case of tilt, the optimum recording azimuths. In this way we can look forward to a growing understanding of the geophysics of the crust and mantle and a new phase of solid tidal science in which effective applications of knowledge could be made in the oceanographic and geodetic fields.

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