SHORT NOTE ON THE MEASUREMENT OF THE ACCELERATION OF GRAVITY AT SEA AND ON AN ITALIAN GRAVIMETRIC CRUISE IN THE TYRRHENIAN SEA

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1. — Before VENING MEINESZ invented, constructed and used his appliance for the *measurement of the acceleration of gravity in a submerged submarine* with so much success, *i.e.*, until within quite recent years (1923), the pendular measurements required for the accurate determination of such data have been made on terra firma only (or on the ice of polar seas). Thus the eight elevenths of the Earth's surface over which are spread the waters were not covered by these precise geophysical observations. Mere acquaintance with the objects to be attained by gravimetric observation will demonstrate how important is this enormous gap and shows how much honour is due to VENING MEINESZ for the method which he proposed and to the Navies of the world which, in spite of great sacrifices and heavy expense, have made possible such observations in practical form.

There is no need to insist here on the general object of gravimetric observations and it is sufficient to point out how, using observations of gravity as basis, the particular form of the geoid which corresponds to the distribution of the observed gravity may be obtained by calculation.

It should be observed that the values of gravity which are used in such calculations are not those obtained directly by experiment, but those which have been reduced to a particular level ; in this case sea-level.

If it be assumed that the irregularities in the values directly observed are entirely due to visible causes of alteration the above reduction is obtained, first, by making the reduction due to the *variation of gravity in accordance with altitude* (reduction in open air of gravity to sea-level) and then by making allowance, in the observed value, for the influence of solid (and liquid) masses above sea-level in the immediate neighbourhood of the station (reduction of BOUGUER).

But the values thus reduced have a still more abnormal and irregular trend than the unreduced values and this leads to the conclusion that the causes of the irregularities which interfere with the calculation of the form of the geoid are not only visible ones, but are also partly invisible ; and the influence of these invisible causes tends in itself to compensate the effect of the visible masses and therefore is of the opposite sign to that of the effect of the latter.

Once the existence of *invisible* causes of perturbation has been established, it is necessary to find a hypothesis as to the internal constitution of the earth to allow this effect of compensation of the external visible masses to be taken into account.

The hypothesis which, so far, has given the most suitable reductions which lead to values of gravity most in accord with geodetic determinations and consequently with the directly deduced shape of the geoid, is that of *isostatic equilibrium* of the Earth (PRATT). More accurately stated it is assumed that the various blocks of the earth's crust (*sial*) which are of lesser density, and in which silica and aluminium predominate, float, so to speak, on a homogeneous plastic material (*sima*) which is denser, in which silica and magnesium predominate and which constitutes the core of the Earth. Thus under every external mass there is an equivalent deficiency in mass due to the displacement of the denser plastic material and conversely each deficiency in external mass is compensated by an excess of the above-mentioned plastic material.

And hence gravimetric observations, quite apart from their geodetic use, have become of the greatest importance in geophysics also. In fact each set of observed values in a definite area (reduced, if necessary, to sea-level, account being taken of the above hypothesis) which does not agree with the theoretical values deduced from the actual dimensions of the geoid, must correspond to an unbalanced state in the floating of the blocks of the terrestrial crust. Knowledge of this unbalanced state makes it possible to ascertain the extent of the forces which cause it, the tendency of the crust to rise or fall, the location of the surfaces of fracture which support two contiguous blocks of the earth's crust in different states of equilibrium and to determine the relation which exists between these surfaces of fracture and volcanic and seismic phenomena.

All the above is a very interesting and attractive problem which fully justifies the attempts which have been made to extend gravimetric observations to the sea, they being already numerous on land, and to vindicate the very considerable expenditure which the various Navies have incurred to make such observations possible.

2. — Before the researches and experiments of VENING MEINESZ had made the determination of acceleration of gravity at sea possible by means of pendular observations, various attempts were made by other methods which will now be briefly recalled. For example, among the most remarkable methods, that conceived by MOHN, commended by such a great authority as HELMERT and applied by HECKER for the determination of the relative gravity (1) first in the Atlantic and later in the Pacific and the Indian Ocean should be quoted. This method is based on the fact that it is possible to determine the pressure of the atmosphere at sea in two different ways, one by means of the *hypsometric barometer* and the other by the mercurial barometer.

By bringing fairly pure water to the boil and determining the temperature of the water-vapour whilst the water is in a state of ebullition by means of a thermometer, it is possible to determine the pressure of the air as a function of this temperature at the moment of observation. This pressure may be expressed (and is in fact expressed in ordinary physical tables) by the corresponding height of a column of mercury at 0° C. and under the gravity corresponding to latitude 45°.

By measuring this atmospheric pressure with a mercurial barometer and applying suitable corrections to reduce the observations taken to the temperature of 0° C. and to eliminate all causes of perturbation which may have any effect on the observed height of the barometric column, the atmospheric pressure is obtained, expressed as the corresponding height of a column of mercury at 0° C. and under the gravity which exists in the latitude φ of the observation spot.

Let P_{45} be the atmospheric pressure obtained from the hypsometric barometer and P_φ that obtained from the mercurial barometer. The following relation should be atisfied :—

$$\frac{g_\varphi}{g_{45}} = \frac{P_{45}}{P_\varphi}$$

as well as the relation :—

$$g_\varphi - g_{45} = g_{45}\,\frac{P_{45} - P_\varphi}{P_\varphi}$$

Though the principle of this determination is very simple, in practice its application meets with serious difficulties on account of the extreme accuracy with which the determination of the two fundamental elements musts be made, *i.e.*, the temperature at ebullition of the water-vapour and the height of the barometric column. It will be easily understood, therefore, that the accuracy of the measurements made by HECKER's method, even with his imposing collection of instruments (*six* barometers, of which some were fitted with photographic recording appliances and *six* hypsometers), is very much inferior to that of the method used on land which is based on pendular observations.

DUFFIELD, who, in 1914, used three such appliances during a voyage to Australia, made experiments which were based on the same principle or at any rate on a similar one.

In one of his appliances HECKER's hypsobarometer was replaced by an aneroid barometer; in the two others the measurement of relative gravity was made by balancing the pressure of a constant mass of air at a temperature of 0° C. against a column of mercury of variable height according to gravity.

One of the latter appliances designed by DUFFIELD, with improvements by H. DARWIN and SCHUSTER, was used by the British physicist to obtain measurements of relative gravity with an accuracy of ± 10 milligals (1).

3. — Results which are certainly far more accurate and are *comparable to those obtained on land*, may now be obtained by the VENING MEINESZ pendular apparatus used in a submerged submarine. The principle of this apparatus is as follows :—

If a pendulum be made to oscillate and if an acceleration of short duration be applied to its support, the character of the oscillation is momentarily disturbed ; at a certain acceleration the pendulum may even be brought to rest or, at another, its oscillation may be amplified, provided suitable relations of phase and amplitude are obtained. In every case, the resulting acceleration is the algebraic sum of the original acceleration and of the acceleration which is added to it, and the movement of the pendulum will be that which results from the sum of the two accelerations. For this reason the pendulum was not found suitable for use on board ship before the researches of VENING MEINESZ.

If instead of a single pendulum a couple of pendulums be observed which have fairly close periods of oscillation and are both oscillating in the same plane and, further, are suspended from the same support, and if the difference of their angular elongations be recorded by suitable appliances, it is possible to eliminate from the record the influence of horizontal disturbing accelerations (vertical accelerations are very small in a submerged submarine). This acceleration produces the same disturbance in the angular elongation of the two pendulums and consequently its effect disappears from the difference. The registration of the difference in the angular elongations of the two pendulums thus comes to the same thing as registering a *single imaginary pendulum* which is undisturbed by the accelerations, provided that they are not too great *as is the case in a submerged submarine.*

In the VENING MEINESZ apparatus (as also in a later and similar English apparatus designed by LENOX-CONYNGHAM) three pendulums m_1, m_2 and m_3 are used, all suspended from the same support and oscillating in the same plane (the longitudinal plane of the submarine in the case of the VENING MEINESZ apparatus).

These pendulums are coupled in pairs, *i.e.*, a suitable system of mirrors oscillating with the pendulums makes a photographic record (by means of a pencil of light which is reflected from these mirrors in succession) of the difference in angular elongations covered by the first and second pendulums (which constitute the imaginary pendulum $m_1 - m_2$) and the angular elongations covered by the third and the second pendulums (which constitute the imaginary pendulum $m_2 - m_3$). This ingenious optical recording system is based on the principle of double reflection (principle of the sextant). If a pencil of light be doubly reflected, it emerges at an angle from its original direction which is double the angle between the two mirrors. According to this principle, in the present case, it is possible to record at any moment the difference in the angular elongations of the two pendulums. The appliance for recording is placed in a small box under the pendulum-case; it includes a shutter which is worked by a chronometer and which interrupts the pencil of light every half second. Thus it is possible (by methods similar to ordinary chronometrical methods) to obtain from the record itself the duration of the oscillation of the two imaginary pendulums $m_1 - m_2$ and $m_2 - m_3$. The record is made on a strip of paper which moves rapidly at the beginning and end of the operation, but slowly during the intermediate part of the observation. The complete record lasts about thirty minutes.

4. — By means of this appliance VENING MEINESZ has already carried out an enormous number of gravimetrical observations in submarines in all the seas of the world, using the means placed at his disposal by the Netherlands and United States Navies.

In the preceding number of this Review (see *Hydrographic Review*, May 1931, page 254), Professor TENANI outlined the important conclusions of a geophysical character which VENING MEINESZ has been able to reach, particularly from the observations carried out with the very effective help of the Dutch Navy in the East Indian Archipelago, which, tectonically speaking, is one of the most active localities in the world.

These results have been observed with great interest in Italy where there are areas which are no less interesting than those already explored by VENING MEINESZ. For this reason an agreement was made, at the Stockholm meeting of the International Union of Geodesy and Geophysics, between Captain ROMAGNA-MANOIA, Director of the *Istituto Idrografico della Regia Marina*, representing the Royal Italian Navy, General VACCHELLI, President of the Italian Geodetic Commission, and Professor VENING MEINESZ, that the last-named should carry out a series of gravimetrical observations in the Tyrrhenian Sea, with the object of making a geophysical investigation of the type of that which he had already made in the East Indies. The programme of these observations, which was commenced on 23rd July, 1931, by the departure from Genoa of the submarine *Vettor Pisani*, is very comprehensive and is limited only by the period of availability of the apparatus which has been kindly lent by the Dutch Geodetic Commission. Professor VENING MEINESZ personally made the *departure station* at the observation pillar of the *Istituto Idrografico* which has already been connected from the point of view of gravimetry, with Potsdam and Padua. He has handed over the apparatus to Professor CASSINIS, of the Italian Geodetic Commission, and to Commander DE PISA, of the Italian Hydrographic Service, who are undertaking the observations during this cruise.

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NOTE

(1) It is well-known that at the numerous field stations made to determine the distribution of gravity on the Earth's surface, g is not measured directly (as this direct measurement is usually limited, on account of the difficulties in making it, to the very few observatories which are well-provided as to staff and material) but instead, the ratio of or difference in the value of gravity g_s at the station under consideration and the value g_b at some station which is selected as the *base station*; in such cases the observation is really the *determination of relative gravity*.

Among the base stations Potsdam must be mentioned (latitude 52°22',86 N., longitude 13°04',06 E. G., altitude 87 m.) for which, according to the absolute measurements made by F. KÜHNEN and Ph. FURTWANGLER, the value has been obtained:

$$g = 981{,}274 \textit{ gals} = 32{,}1940 \textit{ ft/sec}^2.$$

with a mean quadratic error of about:

$$\pm 3 \textit{ milligals} = \pm 0{,}0001 \textit{ ft/sec}^2.$$

The means required and the difficulties met with in the measurement of relative gravity $g_s - g_b$ are not very great. The value of the relative gravity may be determined with great accuracy when the measurement is made with great precision by pendular observations. (This accuracy is represented, now-a-days, in the measurements made on land by a mean quadratic error of: ± 1 *milligal* $= \pm 0{,}00003$ *ft/sec*^{2}.)

The *gal* (which is an abbreviation of GALILEO) has been adopted by international convention to indicate the unit of acceleration ($= 1$ *cm/sec*^{2}); the *milligal* is one-thousandth part of a *gal*.

10^3 *gal* = the unit *leo* (the abbreviation of the name of Leonardo DA VINCI).

1 *gal* $= 1$ *cm/sec*$^2 = 0{,}0328084$ *ft/sec*^{2}.