LARGE-SCALE INVESTIGATIONS OF THE DEFORMATION

BEHAVIOUR OF LAYERS OF ICE SHELVES

by

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ABSTRACT
    For the investigation of time-dependent vertical deformation of upper layers of ice shelves loaded by accumulated snow and/or structures a large-scale field test was started in 1980-81 at Georg von Neumayer station (70°37'S, 8°22'W), Antarctica. Specially developed base plugs were fixed to the bottoms of 5.0 and 10.0 m deep bore holes by melting and refreezing the surrounding firn. The deformations of the snow firn layers will be measured between these base plugs and metal plates placed on the snow surface during installation. The bore holes are kept open by tubes of different diameters in order to allow for load-induced vertical deformations of snow and firn. Some measurements are directly affected by the presence of the station. The design of the measuring device, the procedure of installation, and the measurement of deformation are described. The results of calculations of deformation and measurements of first settlement are presented.

INTRODUCTION
    During the German Antarctic Expedition in 1980-81 a research programme was begun for the investigation of the time-dependent vertical deformation of the upper layers of ice shelves. This depends on the rheological behaviour of the snow or firn. The equipment for long-term observation was installed during the construction of Georg von Neumayer station (70°37'S, 8°22'W) on Ekström Ice Shelf.
    Using an extensiometer the vertical deformation of these upper layers caused by snow accumulation and/or the dead weight of structures will be observed during the next decade. The measuring points are located underneath and outside the buildings.
    The snow and firn layers under consideration are now 5 to 10 m deep, and after 10 a they may lie approximately 12 to 20 m deep, depending on snow accumulation and drift. During the season 1981-82 the installation of measuring devices is planned at 30 to 50 m depths in order to study ice layers.
    The test methods and the measuring device are described. First settlement data are analysed and compared with deformations computed under the assumption of constant compressive viscosity.

1. DENSITY-DEPTH RELATIONSHIP
    The general increase of snow density with depth results from compression of snow by the load of the annual accumulation. This density increase will occur also from other loads such as structures. Snow density is an important factor governing the mechanical

behaviour of snow, firn, and ice including the compressive viscosity n_1.
    During the 1980-81 expedition cores were taken from bore holes down to 12 m on the Ekström Ice Shelf. The density of the snow samples to 10 m depth is shown in Figure 1 as depth-density curve b.
    In addition density values from Maudheim station (71°03'S, 10°55'W) are plotted in Figure 1, curve a (Mellor 1961). The reasonably good fit of both curves may be caused by similar climatic conditions at both places as far as the mean annual temperature and the annual snow accumulation is concerned. The values in Table I are taken from Mellor (1961) and Reinwarth and others (1982).
    Fig.1, curve c, gives some information on the variation with depth of the maximum grain size.
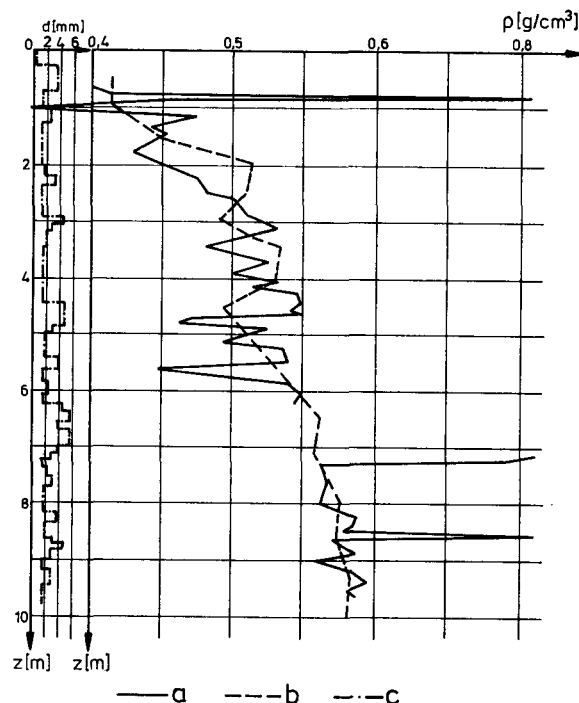

Fig.1. Depth-density curves: (a) Maudheim station, (b) Georg von Neumayer station, (c) stratigraphy at Georg von Neumayer station.

TABLE I. MEAN ANNUAL TEMPERATURE AND ANNUAL SNOW
ACCUMULATION AT MAUDHEIM STATION AND GEORG VON NEUMAYER
STATION

	Maudheim station	G.v. Neumayer station
Mean annual temperature	-17°C	-17.3°C
Annual snow accumulation	~75 cm	~73 cm

Besides the general increase of density with depth
considerable discontinuities were found in the snow
stratigraphy (Reinwarth and others 1982).

2. TEST METHOD

The measuring device specially developed for this
in situ investigation of vertical deformation is
shown schematically in Figure 2(a) and after instal-
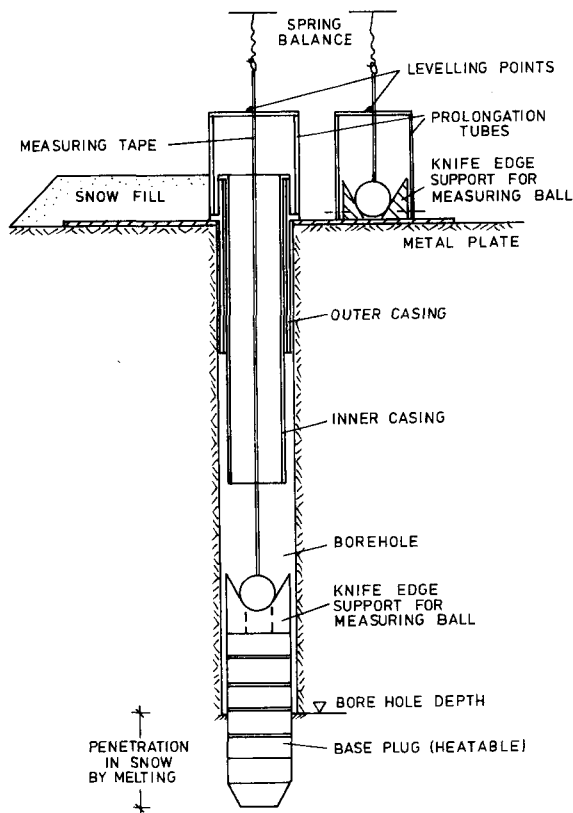lation in Figure 2(b). Essential parts of the extens-

Fig.2(a). Schematic drawing of the measuring device
for long-term observations of vertical deformation.

Fig.2(b). Measuring device after installation.

iometer are the base plug at the bottom of the bore
hole and the upper metal plate which is placed on the
snow surface during installation. After drilling the
bore hole to the desired depth the base plug is
placed at the bottom of the bore hole and heated
electrically. As the firn melts the plug sinks down
for about 20 cm. After the electric heating source
is switched off the plug becomes frozen into the
surrounding snow. The bore hole itself is lined with
tubes of different diameter which act as telescope
casings to permit free vertical movement of the
snow and firn without hindrance. The casings are
attached to the upper metal plate which serves as
the boundary of the firn layer under consideration;
the lower boundary is marked by the base plug.

Additional tubes are fixed to the upper side of
the metal plate. These tubes will be extended in
succeeding years to the new snow surface providing
access for measuring to the base plug and to the
metal plate. The distance from the base plug and the
metal plate, respectively, to the top edge of the
extension tubes will be measured by a calibrated tape
which has a heavy metal ball on the lower end, which
rests on the knife-edge support of the base plug. The
tension of the measuring tape is controlled by a
spring balance at its upper end.

These measuring devices have been installed at
ten sites (P1 to P10), and in four reference points
(F1 to F4, see Fig.3). The sites are located partly
underneath and partly outside the buildings. The
reference points, however, are positioned at a
distance of 100 m from the station to ensure that
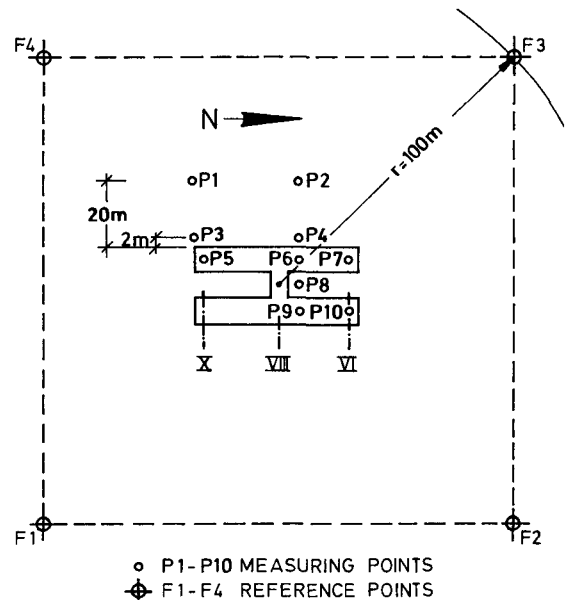the buildings do not exert any influence on the
measurements.

Fig.3. Position of measuring and reference points
near Georg von Neumayer station.

The measurement of the vertical deformation of
two snow/firn layers of different thicknesses is
shown in Figure 4. Loads due to snow accumulation or
to structure dead-weights generate time-dependent
vertical deformation by compaction of the snow.
Immediately after the installation and after a
certain time interval the distance between the base
plug and the upper metal plate is measured, and the
difference Δh of the two readings can be taken as the
vertical deformation of one snow layer ($\Delta h = h-h^*$).

This value Δh represents the deformation of the
whole snow and firn layer between the base plug and
the metal plate. The time-dependent variation of Δh
is caused by the loads and the rheological behaviour
of the material. In this way the Δh data incorporate
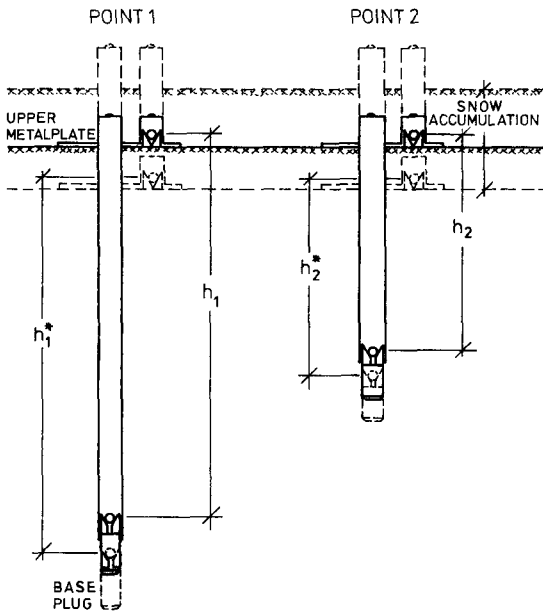
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POINT 1   POINT 2

Fig.4. Description of deformation measurements.

all processes that occur in situ, but cannot be simu-
lated in laboratory tests. Additionally the station
buildings act as loads one order of magnitude greater
than the annual accumulation, so that densification
is faster than it would be with normal snow accumu-
lation outside the station, for example at the
reference points.

Every year at least these measurements will be
repeated. From the measured deformation the change of
the mean density of the snow/firn layer under consid-
eration and the rheological properties of the upper
ice shelf layers can be calculated.

To measure settling rates from the station build-
ings during the winter period, when the reference
points outside the station cannot be reached, measur-
ing scales are installed in ten cross-sections on the
side walls of the main tubes.

3. FORMULATION OF THE DEFORMATION BEHAVIOUR

When considering the time-dependent compression
behaviour of ice-shelf ice, the Burgers model (Fig.5),
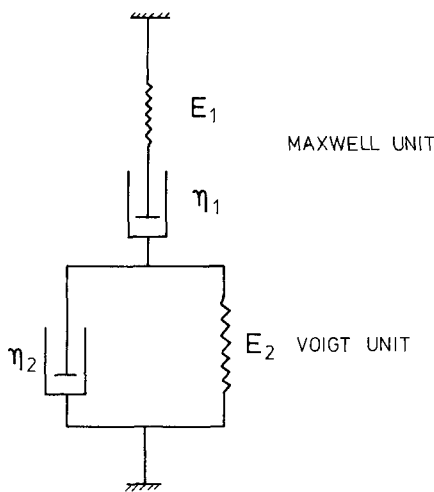which is a combination of a Maxwell unit and a Voigt

Fig.5. Burgers model.

unit can be used (Bader 1962, Mellor 1975). The
deformation derived from this model is

$$\varepsilon = \underbrace{\frac{\sigma}{E_1} + \frac{\sigma.t}{\eta_1}}_{1} + \underbrace{\frac{\sigma}{E_2}(1 - e^{-t/\tau})}_{2},$$

where σ is the load, E_1 the spring constant of the
Maxwell model approximately equal to Young's modulus
of the snow, E_2 the spring constant of the Voigt unit,
η_1 the viscosity, t the time, and τ the reference
time. In this equation, part 1 is related to the
deformation of the Maxwell unit and part 2 to the
relaxation deformation of the Voigt unit. This later
part can be neglected with regard to long periods
(Bader 1962). It is assumed also that the instantan-
eous elastic deformation $\varepsilon = \sigma/E_1$ can be neglected
because of the magnitude of the modulus of elasticity
E_1 appropriate to the snow density of the upper zone
of the Ekström Ice Shelf (Mellor 1975, Jessberger and
Dörr 1981). For the given conditions (small load,
high modulus of elasticity, sufficient loading time)
only the viscous deformation $\varepsilon = \sigma.t/\eta_1$ remains and
this depends linearly on the time and inversely on
the compressive viscosity η_1.

Ramseier and Pavlak (1964) reported experimental
results for the compressive viscosity (Fig.6), which,
according to Haefeli and Brandenberger (1968), can
also be calculated for a distinct location from the
depth-density relation. Appropriate viscosity values
calculated by the authors for Georg von Neumayer
station are plotted in Figure 6. These data compare
reasonably well with the η_1-ρ relation for Byrd
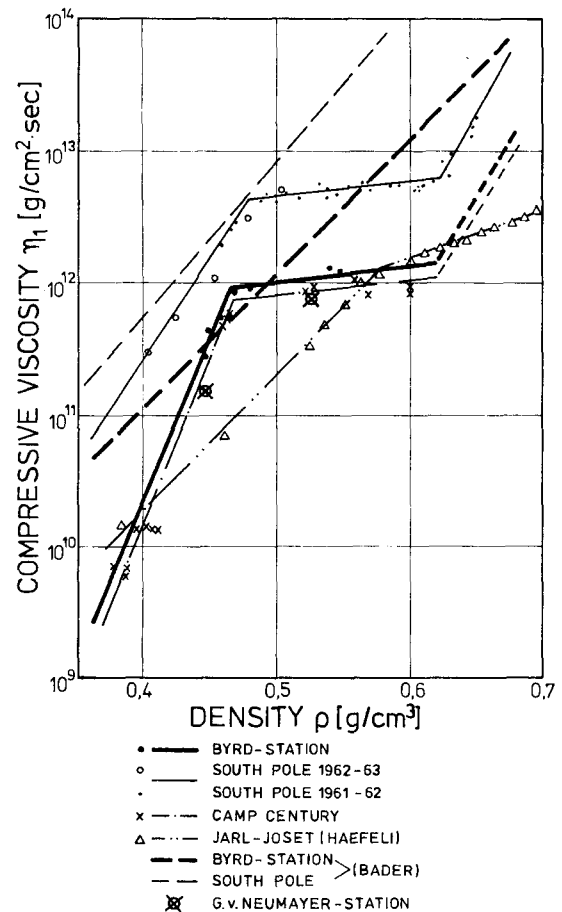station.

Fig.6. Compressive viscosity vs density (Ramseier
and Pavlak 1964).

4. CALCULATED AND MEASURED VERTICAL DEFORMATIONS

The following discussion refers to the east tube of the station, which has a ground area of about 50 x 8 m and a foundation pressure of roughly 50 kPa. Because of the viscous properties of snow and firn the vertical deformation of the layers underneath the tube will increase with time. During the Antarctic winter and summer of 1981-82 this behaviour was determined by measuring the differential settlement of the tube.
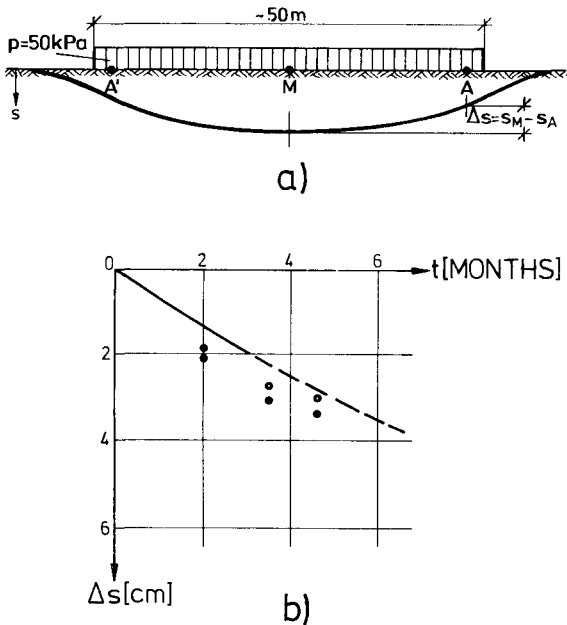

a)

Δs[cm]   b)

Fig.7. (a) Generalized settlement curve.
       (b) Time-dependent differential settlements.

The centre point M of the ground area in Figure 7(a) corresponds to cross-section VIII in Figure 3, the outer points A and A' correspond to cross-sections VI and X respectively. In Figure 7(b) the measured differences in the settlement of the tube are shown. The open and full circles belong to the differential settlement $(s_M - s_A)$ and $(s_M - s_{A'})$ respectively.

The calculation of the settlement of the tube at point M and A has been performed in the following way (Fig.8). The stress distribution versus depth was calculated according to Boussinesque down to the depth z = 20 m. The viscous strain ε_i of any chosen layer i is calculated to be

$$\varepsilon_i = \sigma_{zi} \cdot t/n_{1(i)}$$

where σ_{zi} is the vertical stress in the middle of layer i, t the time, and $n_{1(i)}$ the compressive viscosity depending on density (see Fig.6). The total settling of each point is

$$s = \sum_i \varepsilon_i \cdot \Delta z_i \, .$$

The different vertical stress distribution underneath M and A(A'), leads to the differential settlings

$$\Delta s = s_M - s_A$$

given in the line of Figure 7(b).

It should be mentioned that the vertical deformation of the firn causes an increase of density followed by an increase in viscosity. However, during the period of observation, so far, this change is not yet significant so that the assumption that the viscosity has been constant should be acceptable. The differences between the calculated and the measured Δs values are caused by the assumption made for the calculation and also by the procedure of the station construction. The comparison between calculated results and these first measurements is encouraging. These vertical deformation measurements, therefore, together with vertical magnetic probe extensiometer readings and inclinometer readings in special grooved deformable casings will be included in long-term observations made at the station.

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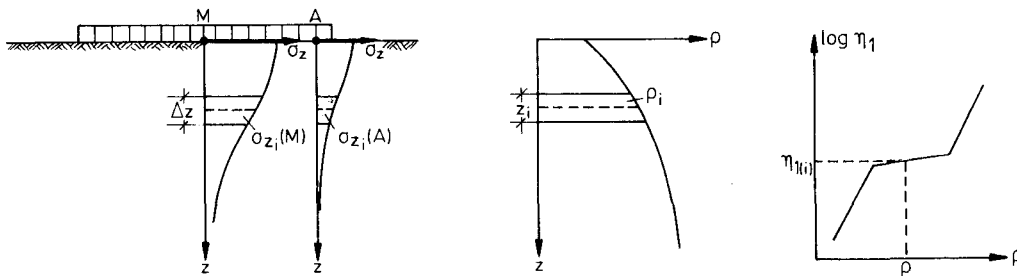
Fig.8. Process of calculation of settlements under loads on a viscous medium.