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Long-Term Measurement of Deformations in Concrete Tunnel Linings

Mesure à long terme des déformations dans le revêtement de galeries en béton

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Summary

Since October 1955 use has been made of internal concrete measuring elements to record deformations in the concrete linings of underground roadways in Dutch coal mines. These elements, in principle, consist of an electrical wire resistance strain gauge enveloped by silver foil. After a short description of this gauge details are given of the procedure of mounting the measuring elements and the method of carrying out the measurements.

Special attention is paid to the measures which proved necessary to maintain a high insulation resistance also during a long period of time. Mention is made of some troubles which were initially experienced and of the means with which they were overcome.

In conclusion, a few measuring results are discussed.

Sommaire

A l'aide d'éléments de mesure intérieurs on a effectué depuis Octobre 1955 des mesures de déformation dans les revêtements de galerie en béton des charbonnages néerlandais.

Les éléments de mesure utilisés à cet effet se composent en principe d'un extensomètre à fil résistant enveloppé d'une pellicule en argent.

Après avoir décrit brièvement ces éléments, l'article donne quelques détails de la technique de montage et de la réalisation des mesures.

L'attention est spécialement appelée sur les précautions à prendre pour maintenir durant une longue période une résistance d'isolement élevée. Quelques difficultés rencontrées au début sont mentionnées, les moyens grâce auxquels on a pu les surmonter indiqués.

La discussion de quelques mesures est donnée en conclusion.

1. Introduction

Reinforced concrete is often used for the lining of shafts and pit-bottoms in the underground works of coal mines. The determination of the dimensions of a lining is based on experience and on strength requirements derived from available load hypotheses for tunnels and shafts, e.g. those of Kommerell, Stini, Terzaghi, Caquot, Oberti, Mindlin, Labasse and others.

The author wished to enlarge his knowledge of this subject on account of the great number of existing hypotheses and the resulting uncertainty in this field, as welle as in view of the high construction-costs of tunnels and shafts, and the high standards of safety and reliability which must be maintained.

For this purpose, it was mainly essential to obtain reliable strain measurements, both external and internal, on such concrete structures, over a period of a few years.

The vibrating-wire concrete measuring elements then obtainable met with some technical disadvantages, while moreover the high price hampered a large-scale application. As technical disadvantages, especially with a view to their application underground, can be mentioned the limited measuring range and the lack of an intrinsically-safe measuring-box.

Hence the author undertook in 1953 the development of an internal concrete measuring element, while starting from the existing resistance strain gauge.

After a suitable measuring element had been developed in our laboratory and had been tested, through all kinds of experiments, for long-term accuracy and reliability, it was applied underground for the first time in 1955.

Some further improvements were afterwards made on the measuring element and its leads, which resulted in a lower vulnerability and a higher insulation resistance of the element under very moist conditions.

These internal concrete measuring elements, made in accordance with an agreement between Staatsmijnen and N. V. Philips, Eindhoven, have been manufactured and marketed by the latter under type-number PR 9 239 since early 1958. In close co-operation between the two companies some additional improvements were brought about in the design of the element, which were amongst others, beneficial to its insulation resistance.

2. Description of the internal concrete measuring element

The actual measuring element consists of a strain gauge which has an active length of about 8 cm and is enveloped by a watertight cover of silver foil (Fig. 1). This particular measuring length has been adopted in view of the heterogeneous nature of the concrete with its coarse gravel particles. The overall length of the measuring element is 20 cm and the element is provided with a compensating resistance. When embedded in the mass of the concrete, this element is insensitive to temperature fluctuations. It is therefore necessary to apply a temperature-independent resistance as a dummy, for which purpose a temperature-compensated strain gauge bonded to a steel strip was used.

The insensitivity of the embedded strain gauge to temperature fluctuations is absolutely essential for measurements to be carried out inside a thick-walled concrete structure. This is due to the fact that it is not possible to have a dummy which simply follows the same temperature fluctuations as the strain gauge, as is the case during normal measurements with bonded strain gauges.

The characteristics of the internal concrete measuring element are as follows :

Fig. 1 Internal concrete measuring element.
Elément de mesure intérieur.

Philips, type PR 9 239,
R = ca. 120 Ω,
k = ca. 2,
measuring length = 8 cm,
overall length = 20 cm,
thickness = $\frac{1}{4}$ mm,
width = 12 mm.

The measuring cable employed is 2 × 1·5 mm car cable equipped with a thick P.V.C. coating (type Draka, Amsterdam).

3. Methods of mounting internal concrete measuring elements

Two methods are available for mounting the measuring elements :

1. The element is installed in the shuttering under moderate tension (ca. $\frac{1}{2}$ kg), which is followed by grouting.
2. The element is first embedded in a concrete tile (Fig. 2).

The "measuring tile" is then placed inside the shuttering of the concrete to be measured, after which grouting takes place.

Fig. 2 Concrete measuring tile with embedded measuring element.
Dalle de mesure en béton avec élément de mesure encastré.

The first method calls for special care during grouting and is only applied when it is practicable and desirable to do so, e.g. in the case of creep or shrinking tests on concrete samples in a laboratory. In such cases the application of measuring elements has turned out to be an advantage over the application of other conventional measuring devices, such as dials, etc. When embedded, the elements are well protected, insensitive to vibration and practically free from hysteresis. Furthermore, measurements can be started at a very early setting-stage of the concrete, if desired.

The second method is to be recommended for practical applications, since the measuring tile is robust and easy to handle. When the tile has been incorporated into a concrete structure with dimensions many times greater than those of the tile, the measuring tile, and hence also the measuring element, will be deformed to practically the same extent as the surrounding concrete.

4. Manufacture of the measuring tile

The type of measuring tile used by the author measures 250 × 70 × 40 mm in size. The two widest sides have a "honeycomb" profile in order to improve the bond between the tile and the surrounding concrete.

The grout used has the following composition (parts by weight) :
cement : sand : gravel = 1 : 2 : 3,
water-cement ratio = 0·5.

The type of cement used is Encilite B ; the particle size of the gravel varies between 3 and 5 mm.

Neither the type of cement nor the age of the measuring tile at the moment of embedding appears to have a noticeable influence upon the measuring results. The age of the measuring tiles tested by the author ranged from two weeks to six months.

A steel mould for making ten tiles simultaneously was used, and this could readily be dismantled or assembled. The measuring elements are installed in this mould under a tensile force of from 0·5 to 0·6 kg. The procedure is illustrated in Figs. 3 to 5 inclusive.

Fig. 3 Mould with installed measuring elements and removed front plate.
Moule avec éléments de mesure. Plaque frontale enlevée.

Fig. 4 Grouting of measuring tiles.
Remplissage des moules.

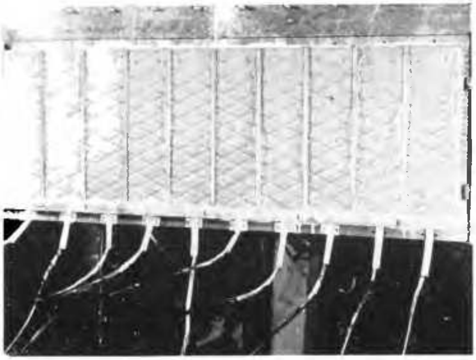

Fig. 5 View of hardened measuring tiles after removal of front plate.
Vue des dalles de mesure durcies, après l'enlèvement de la plaque frontale.

5. Provisions prior to embedding the measuring tiles

To check the insulation resistance as well as to prevent undesired desiccating effects, the measuring tiles were placed in a water tank immediately after dismantling and were kept there until the moment of embedding. The insulation resistance, which is $\geqq 10^4$ $M\Omega$, must not decrease in the meantime.

During preparations for embedment some insulation provisions are made. The concreting underground is usually done by the blowing method, whereby the grout is fed behind the steel shuttering in the form of a powerful jet. Initially it sometimes occurred that a measuring tile was pulled out of its position and the insulation coating of the cable was damaged by pebbles which were thrown against it. It sometimes also occurred that the measuring cable was damaged by some hard object during placing of reinforcement.

For these reasons the measuring cables were provided along the whole length (max. 8 m) with shrinking coating (Drakavita tube, grey, type 12, wall-thickness 0·25 mm, manufactured by Draka, Amsterdam). This yielded very good results.

However, as this procedure is rather time-consuming, it was later decided to accommodate the measuring cables within a P.V.C. tube of from 24 to 31 mm diameter (Stokvis, Rotterdam). This tube was cut open along its full length and contained 6 or 7 measuring cables, thus providing perfect mechanical protection. Only the two ends of the cable, which cannot be housed in the protective tube, are still provided with shrinking coating.

Under very wet conditions, however, this coating is still applied along the entire length of the cables. This procedure is very satisfactory.

In wet circumstances it was necessary to take some additional moisture-insulating measures with regard to the free ends of the cables (Fig. 6).

The Araldit used for this purpose is type 123 B with 954 N hardening agent. The cotton covering at the end of the core was immersed for about 24 hours in silicon oil.

6. Mounting of measuring elements

After the cables of the measuring tiles had been treated in the above way, the resistance and the insulation resistance of the tile itself were measured, while the latter was immersed in water.

During mounting, the measuring tiles were fastened to the reinforcement, on the right spot and in the desired direction by means of thin iron connecting-wire, which was inserted through holes at the four corners of the tile. The cables are preferably laid inside the concrete as far as the spot where the terminal box is placed and where they are drawn outside through a hole in the shuttering. The cables are led through a P.V.C. tube, which is fixed to a reinforcing rod every ½ to 1 m by means of insulating tape. This is done in such a way as to obtain for the tube the best possible protection against

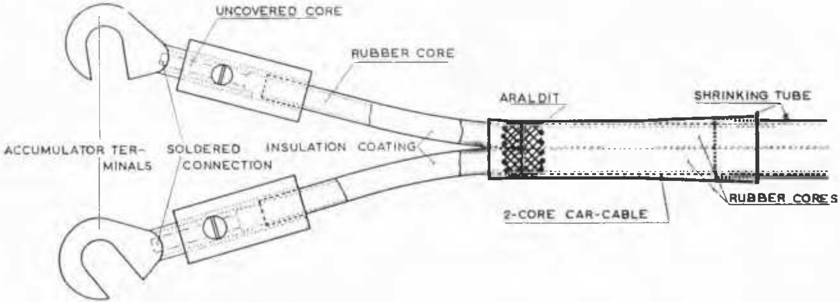

Fig. 6 Arrangement of end of measuring cable.
Tronçon terminal du câble de mesure.

damage by the powerful grout-jet or the vibrating needle or stirrer. The measuring cables should never be fastened with wire since the grooves thus caused in the P.V.C. coating greatly reduce the insulation resistance of the cables.

When a measuring cable has to bridge a free distance within the concrete, e.g. from the outside to the inside of a thick concrete lining, it is accommodated in a channel ([3) for the sake of mechanical protection.

The measuring elements are always placed in pairs and arranged tangentially (Figs. 7 and 8) *. In this way it is possible to measure not only the average tensile or compressive strain but also the variations in curvature of the concrete wall. The dimensions *a*, *h* and *b*, which must be known for this purpose, are measured after the tiles have been mounted (Fig. 7).

In order to eliminate capacitive and temperature effects, as much as possible, one dummy cable is embedded for each set of measuring elements measured from one terminal box. The length of the dummy cable is equal to the average length of the measuring cables of the set concerned. The two ends of the dummy cable end in the terminal box. During measurement one end is connected to the dummy resistance, the other to a strain meter.

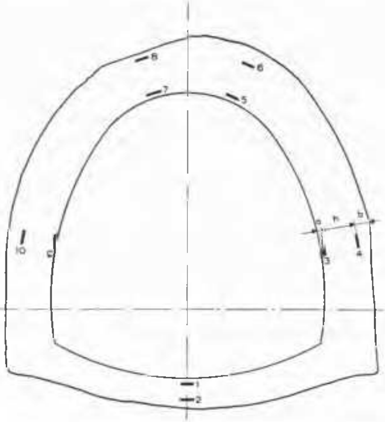

Fig. 7 Location of measuring elements in concrete lining of pit bottom.
Disposition des dalles de mesure dans le revêtement en béton du fonds du puits.

Fig. 8 Measuring element behind shuttering before grouting.
Elément de mesure derrière le cuvelage avant l'injection du béton.

The ends of the measuring cables, which are drawn outside through a hole in the shuttering, are accomodated in a cast-iron terminal box (fuse box, type 25 A, manufactured by Hazemeijer, Hengelo). They are introduced into this terminal box through a hole at the back, the inlet being sealed off temporarily with plasticine. The terminal box is bolted to the shuttering on two bushes which have been previously embedded.

When the shuttering can be removed after setting of the concrete, the terminal box is then taken away, and the ends of the measuring cables are pushed back carefully through the hole in the plate of the shuttering. Immediately after removal of the shuttering the terminal box is re-fastened to the concrete, after the ends of the cables have been introduced again into the box.

7. Provisions for long-distance measurements

When the cables are exceptionally long, it is possible for temperature fluctuations to cause unreasonably large errors in measurement. In that case it is necessary to install a complete Wheatstone bridge at each measuring-point. The active branch of the bridge remains the same, viz. the measuring tile, while the opposite branch is a temperature-compensated strain gauge. The other two branches consist of normal strain gauges which need not be compensated, but should have the same temperature coefficient and *k*-factor. These three resistances are bonded on a cast-iron strip, as this has about the same coefficient of expansion as concrete (ca. 10-11 μ strain/°C).

This strip is put into a watertight tube, which is embedded in the concrete near the measuring tile.

Under moderate temperature fluctuations, the measuring cables may be hundreds of metres long without unreasonable errors occurring.

As four outside leads are required for each measuring bridge, it is necessary to employ in this case a long multicore measuring cable. 48 cores are already needed for the use of e.g. 12 measuring tiles. However, when applying a tele-operated change-over switch, it will be adequate to employ only 4 cores.

Fig. 9 illustrates the design of switch used by the author, a telephone selector being used for this purpose (Uniselector, Siemens, London). These selectors, when commercially available, are operated by an electric coil. However, in view of the safety regulations applicable to coal mines it was much cheaper and more practicable to provide the switch with a pneumatic tele-operation system. The small metal bellows used for this purpose can be seen in the circular box (bottom of Fig. 9). The measuring cables leaving the concrete are introduced at the back of the rectangular box shown in Fig. 9. The 4-core cable leaves this box on the left, and the pilot-air line is connected to the circular box on the left-hand side of the bottom. The box shown in Fig. 10 is on the spot where readings are taken. The ends of the measuring cable, introduced at the bottom, are housed in this box, while being provided with accumulator terminals. A compressed air supply under a pressure of 6 atmospheres enters the left side of the box. After being reduced to 3 atmospheres, this air is admitted via a three-way valve to a pilot-air line which leaves the box on the right. When opening the valve, the switch shown in Fig. 9 is changed over to the next measuring element after about 5 seconds.

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* The photograph was taken at the time when the measuring cables were not yet housed in PVC-tubes.

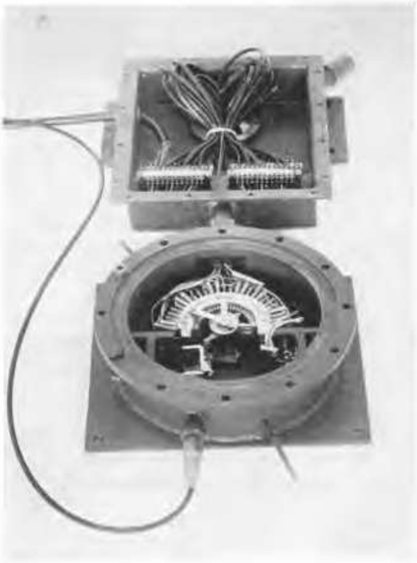

Fig. 9 Pneumatically-operated tele-switch for a number of embedded measuring elements with complete Wheatstone bridges.
Téléinterrupteur à commande pneumatique pour de nombreux éléments de mesure encastrés, avec pont de Wheatstone complet.

Fig. 10 Terminal box for tele-switch according to Fig. 9.
Boite de jonction faisant partie du téléinterrupteur de la Fig. 9.

This method of tele-measuring by means of a tele-switch has been applied by the author since January 1959 and has been most satisfactory.

Fig. 11 Strain measurement equipment in place underground
Mesure des déformations au fond de la mine.

8. Execution of measurements. A few measuring results

Fig. 11 illustrates how a measurement is carried out and how, for this purpose, the measuring box is placed on a transportable and folding frame, suspended from the terminal box.

Both the strain value and, for checking purposes, the insulation resistance against earth are measured during each measurement. If necessary, measurements are not started until the instruments have assumed the temperature of their surroundings. Moisture and dust deposited on the cable-ends are carefully removed with a clean dry cloth. The measurements are carried out periodically, varying from once per week to once every two months, depending on the rate at which variations occur. Since 1955 well over 40 measuring stations have been installed in underground works.

Fig. 12 shows a measuring station the results of which are given below in brief.

As the measuring elements are always placed in pairs, it is possible to determine the average tangential tensile or compressive strain ε_m as well as the curvature variation ΔC at the measuring point. This affords a picture of the tangential normal force and the bending moment at the station concerned.

The values for ε_m and ΔC are found as follows :

$$\varepsilon_m = \frac{\varepsilon_0 + \varepsilon_i}{2} \tag{1}$$

$$\Delta C = \frac{1}{R + \Delta R} - \frac{1}{R} = \frac{\varepsilon_0 - \varepsilon_i}{h} \tag{2}$$

The meaning of these symbols appears from Fig. 13.

Fig. 14 represents the strains measured at the measuring station shown in Fig. 12. The average strains and curvature variations obtained are incorporated into Fig. 15.

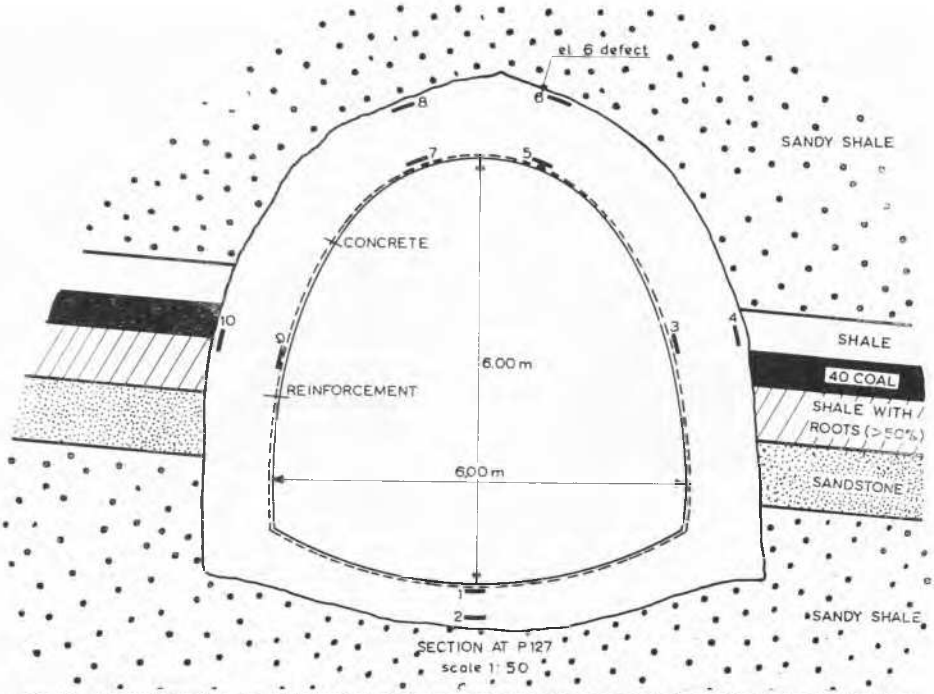

Fig. 12 Measuring-station at a pit bottom where the measuring elements are mounted according to the usual pattern.
Poste de mesure au fond d'un puits où les éléments de mesure sont disposés normalement.

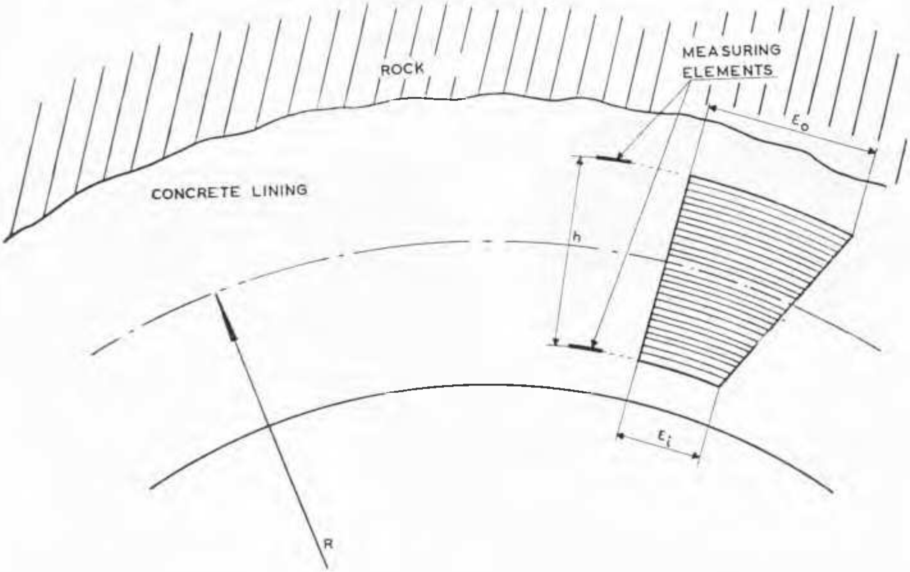

Fig. 13 Deformation of concrete lining.
Grandeur des déformations dans le revêtement en béton.

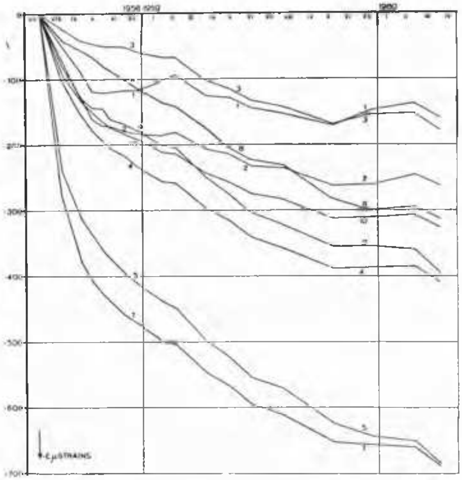

Fig. 14 Tangential strains measured at measuring station shown in Fig. 12.

Déformations tangentielles mesurées au poste de mesure reproduit à la Fig. 12.

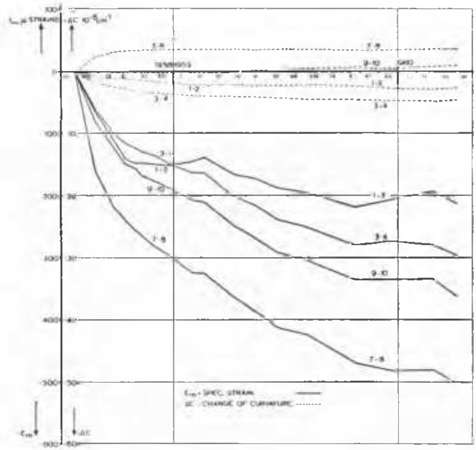

Fig. 15 Average tangential strains ε_m and curvature variations ΔC derived from Fig. 14.

Déformations tangentielles moyennes ε_m et variations de la courbure ΔC, dérivées de la Fig. 14.

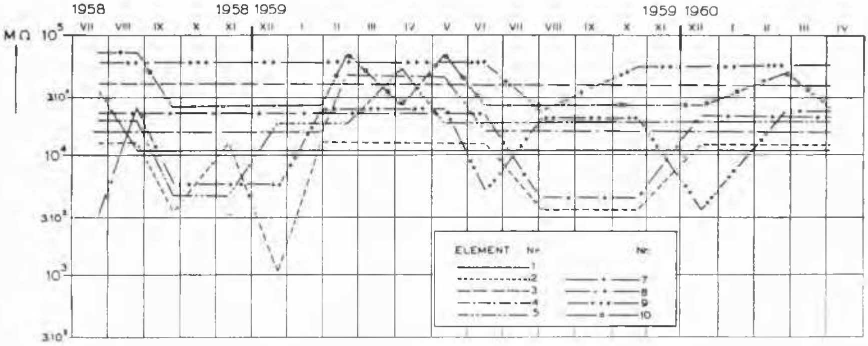

Fig. 16 Insulation resistance against earth of measuring elements shown in Fig. 12.

Résistance d'isolement d'éléments de mesure de la Fig. 12.

Finally, Fig. 16 shows the insulation resistances against earth of the measuring elements of this station.

The deformations measured show great scatter between both the various measuring stations and the measuring points of one particular station. In the interpretation of measuring results account should be taken of the elastic as well as of plastic deformations caused by the load on the concrete.

The author has been able to establish certain relationships between the measurements, which have enabled practical conclusions to be reached. These in turn have led to improved designs and saving of cost. The use of internal concrete measuring elements has been established as a standard method of studying the stresses in new concrete structures under load