ROYAL SWEDISH
GEOTECHNICAL INSTITUTE
PROCEEDINGS
No. 10

ACCURATE MEASUREMENT OF SETTLEMENTS

By

W. KJELLMAN, T. KALLSTENIUS,
and Y. LILJEDAHL

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Preface

The present report describes the developments in accurate measurement of settlements made in 1944—1954 at the undersigned Institute.

These developments are mainly due to W. Kjellman, Head of the Institute, T. Kallstenius, Head of Mechanical Department, and Y. Liljedahl, Research Department Engineer. W. Bergau, of Mechanical Department, evolved the method of temperature compensation in the water hose device described in § 7 d.

The report was prepared by Mr Kjellman.[1]

Stockholm, July, 1955

ROYAL SWEDISH GEOTECHNICAL INSTITUTE

[1] The unfortunate death of Mr Kjellman occurred shortly after this paper had been sent to the press.

§ 1. Introduction

The measurement of settlements of buildings, embankments, and the like, resting on soft soil layers is important for both theoretical and practical reasons. The requisite accuracy of these measurements varies considerably from one case to another.

Let us first assume that the ground has been properly investigated and a prognosis of the magnitude of the settlements and its variation with the time has been made before the construction begins. The purpose of the settlement measurements is then to check the prognosis in order to make sure that there is no tendency to ground rupture or ground water erosion and that the structure is not exposed to greater strain than foreseen. Such measurements, which usually continue through many years, need not be highly accurate. The ordinary measuring methods, involving errors up to 1 mm or 1 cm, will then be sufficient.

Too often, however, even important buildings are constructed without a proper ground investigation. It happens that, after some years, alarming settlements and damages have occurred, liabilities and remedies are disputed and now a geotechnicist is called in. The total amount of the settlement can be roughly estimated, but the accounts of its variations with the time are usually confused. In this situation the geotechnicist must determine the velocity of the settlement in progress. If he were to do this by the ordinary, inaccurate methods, he would have to continue for perhaps a year in order to get a reliable result. If he uses the accurate methods described below, in which the accuracy is, say, 100 times as large, he needs only a week or so.

A ground investigation should comprise a check to find out whether the ground is settling even before the building is erected. Such a settling may occur if the site has been filled up, perhaps many years ago, or if the ground water pressure has decreased on account of drainage or wells. If this settlement is not detected, it may cause considerable damage. In case the building is founded on point-bearing piles, the ground will hang on the piles, which will therefore be over-loaded. In other cases the real settlements will exceed those predicted, and the building will be excessively deformed, conduits will be broken, etc. The above-mentioned check to ascertain whether any settlement is already in progress can be afforded within a reasonable time only by means of an accurate method.

Accurate methods of measuring settlements are also necessary in the scientific stndy of some geotechnical problems. One of these is the question whether the so-called secondary settlements, which are conspicuous in the laboratory, exist in the field. Another is whether the thickest deposits of very fat clay have been fully consolidated under the action of their own weight. A third question is whether the load on a natural clay layer must exceed a certain limit before any settlement occurs at all, as has been suggested by Terzaghi. A fourth problem, finally, is the influence on the settlements of repeated loadings, *e.g.* those due to the tide.

The measurement of settlements consists in determining from time to time the level of the observation point with reference to that of a bench mark. Therefore, the procedure depends on the location and the construction of the bench mark, the location and the construction of the observation point, and the method of measurement. Each of these items will now be studied separately.

§ 2. Bench Mark

§ 2 a. Earlier Appliances

In many cases an easily accessible bench mark can be made simply by inserting a metal plug in an adjacent rock outcrop or in the wall of an adjacent building founded on the firm bottom.

In other cases, however, such outcrops and buildings are too distant. Then a steel rod can be driven through the soft soil layers into the firm bottom, and its top can be used as a bench mark. This method was developed as early as in 1922 by the Swedish State Railways (1)[1], and has since also been applied in several other countries.

However, when the soil settles, downward shearing stresses are produced on the surface of the rod. If the shear strength of the clay and the length of the rod are great, there will be an appreciable axial compression of the rod[2] and, if the firm bottom is not very hard, also an appreciable subsidence of its lower end. Then its upper end will not form an accurate bench mark.

In order to prevent the soil from hanging on to the rod, Terzaghi (2) proposed in 1930 that the rod should be coated with asphalt and wrapped in oil-soaked waste. In this state it should be lowered into a bore hole, which may have

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[1] The numbers in parentheses refer to the bibliography at the end of this report.

[2] Assume, for instance, that the rod has a length of 20 m, a diameter of 2 cm, and a modulus of elasticity of 2 000 000 kg/cm^2, and that the clay has an average shear strength of 0.2 kg/cm^2 fully developed. Then, on account of the axial compression of the rod, its upper end subsides $(0.2 \cdot \pi \cdot 2 \cdot 2000 \cdot 1000) / (\pi \cdot 2000000) = 0.4$ cm.

been put down for some other purpose, and should be rammed into the bottom of this hole. Then the casing of the hole should be withdrawn.

According to Lohmeyer (3), the wrapping in oil-soaked waste is hardly feasible in practice, and the effectiveness of the asphalt alone can be questioned. The Authors have found no reference in the geotechnical literature as to whether Terzaghi's proposal has been realized. The device described in § 2 b 1 can, however, be regarded as a development of his proposal.

§ 2 b. The SGI Device

§ 2 b 1. Main Part of Device

The Institute, which uses no casings in ordinary bore holes, recommends the bench mark device described in what follows, see Fig. 1.

The rod, 19 mm in diameter, consists of sections, 1 m long, threaded at both ends. They are screwed together by means of a pin stuck through a hole in each section. The whole length of each section has a coating, about 1 mm thick, of an asphalt with certain definite properties specified in § 2 b 2, and is wrapped in an axial strip of aluminium foil, 0.05 mm thick.

The rod is inserted into a casing, 25 mm in inner diameter. This casing consists of sections, 1 m long, connected by means of outer couplings. At its lower end the rod has a point, whose diameter is somewhat larger than the outer diameter of the casing. The point has a shoulder fitting tightly into the casing. At its upper end the casing is firmly clamped to a short piece of rod without asphalt, screwed on temporarily to the uppermost ordinary rod section.

The whole device is driven down through the soft soil layers by pushing or ramming, the rod and the casing being successively lengthened by screwing on new sections. When the firm bottom has been reached, the point is rammed a bit into it, if possible. Then the casing is withdrawn, the reactive force being applied to the rod in order to prevent its lifting. The space left by the casing will be filled with soil, at once or in the course of time. The upper end of the rod constitutes an accurate bench mark.

The rod sections must be dry and hot, while the asphalt is applied. After they have cooled, the foil is put on, and then they can be packed into a case and sent to the site where settlements are to be measured. The foil prevents the asphalt from sticking to anything that may happen to touch the rod sections during their transport and during the installation of the bench mark. Furthermore, the foil to a certain extent protects the asphalt coating from being scratched by the grains of the adjacent soil, which, after the installation of the bench mark device, subsides with respect to the rod.

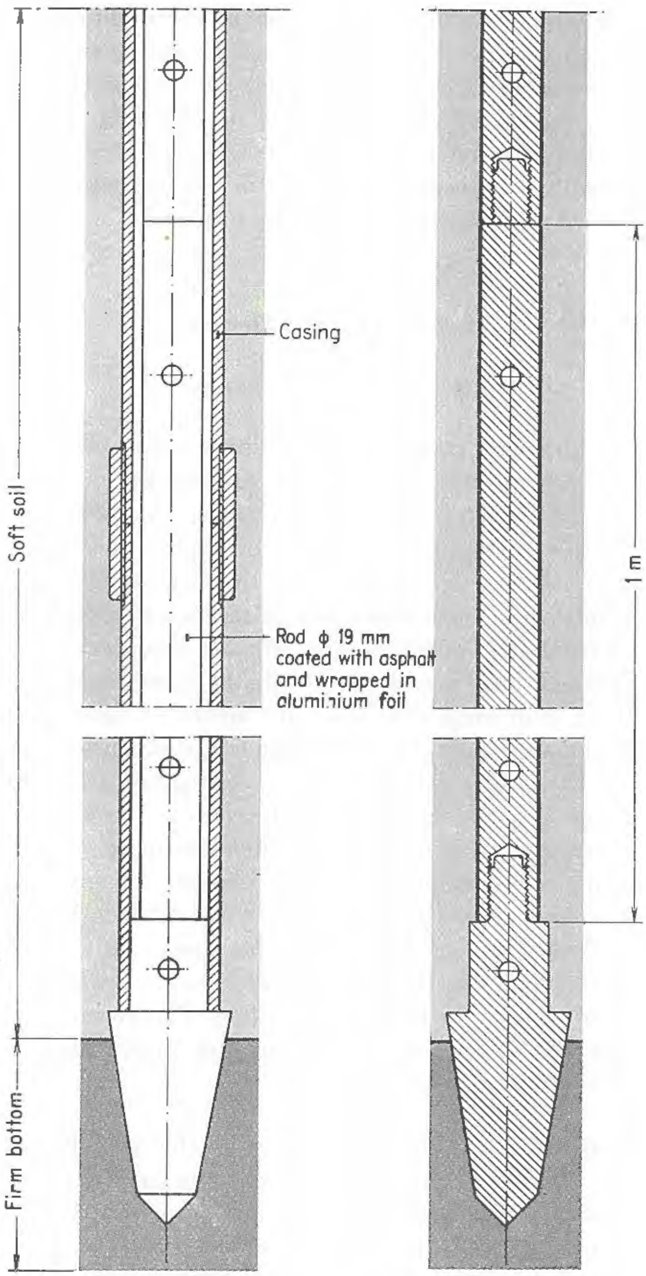

Fig. 1. Bench mark device. Main part.

Left: Immediately after driving.
Right: In working position.

§ 2 b 2. *Properties of Asphalt Used*

The principal feature of the method described in § 2 b 1 is that the asphalt used for the coating shall have such well-defined and controlled rheologic properties that it can transmit no appreciable shearing stress from the soil to the rod. Practically, this means that, at the temperature prevailing in the ground, the asphalt must possess a shear strength equal to zero and a viscosity lower than a certain definite value. If a certain maximum subsidence of the upper end of the rod due to axial compression is allowed, the maximum allowable viscosity can be computed. The computation depends on the way in which the consolidating soil is drained, and can be rather complicated.

For the sake of simplicity we shall confine ourselves to the least favourable case. We assume that the soil is drained only at the firm bottom and that the rate of settlement is greatest, *i.e.* that the consolidation process has just begun. At that time consolidation takes place only in the soil layer which is very close to the firm bottom. Thus, nearly the whole soil mass subsides at the same rate as the ground surface. In comparison with this rate, the rate of sinking of the rod is so small that it may be disregarded. Therefore, the shearing stress in the asphalt is the same on all levels, and the axial compressive stress in the rod increases linearly from the ground surface, where it is zero, to the firm bottom.

Using the following symbols

Length of rod	L cm
Diameter of rod	D cm
Modulus of elasticity of rod	E kg/cm^2
Thickness of asphalt coating	t cm
Viscosity of asphalt	η kgsec/cm^2
Rate of subsidence of ground surface	v cm/sec
Drop of upper end of rod	s cm

we get

$$\frac{v\,\eta}{t} \cdot \pi DL \cdot \frac{4}{\pi D^2} \cdot \frac{L}{2E} = s$$

or

$$\eta = \frac{EDts}{2L^2 v} \qquad (1)$$

As an example we assume $E = 2\,000\,000$ kg/cm^2, $D = 2$ cm, $t = 0.1$ cm, $s = 0.01$ cm, $L = 2\,000$ cm, and $v = 1$ cm/month $= 4 \cdot 10^{-7}$ cm/sec. Equation (1) then gives $\eta = 1\,250$ kgsec/cm^2, *i.e.* $\eta = 1.23 \cdot 10^9$ P. Thus the viscosity must be lower than this value even at a temperature slightly above zero and at a shearing stress as low as $v\,\eta/t = 0.005$ kg/cm^2. On the other hand, the viscosity should not be unnecessarily low, because accurate installation of the bench mark may then be difficult.

The common brands of asphalt vary considerably in viscosity, and some of them possess an appreciable shear strength. Therefore, no asphalt can be used for a bench mark device before its behaviour under very small shearing stresses has been duly investigated. An apparatus for this investigation has been devised by the Institute, and is described in the Appendix.

§ 2 b 3. Upper Part of Device

The top of the rod forming the bench mark must of course be protected against damage. If the bench mark is located below a building, the rod can simply end in a recess in the basement floor covered by a removable lid. If the bench mark is located out of doors, the rod should be surrounded by a protective tube, 50 mm in inner diameter, which reaches at least 50 cm below soil surface. The top of the tube is covered by a removable lid, which can be locked. In normal cases this protective tube projects somewhat above soil surface, as shown in Fig. 2. Where this is not permitted, the top of the device is kept below soil surface and covered with sand, or the like, which is temporarily removed each time the bench mark is used.

If the bench mark is to remain in place during winter, the uppermost part of the rod must be prevented from sticking to the soil, when the asphalt coating gets hard on account of the low temperature. This is done simply by using silicon grease, which is not influenced by the temperature, instead of asphalt on the uppermost part of the rod.

In frost-heaving soil the aluminium foil could easily be torn asunder, and the silicon grease skin could be partly destroyed. Furthermore, the protective tube would be lifted a little higher during each freezing period. This can be prevented by excavating the frost-heaving soil around the bench mark to an adequate distance and by refilling with sand, or the like.

§ 3. Observation Point

If the settlements to be measured are those of a building, observation points are easily obtained by inserting metal plugs in the walls of the building. In other cases, special appliances must be used.

§ 3 a. Observation Point for Top Soil Layer

When the settlement of the top layer of a natural or artificial soil is to be studied, the seasonal movements of the superficial layer due to freezing or drying and soaking are, as a rule, of no interest. Therefore, the observation point commonly consists of a vertical rod welded to a horizontal plate that is placed on a level below which no freezing or drying and soaking occurs.

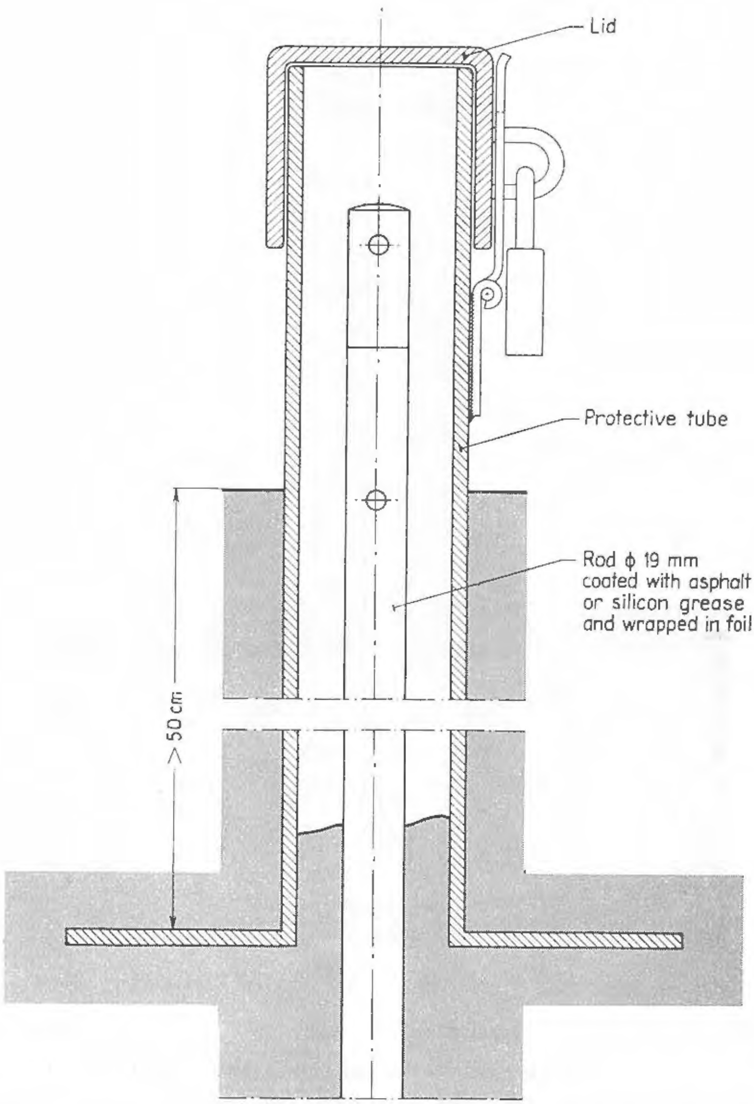

Fig. 2. Bench mark device. Upper part. Case: device projecting above soil surface.

Unfortunately, this simple appliance is, as a rule, not accurate. The plate is usually not rigid, and it is extremely difficult to secure close contact between the plate and the soil below. Owing to the seasonal influences, vertical shearing stresses due to the soil act on the rod. As a result, the rod and the plate are deformed and move a little up and down.

In order to avoid these errors, the Institute recommends the following observation point device. The lower part of the device, which is shown in Fig. 3,

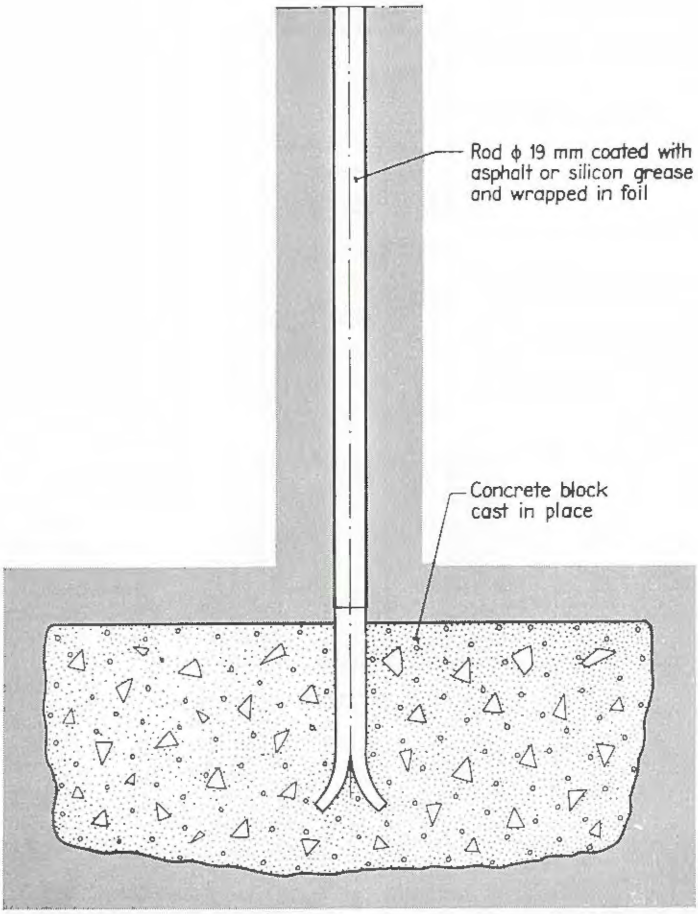

Fig. 3. Observation point device for top soil layer. Lower part.

consists of a concrete block cast in the soil, on a level below which no freezing or drying and soaking occurs, and a vertical rod, whose lower end is fixed in the concrete. The rod is coated with asphalt or silicon grease and wrapped in aluminium foil. The uppermost part of the device is identical with the uppermost part of the bench mark device described in § 2 b 3.

§ 3 b. Observation Point for Base of Embankment

Sometimes it is required to study the settlements of the base of an embankment, or the like, resting on soft soil. For this case Krynine (4) recommends a vertical rod surrounded by a tube, both standing on the same horizontal steel plate placed at the base of the embankment and both reaching to the surface of the embankment. The purpose of this device is to ensure that the soil of the embankment, when settling within itself, shall be prevented from hanging on to the rod and compressing it axially.

Unfortunately, this appliance is not accurate. When the embankment settles within itself, it hangs on the tube, which exerts a great pressure on the plate. Owing to its low rigidity and its incomplete contact with the underlying soil, the plate will deform and subside a little, and the rod will follow this misleading movement.

The Institnte avoids this error by means of a device which differs from that described in § 3 a only in being provided with a rod that is much longer, as it extends through the whole embankment (cf. also Fig. 4).

§ 3 c. Observation Point for Interior of Soft Soil Layer

Terzaghi (2) has pointed out that the measurement of settlements at points in the soft soil layer is also advisable. For this purpose he uses the same device as for a bench mark, see § 2 a.

This device would probably not be accurate in a quite soft soil layer. The diameter of the point cannot be much larger than that of the rod, lest the surrounding soil be too badly disturbed during the driving of the rod. Later, this narrow point may easily subside a little below its correct level on acconnt of the weight of the rod and the small shearing stress transmitted through the asphalt.

In this case the Institute recommends a device that differs from the bench mark device described in § 2 b only in having a rod with a short, wide screw at its lower end, as is shown in Fig. 4. The lower end of the casing engages this screw, so that the whole device is screwed down into the soil by turning the upper end of the rod and the casing. When the requisite depth has been reached, the casing is withdrawn.

It is very important that the shape of the screw is exactly helical, so that the screw in its final position is completely in contact with the clay that is as undisturbed as possible. For the same purpose it is advisable to guide the upper end of the device during the last part of the driving, so that the ratio of sinking and turning at each moment equals the pitch of the screw.

§ 4. Bench Mark and Observation Point on Same Vertical

As will be seen in § 8 below, great advantage can be derived from placing a bench mark and an observation point on the same vertical. For this purpose we exchange the rod of the observation point device for a pipe, which is fitted over the upper part of the rod of the bench mark device. This method was

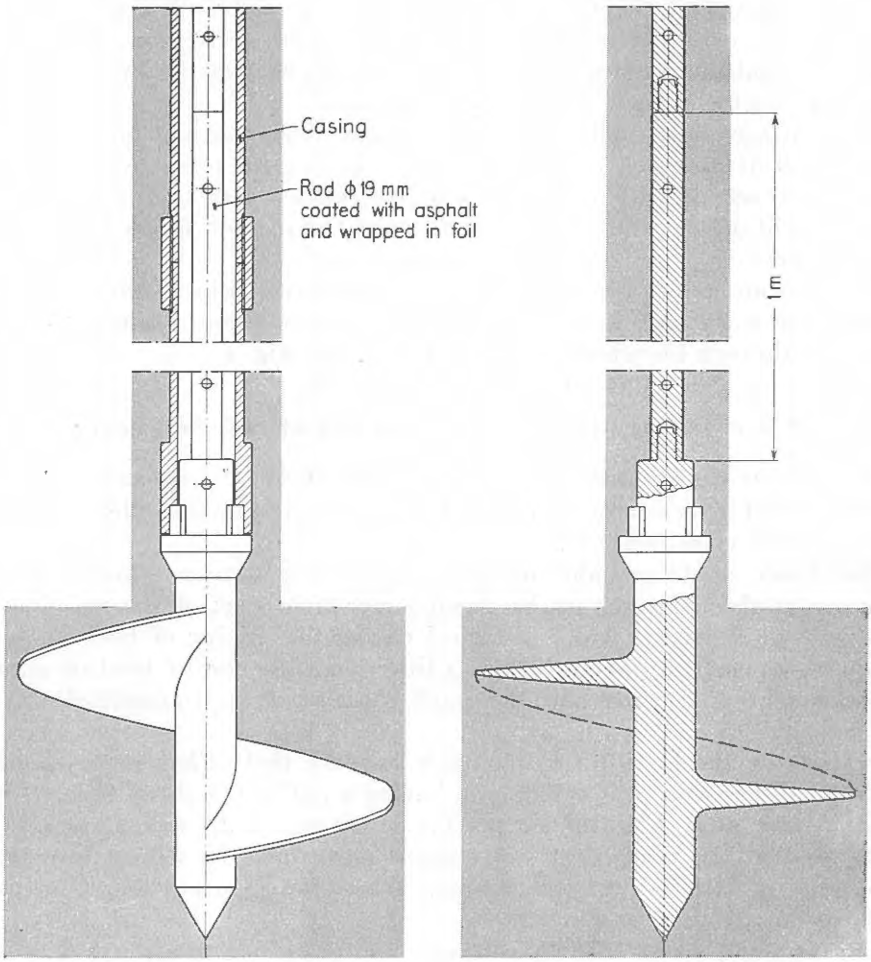

Fig. 4. Observation point device for interior of soft soil layer. Lower part.

Left: Immediately after driving.
Right: In working position.

evolved by the Swedish State Railways (1) as early as in 1922. It is mentioned by Krynine (4), but seems not to have been used outside Sweden.

The Institute combines its bench mark device with its observation point device for top soil layer. The combined device is shown in Fig. 5. It extends above ground surface, and its top carries the measuring apparatus described in § 8 below. A short piece of the foil of the rod is removed at the lower end of the pipe, lest it get stuck there, when the pipe moves downward. Excess

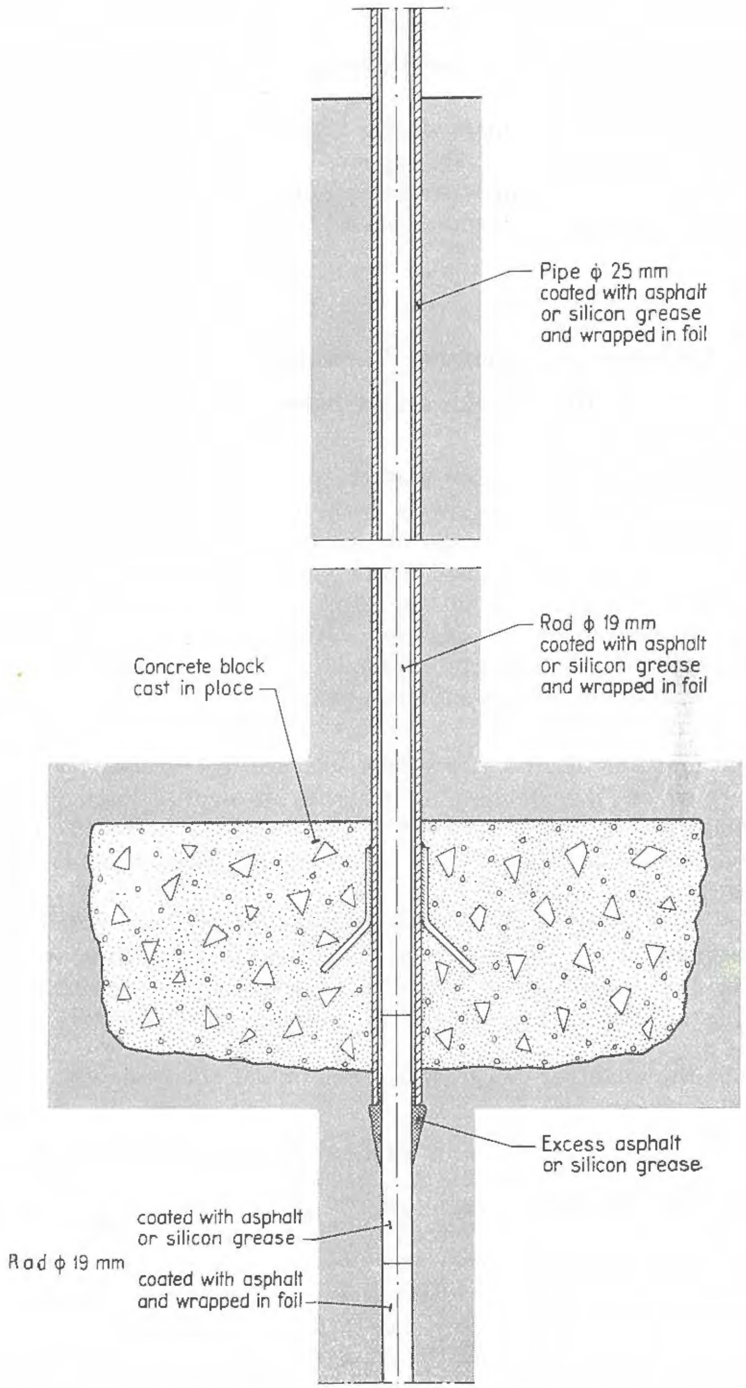

Fig. 5. Combination of bench mark device and observation point device for top soil layer. Lower part.

asphalt or silicon grease at this point prevents the soil from entering the interspace between rod and pipe.

By combining the bench mark device with the observation point device for base of embankment, we get an appliance which differs from the one just mentioned only in having an observation point pipe which is much longer, as it extends through the whole embankment.

§ 5. Influence of Seasonal Variations in Temperature on Bench Marks and Observation Points

The temperature in the upper part of the ground and of the bench mark and observation point devices varies with the time, and thus influences the levels of the bench marks and the observation points. The daily temperature variation extends to a very small depth only, and can easily be reduced by insulation. Since its influence on the level is therefore slight, it will be disregarded here. The annual temperature variation, on the other hand, spreads to a considerable depth, and can hardly be reduced; it causes an error in the level, whose magnitude will now be computed.

We have found in the literature only one account of measurements of soil temperature variation extending to a sufficient depth. They were made in Königsberg (5), near the south coast of the Baltic, in 1873—86. Fig. 6 shows the average monthly temperature as a function of depth on an average for the whole period.

The heat flow in any material is determined by its heat capacity K and its thermal conductivity α. Known values of K and α for granite and water are given in Table 1, together with estimated values for a sand having a porosity of 35 % and a clay having a porosity of 65 %, both saturated with water. Finally, we compute the quantity $\sqrt{\frac{\alpha}{K}}$, which determines the heat flow.

Table 1

Material	Content kg/l		K $\frac{\text{kcal}}{\text{l}}$	α $\frac{\text{kcal}}{\text{m h °C}}$	$\sqrt{\frac{\alpha}{K}}$	δ 10^{-4}	m
	mineral	water					
Granite	2.65	0.00	0.50	3.00	2.47	0.09	4.5
Water	0.00	1.00	1.00	0.50	0.71	0.30	2.0
Sand	1.72	0.35	0.68	1.61	1.54	0.09	3.2
Clay	0.93	0.65	0.88	1.04	1.12	0.28	2.0

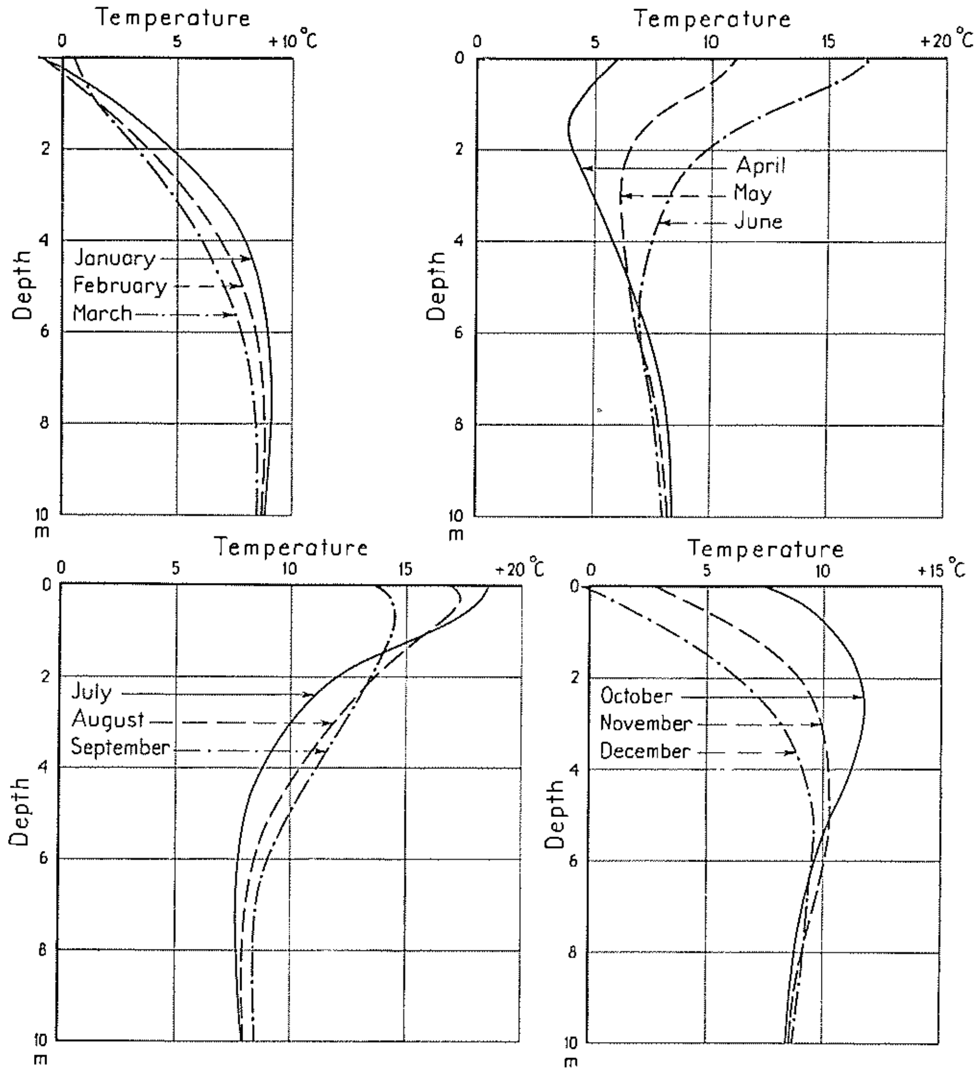

Fig. 6. Königsberg investigation. Average monthly temperature as function of depth.

The kind of soil in the Königsberg investigation was not stated, but we assume that it was sand similar to that in Table 1. All the curves in Fig. 6 will then be applicable to clay soils if we multiply the figures on the ordinate scale by $\frac{1.12}{1.54}$. They will be applicable to rock if we multiply the ordinate scale by $\frac{2.47}{1.54}$.

When the temperature of the upper soil or rock layer increases, its volume increases, and so does the horizontal pressure. We introduce the following symbols:

δ = linear coefficient of thermal expansion,
t_1 = temperature at depth H at instant 1,
t_2 = temperature at depth H at instant 2,
σ_h = horizontal pressure increase at depth H,
ε_v = vertical strain increase at depth H,
E = modulus of elasticity,
m = Poisson's ratio.

We get the equations

$$\varepsilon_v = -(t_2 - t_1)\,\delta - \frac{2\,\sigma_h}{m\,E}$$

$$0 = -(t_2 - t_1)\,\delta + \frac{\sigma_h}{E} - \frac{\sigma_h}{m\,E}.$$

Eliminating $\frac{\sigma_h}{E}$ between them, we find

$$\varepsilon_v = -(t_2 - t_1)\,\delta\,\frac{m+1}{m-1}$$

The heaving of the soil surface from the instant 1 to the instant 2 is, in millimetres,

$$\triangle = \int_{H=0}^{H=\infty} \left(t_2 - t_1\right)\,\delta\,\frac{m+1}{m-1}\cdot 1\,000\,dH$$

or

$$\triangle = \delta\,\frac{m+1}{m-1}\left|\int_0^{\infty} t_2\,dH - \int_0^{\infty} t_1\,dH\right|\,1\,000$$

In order to compute the integrals, we have measured in Fig. 6 the area A between each curve and the 0°C line, taken from the soil surface to a depth of 10 m, below which the temperature variation can be disregarded. This quantity A, expressed in $m\cdot{}^\circ$C, is plotted in Fig. 7 as a function of the month. It is applicable to places with the same soil and the same temperature difference between summer and winter as Königsberg.

The integrals in the above equation are the values of the quantity A at the two instants in question. Thus

$$\triangle = \delta\,\frac{m+1}{m-1}\,(A_2 - A_1)\;1\,000 \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The known values of δ and m for granite and water[1] are given in Table 1. Assuming that the water moves freely in sand but does not move at all in clay, we have estimated δ and m for sand and clay and given them in Table 1.

[1] For water, the average δ between 0°C and 20°C was taken.

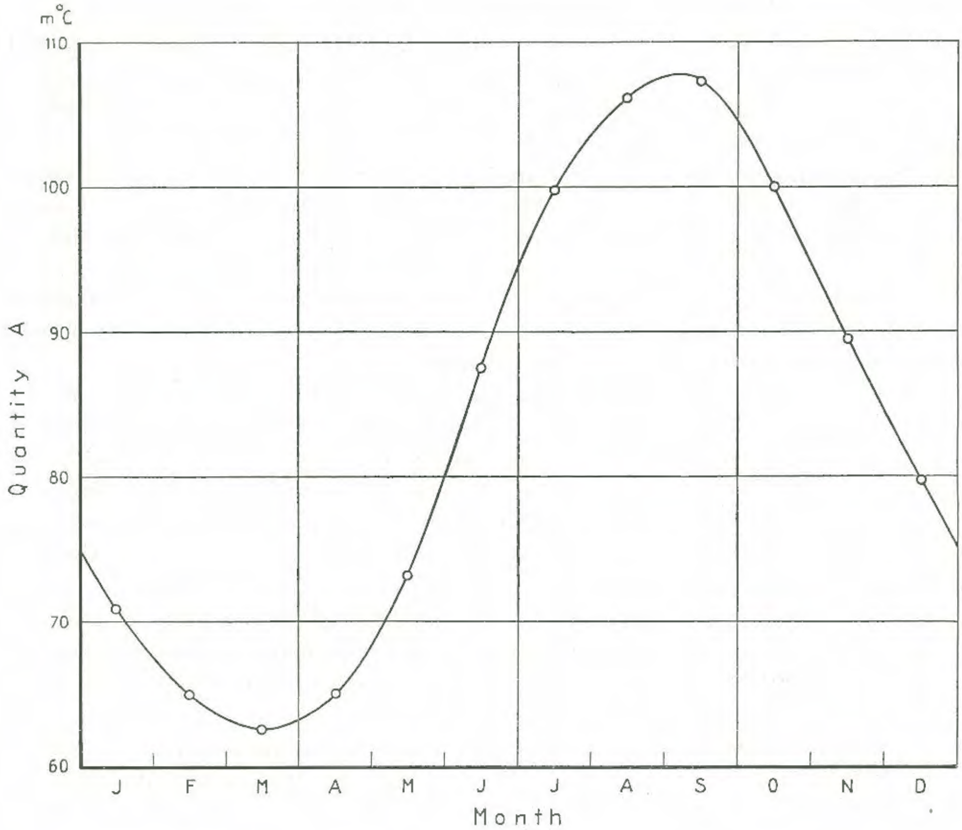

Fig. 7. Königsberg investigation. Quantity A as function of month.

We can now compute the amplitude $\triangle_{max}$ of the thermal displacement of the ground surface. According to Fig. 7, the extreme values occur in March and September, and we have, for sand, $A_1 = 62.5$ and $A_2 = 108.0$, *i.e.* $A_2 - A_1 = 45.5$. Thus we get for

$$\text{sand:}\quad \triangle_{max} = 0.09 \cdot 10^{-4} \cdot \frac{4.2}{2.2} \cdot 45.5 \cdot 1\,000 = 0.78 \text{ mm}$$

$$\text{clay:}\quad \triangle_{max} = 0.23 \cdot 10^{-4} \cdot \frac{3.0}{1.0} \cdot 45.5 \cdot \frac{1.12}{1.54} \cdot 1\,000 = 2.28 \text{ mm}$$

$$\text{rock:}\quad \triangle_{max} = 0.09 \cdot 10^{-4} \cdot \frac{5.5}{3.5} \cdot 45.5 \cdot \frac{2.47}{1.54} \cdot 1\,000 = 1.03 \text{ mm}$$

We see from Fig. 7 that the maximum vertical velocity of the ground surface occurs in June and is $\frac{\triangle_{max}}{87\,days}$, *i.e.* 0.009 mm/day for sand, 0.026 mm/day for clay, and 0.012 mm/day for rock.

In these computations the effect of fissures in the upper region of the soil has not been taken into account. Usually there are fissures, and they reduce the vertical thermal displacements of the ground surface to some extent, which is impossible to compute.

The amplitudes and the velocities computed above apply to a bench mark located in a rock surface and to an observation point for top soil layer. A bench mark or an observation point located at a depth > 10 m involves an error due to the thermal expansion of the rod. If the rod is made of steel with $\delta = 0.11 \cdot 10^{-4}$, the amplitude is $\triangle_{max} = 0.11 \cdot 10^{-4} \cdot 45.5 \cdot 1\,000 = 0.5$ mm, and the maximum velocity is 0.006 mm/day. The error can be reduced by 85 % if the upper part of the rod is made of invar and not of steel.

If a bench mark or an observation point is located at a depth < 10 m, the error is composed of the expansion of the rod and the expansion of the soil below the bottom of the rod, as temperature changes are insignificant below this level for the problems actual here. In order to compute these two amounts of expansion, we can use Fig. 6, but the curve in Fig. 7 must be replaced by two curves, *viz.*, one for the soil above the bottom of the rod and the other for the soil below it.

A bench mark or an observation point located below a wide heated building will hardly have any temperature error. If a bench mark and an observation point are both located on the same vertical and at a depth > 10 m, their temperature errors compensate each other.

We have now described the temperature errors in the measurement of settlements. These errors are not great, and can usually be disregarded. But in those cases which require a very high accuracy something must be done about them. Usually the errors cannot be prevented by insulation or otherwise. However, they can be computed and the results of measurements can be corrected for them.

The simplest way of doing this is to estimate the temperature change in the ground from the instant 1 to the instant 2 and the coefficient of thermal expansion of the soil, and then to compute the error in the manner shown above. But both these estimations are unreliable, so that the result will be roughly approximate.

A better result can be obtained, if the temperature change in the ground is measured. This can be done, for instance, by means of electrical resistance thermometers.

A still higher accuracy can be obtained, if the coefficient of thermal expansion of the soil is also determined. For this purpose it is necessary to find a nearby place with the same soil but without settlements other than those caused by the temperature change. The settlement and the temperature change are measured in this place, and the coefficient of thermal expansion is calculated from these values. It should be observed that the influence of fissures is also found in this way.

§ 6. Levelling with Engineer's Level and Rod

The common method of measuring settlements is levelling with an engineer's level and rod. This method is handy, when one bench mark and many observation points can be read from each station of the level.

If a bench mark can be read from the station, the error in the measured level of the observation point has normally an order of magnitude of 1 mm, provided that the measurement is made by a trained man with an accurate level. If, on the other hand, the nearest bench mark is distant, the error is normally much greater. On a very important building site known to the senior author, where numerous observation points were levelled through many years by specialists with good levels, errors up to 1 cm were frequent.

§ 7. Levelling with Water Hose

§ 7 a. Common Method

A method of levelling, employed as early as in 1629, is to use a hose extending from the bench mark to the observation point and furnished with a glass stand pipe at each end. The stand pipes are mounted roughly on the same level, and distilled water is filled into the system, so that a meniscus is visible in each stand pipe. The two menisci are supposed to hold the same level according to the law of connected vessels.

In 1904 Seibt (6) employed this method for the measurement of settlements. Terzaghi (7) in 1933 improved the accuracy of readings by introducing pointed micrometer screws similar to those used in hydrometry. Since then this method is commonly used in several countries (8). It is sometimes handier than levelling with an engineer's level and rod, for instance, in the basement of a building, where the sight is obstructed by partitions, stored goods, etc.

The accuracy of the water hose method is commonly but wrongly supposed to be high. Krynine (4) mentioned an error of 0.05 mm, and Peckover (8) stated that the error hardly ever exceeds 0.15 mm and is usually less than 0.08 mm. This question is discussed in § 7 b and § 7 c below.

§ 7 b. Influence of Local Variations in Atmospheric Pressure

The water hose method, as hitherto used for measuring settlements, is based on the tacit assumption that the atmospheric pressures at the two stand pipes are equal. In reality, however, these two pressures are as a rule different. The resulting error in measurements is equal to the pressure difference expressed in water gauge.

Buildings are designed to withstand a wind pressure of, say, 100 kg/m^2. Nobody would of course try to level in such a storm, but levelling is probably sometimes carried out in a wind producing, say, one tenth of this pressure. Then, if a water hose is used to level an observation point on the windward side of a house with reference to a bench mark on the lee side, the wind causes an error of 10 mm. Thus, errors up to this value may easily occur, when the method is used in routine work.

This error may also occur when levelling the basement of a house, even if all doors and windows are closed, so that the wind is not felt inside. The air pressure in a room can have any value between that on the windward side of the house and that on the lee side, as it depends on chinks at doors and windows, vents, etc.

A similar error may occur even during dead calm on account of ventilation, non-uniform heating, or intense sunshine. The local air pressure variations originating from these causes are well known in ventilation engineering, and often amount to a few millimetres water gauge.

This error could be roughly compensated by measuring the air pressure at both stand pipes, as is done by geodesists when using the water hose method (9). But this would be troublesome in routine work, and no high accuracy can be achieved in this way.

Another way of reducing the error would be to use mercury instead of water in the hydraulic system. But mercury is poisonous, and therefore dangerous to handle in open vessels during routine work. Further, about 7 % of the error would remain, and that is still too much for accurate measurement of settlements.

§ 7 c. Influence of Local Variations in Temperature

The water hose method as hitherto used is based on the assumption that the temperature of the water is the same at all points of the system. In reality, however, there are as a rule appreciable temperature differences. Sometimes these differences may happen to counterbalance each other, but normally they cause an error in the levelling result.

Let us assume, for instance, that each end of the hydraulic system has a vertical part 1.65 m long[1]. The temperature difference between these parts may easily be 10°C, if one is in the sun (though protected from direct sunshine) and the other in the shadow, or if one is inside and the other outside a house. The resulting error is 3 mm.

This error could be reduced by artificial adjustment of the temperature of the hydraulic system by means of insulation or heating. If the temperature difference were kept within 1°C, which would probably be the best result to be expected, the error would lie within 0.3 mm. But this regulation would considerably complicate the method, and the error would still be great.

[1] Peckover (8) recommends to have the observation points 1.65 m above the floor and the main part of the hose on the floor.

Another way would be to measure the temperature difference and to compute the correction of the level, as is done by geodesists when using the water hose method (9). But this procedure, too, would be a troublesome complication of the method, and no high accuracy could be expected.

A third way of reducing the temperature error would be to ensure that the whole hose should be as nearly horizontal as possible. Then the vertical extent of the water system, and hence the temperature error, would be considerably reduced. However, this arrangement would be troublesome and sometimes impossible.

§ 7 d. The SGI Device

As has been shown above, the great error in the water hose method as hitherto used is due to local variations in the air pressure. We have completely eliminated this error simply by connecting the upper ends of the two stand pipes by means of a narrow air-filled rubber hose.

In those cases which require a high accuracy, we also eliminate the temperature error. For this purpose we use two hydraulic systems containing liquids with very different coefficients of thermal expansion, *e.g.* water and turpentine. The two liquid-filled hoses lie close to one another, so that the temperature can be assumed to be the same in both of them. At each end of the device the two stand pipes are mounted on the same steel plate and read on the same scale (Fig. 8).

We designate by

- R the readings on the scales,
- $\triangle$ the temperature errors,
- a the coefficients of thermal expansion

and by the indices

- b the bench mark,
- o the observation point,
- w the water system,
- t the turpentine system.

We get the equations

$$(R_{ot} - R_{ow}) - (R_{bt} - R_{bw}) = \triangle_t - \triangle_w \quad \dots\dots\dots\dots \quad (3)$$

and

$$\frac{\triangle_w}{\triangle_t - \triangle_w} = \frac{a_w}{a_t - a_w} = \frac{0.00018}{0.00094 - 0.00018} = 0.24 \quad \dots\dots \quad (4)$$

Thus we get the temperature error $\triangle_w$ in the water system very easily from the four readings.

In other respects the SGI water hose device does not differ from other modern devices of this kind. Therefore it will not be described in detail here.

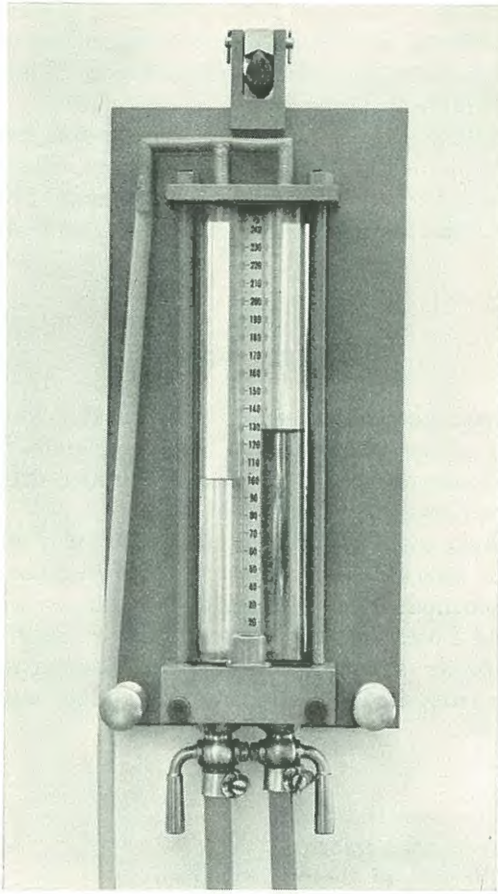

Fig. 8. SGI water hose device. End instrument.

§ 8. Direct Measurement

The difference in level between a bench mark and an observation point can sometimes be measured directly, and this is a great advantage. This is possible in those cases, described in § 4, in which the observation point is located on the vertical through the bench mark. It is also possible, if the observation point is located close to this vertical. If, for instance, a bench mark can be installed near a building whose settlement is to be measured, a steel shelf reaching out over the bench mark can be attached to a wall, as indicated in Fig. 9. Another example is seen in Fig. 10, showing how the settlement of a conduit is measured directly by means of a steel beam connecting two bench marks installed on the sides of the conduit.

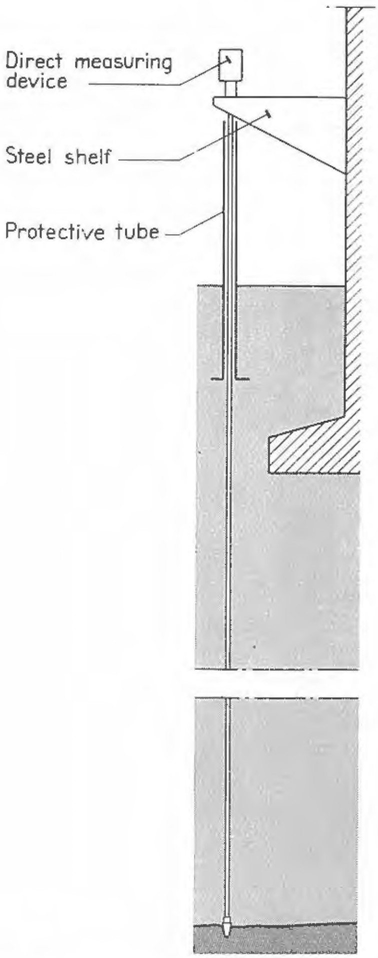

Fig. 9. Appliance for direct measurement of settlements of building.

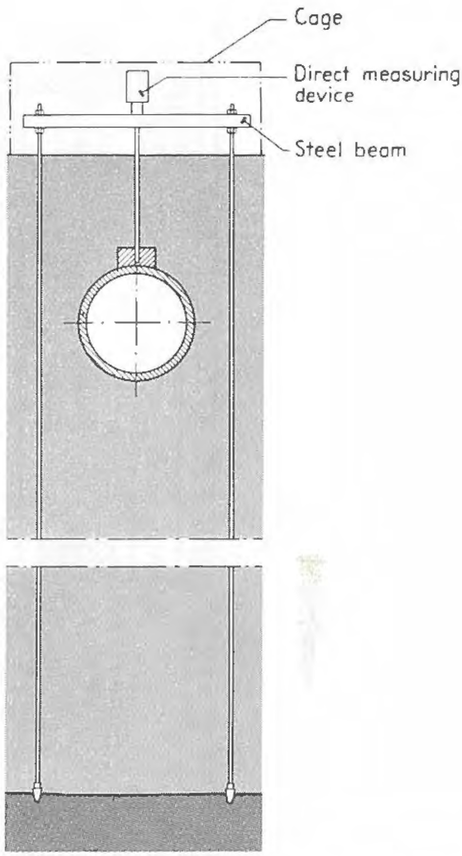

Fig. 10. Appliance for direct measurement on settlements of conduit.

Direct measurements can be made simply by reading a millimetre scale attached to the observation point device with reference to a pointer attached to the bench mark device. The error in this method, which was first used by the Swedish State Railways (1), can be estimated at 0.2 mm.

A more accurate method devised by the Institute is to measure by means of a micrometer the vertical distance between two small bolts, *viz.,* one on the observation point pipe and the other on the bench mark rod, as shown in Fig. 11. The heads of the bolts are made from stainless steel in order not to corrode, and are protected against dirt and damage by a removable hood. The upper part of the bench mark rod is guided in the observation point pipe. The error involved in this method is about 0.01 mm, provided a first-class micrometer is used.

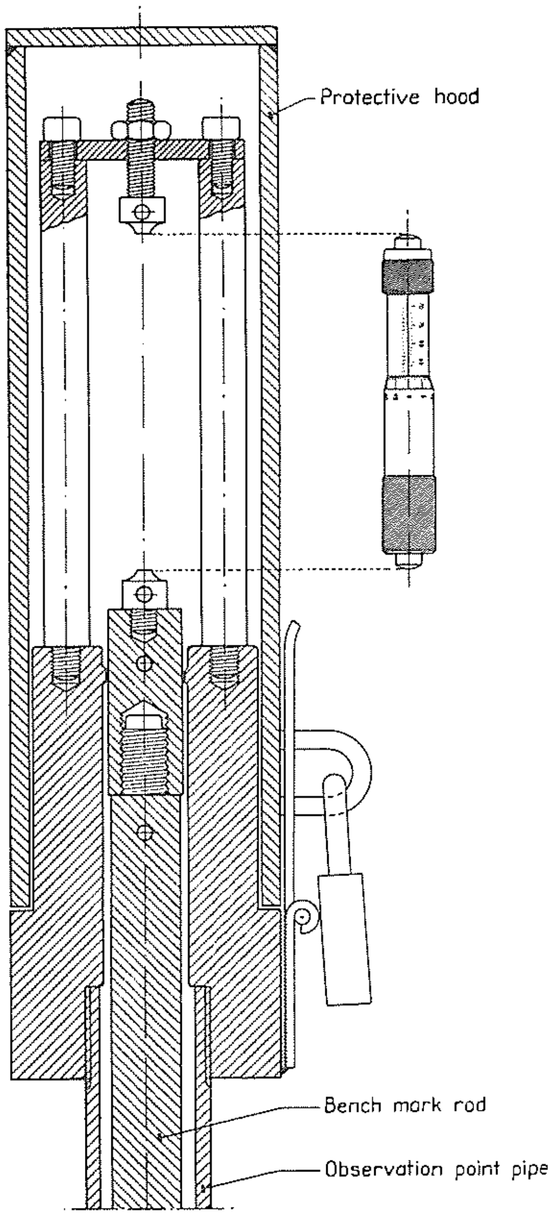

Fig. 11. Direct measurement by means of micrometer.

Another accurate method used by the Institute is shown in Fig. 12. A dial gauge[1] is attached to the observation point pipe and its feeler touches the

[1] The use of a dial gauge was suggested by Terzaghi (7), but seems never to have been tried until now.

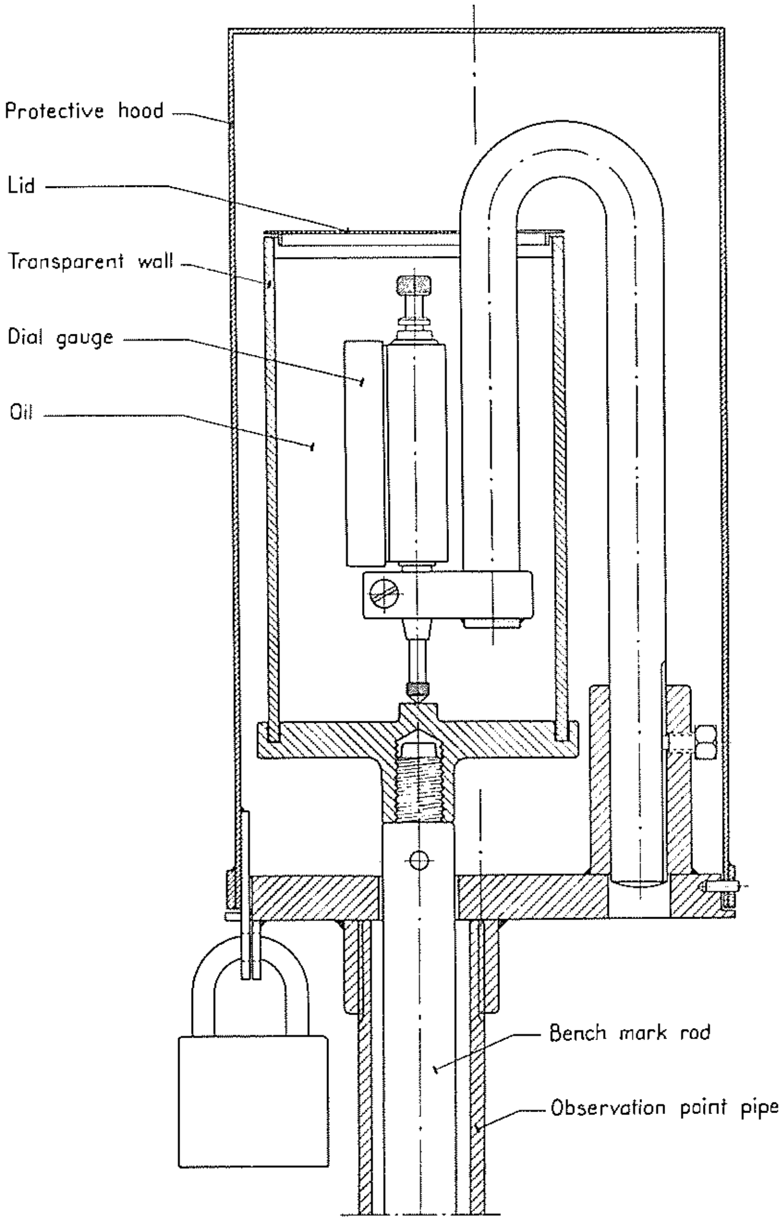

Fig. 12. Direct measurement by means of dial gauge.

bench mark rod. It is placed in a vessel, which has a transparent wall and is filled with a transparent oil. An outer steel hood protects the device against damage. The error in this method is about 0.01 mm, provided a first-class dial gauge is used.

§ 9. Summary

Earlier bench mark devices and observation point devices are criticized, and appliances evolved by the Institute are described. The principal feature of the latter is that the vertical extension rods and pipes are insulated from the surrounding soil by means of a coating which has such well-defined and controlled rheologic properties that it cannot transmit any appreciable shearing stress. A special apparatus for testing these properties is described.

The temperature in the ground varies appreciably with the season down to a considerable depth, and causes annual variations in the levels of most bench marks and observation points. The amplitude and the maximum velocity of these movements are computed.

Then the water hose method, as commonly used for measuring settlements, is discussed. The high accuracy often claimed for this method is purely imaginary, since very great errors are caused by local variations in atmospheric pressure and temperature. These errors are eliminated in the modified method developed by the Institute.

Finally, the methods for direct measurement used by the Institute are described. One of these methods consists in measuring by means of a micrometer the distance between two stainless steel bolts. The other involves the use of a dial gauge mounted on the observation point pipe and measuring the bench mark movement.

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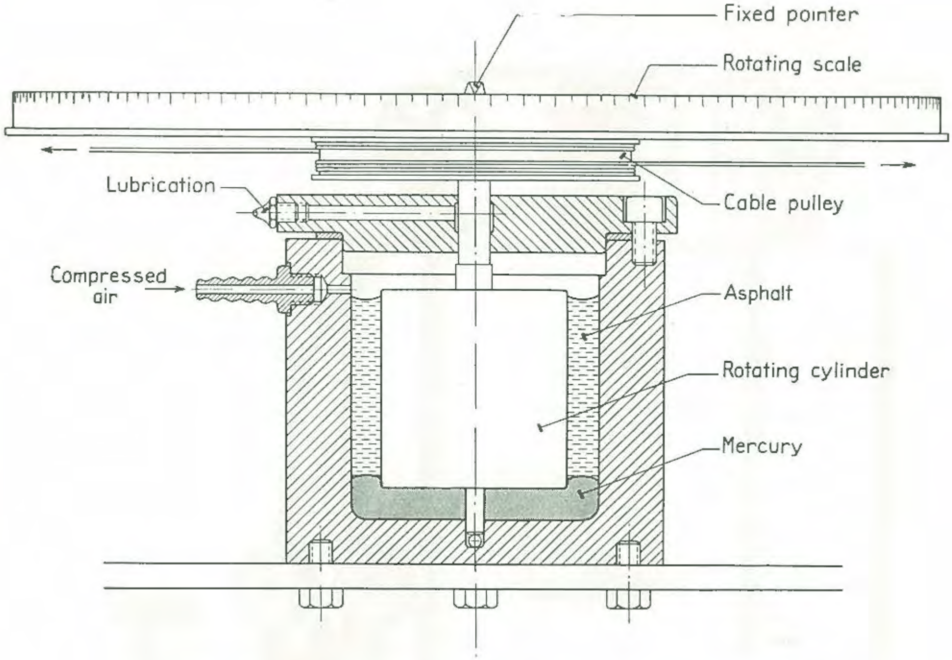

Fig. 13. Apparatus for testing asphalt. Section through main part.

Appendix

Apparatus for Determining the Rheologic Properties of Asphalt

Asphalt is used on the SGI bench mark rod and on the SGI observation point rod or pipe as a lubricant between them and the soil. Asphalt has also been applied, at least once, in an earth dam as a lubricant between the concrete core and the earth fill. In concrete dams, finally, a string of asphalt is often used to tighten the joint between two units, and the string is then fed from an asphalt reservoir.

It is important in these cases to know the rheologic properties of the asphalt under the conditions prevailing in the device or structure, *i.e.* at a low temperature, a very low shearing stress, and a normal stress that varies between wide limits. The necessity of testing the asphalt in these respects is emphasized by the following facts:

1. The viscosity of an asphalt is in general strongly influenced by the temperature.
2. The viscosity of various asphalts at the same temperature varies enormously.

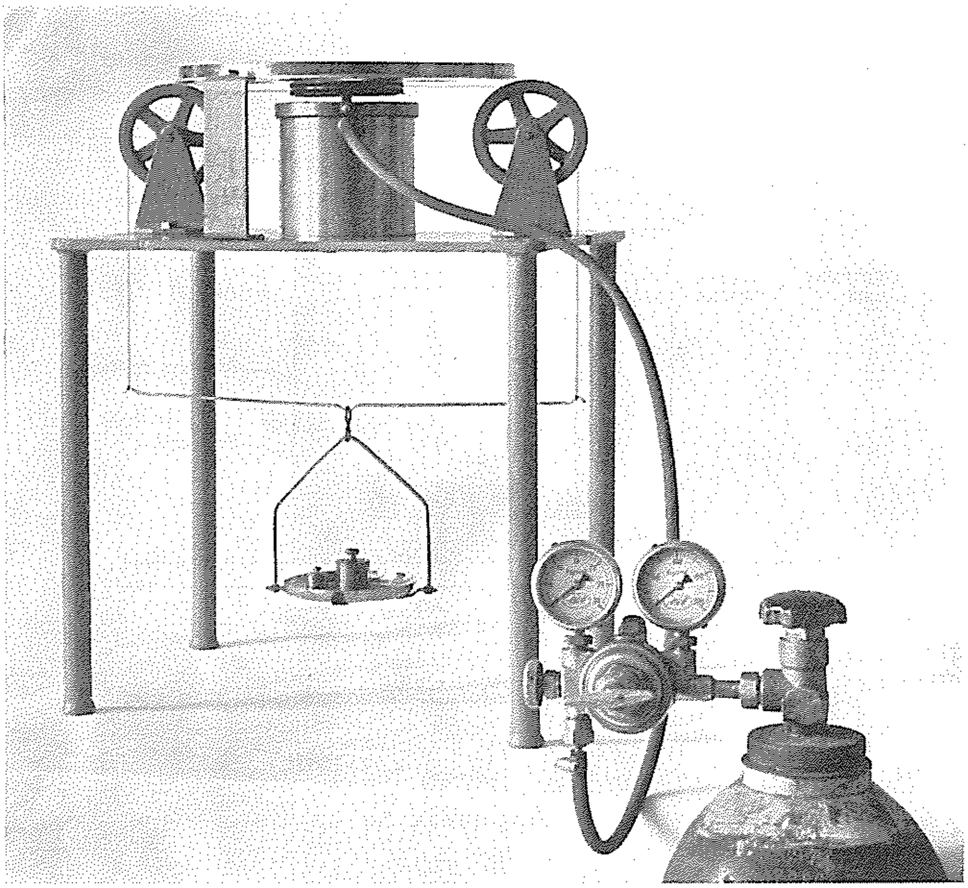

Fig. 14. Apparatus for testing asphalt. Assembly.

3. The viscosity of some asphalts is strongly influenced by the normal stress.
4. Some asphalts possess an appreciable shear strength.
5. Some asphalts have certain elastic properties.

The apparatus designed by the Institute for testing asphalt in the above respects is shown in Fig. 13, which is a vertical diametrical section. It consists of a stationary cylindrical vessel with a removable lid and a rotary cylindrical body concentrically placed in the vessel. The interspace between the rotary body, whose diameter is 6 cm, and the vessel is filled with mercury in its lower part, asphalt in its intermediate part, and compressed air in its upper part. The shaft of the rotary body has one bearing in the bottom of the vessel and another in the lid, the latter being lubricated and sealed against the compressed air by means of grease under pressure. The shaft projects through the lid, and its upper end carries a cable pulley and a circular scale. The scale is read with reference to a pointer fixed on the vessel, and thus indicates the torsional displacement of the rotary body with respect to the vessel.

The annular interspace between the rotary body and the wall of the vessel is 1 cm wide. The asphalt here floats on the mercury, and the compressed air presses on the asphalt. The pressure comes from a steel bottle with compressed air, is regulated by means of a reducing vent, is read on a Bourdon gauge, and is transmitted into the vessel through a nipple in the wall, see Fig. 14.

The torsional moment is applied by putting weights on a pan suspended in a yoke below the vessel. The yoke produces equal vertical forces in two cables, each of which is deflected by a pulley from a vertical to a horizontal direction. The cables reach the circumference of the pulley from opposite directions and at diametric points. They are wound around the pulley and attached to it. Thus the load on the pan produces uniformly distributed shearing stresses in the asphalt specimen.

The normal stress can be increased up to 6 kg/cm^2 and the shearing stress up to 0.5 kg/cm^2. For a low shearing stress, the error in this stress is < 0.001 kg/cm^2.

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