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State-of-the-Art Report on Field Instrumentation for Pavement Experiments

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The various instruments available for taking in situ measurements of stress, strain, deflection, temperature, pore pressure, soil suction, and axle load in pavement experiments are described. Discussions of the desirable objectives of pavement experiments and comments about instrumentation concerning the unavailability of general purpose equipment and the need to design instruments for specific applications are presented. Earth pressure cells are discussed and information is given on the theory of their in situ performance, design considerations, and installation procedures. The need for correct calibration is emphasized. Pressure cells that have been used in various projects are described as illustrative of the kinds of instruments that can be used. A detailed design procedure for the simplest type of cell and a discussion concerning the use of charts to assist with the calculations are provided. Strain measuring devices for use in soils, granular materials, and asphalt materials are described and comments are made on the relative merits of each. Even though there is a lack of available information about other instrumentation, the current state of the art is described for each case presented.

Developments in analytically based design procedures for flexible pavements have reached the stage in which information about theoretical analysis and material properties is available. Furthermore, design methods that use the information dealing with the traffic-associated failure mechanisms of cracking and rutting have been reported in some detail in the literature. However, in practice the situation is that design agencies still use empirical methods based on the findings from limited, full-scale test sections and often incorporate an overall California bearing ratio (CBR) thickness requirement.

The gap between current practice and current research knowledge available can best be bridged by more agencies carrying out well-instrumented, full-scale experiments that are properly planned to monitor for correct parameters. In short, recent research developments must be verified in practice on a scale larger than that previously used so that the economic worth of these developments can be assessed by highway engineers.

The success of full-scale or pilot-scale experiments in assisting with the development of improved design procedures depends to a large extent on the accuracy of the measurements made on the structure. This success can only be achieved by use of adequate instrumentation that is installed correctly. This report explains the principles of the various instruments that can be used in pavement experiments and describes many of those that are successful in practice. The emphasis is on stress-measuring devices because these have been researched in the past. Instrumentation for evaluating in situ stress, strain, deflection, temperature, pore pressure, soil suction, and axle load is discussed. Because the amount and kind of instrumentation depends on the objectives of the experiment and the money available, this report can be used to assist engineers in planning future experiments.

Instrumented pavement experiments, particularly on public highways, should not be undertaken lightly. These experiments can be expensive both in terms of instrumentation and labor as well as in interruptions to the normal processes of construction. It is better to use fewer instruments that are well understood and reliable to provide good but limited data, than to use a vast array of ironmongery whose behavior is something of a mystery. Currently, field instrumentation is definitely not a matter of buying commercial equipment that can be easily installed in the road and expected to produce quick and reliable answers. While there is some equipment commercially available for measuring some parameters, this equipment should only be used with a full understanding of its operating principles because it is rare that field instruments have universal applicability. These instruments generally need to be designed for a purpose.

Many of the difficulties and costs of full-scale experiments on public highways can be avoided by using pilot-scale experiments or full-scale trials on special test roads. Many more projects involving these more carefully controlled experiments seem desirable because, if new design concepts do not work under such conditions, they are unlikely to be successful in practice.

Instruments that have to be installed in the pavement structure clearly need to be designed to resist the rigors of the construction process, both environmental and mechanical. These factors can account for several instrument failures in a particular experiment and point to the need for duplication of instruments. Instrumentation research has clearly shown that one of the major sources of error, even for well-designed instruments, arises from installation effects. Even experienced technicians using well-tried methods cannot guarantee freedom from this problem because it is related to the overall problem of interference. Interference results from the presence of the instrument in the pavement, which causes errors in reading. Because of these uncertainties, the more instruments that can be installed to provide duplicate measurements the better the results will be. However, this problem should not be allowed to create a situation in which instruments are placed too close to each other because a pavement full of instruments is unlikely to perform representatively.

A comprehensively instrumented test section is likely to produce a considerable amount of data and in such circumstances, particularly if the experiment is long term, thought should be given to the provision of adequate data-acquisition and data-processing procedures. It is important that full-scale performance data should be used and not left in the cupboard in the form of uninterpreted recorder traces. In this context, the relative costs of a labor-intensive simple system and of an automated procedure should be carefully weighed.

EARTH PRESSURE CELLS

Instruments for measuring both long-term changes in stress and transient effects under free-field and boundary conditions have been extensively studied. The performance of these earth pressure cells, or soil stress gauges as they are variously described, has received more attention in the literature than the performance of most other field instrumentation that is of interest to the highway engineer. Good reviews have been published by Selig (1) and Triandafilidis (2). The determination of in situ stress, however, remains a difficult problem because it cannot be measured directly and must rely on a measurement of strain or deformation within the instrument by using an appropriate transducer. Because of the many difficulties involved, accuracies better than about 20 percent cannot be expected.

All earth pressure cells incorporate a diaphragm that is in contact with the soil. The pressure exerted on the diaphragm by the soil is then evaluated in a variety of ways that depend principally on the particular practical application. A typical, simple type of cell is shown in Figure 1. This cell has a diaphragm that is built into an outer ring and is free to deflect under the action of soil pressure. The strain on the inside of the diaphragm, or its deflection, is then measured by using a suitable transducer. Other pressure cells have diaphragms that are restrained by mercury or oil contained within the cell and that transmit the pressure to a second internal diaphragm, which carries the strain gauges. Detailed descriptions of particular instruments of both kinds follow.

The introduction of a measuring instrument into a soil mass disturbs the stress distribution, as shown in Figure 2 (1). The overall aim in designing pressure cells is to obtain a measure of the free-field stress, that is, the value that would have occurred at the location if the instrument had not been present. This measurement can best be achieved by designing an instrument that has a minimum disturbing effect, though, as in most design problems, this involves certain compromises because of conflicting considerations. The redistribution of stress over the diaphragm, as shown in Figure 2, means that the instrument will usually overregister the free-field stress, though underregistration is also possible.

Theory

An understanding of the interaction between pressure cells and the surrounding soil has been developed by the use of both theory and experiment. The main requirement is that the degree of overregistration or underregistration should be predictable and that it should be relatively constant for a particular cell.

Cell registration (C) has been defined as follows:

$$C = \text{stress indicated by cell/free-field stress} \tag{1}$$

The stress indicated by the cell is based on relating the electrical output from the instrument to stress by way of a mechanical bench calibration test in which a known stress is applied directly to the diaphragm. Such a test can be carried out by placing the cell in a pressure chamber of by using the arrangement shown in Figure 3.

Early work on the theoretical evaluation of cell registration by Taylor (3) and Monfore (4) was extended by Tory and Sparrow (5). The latter considered the pressure cell to be located in a uniaxial stress field and summarization of their results are shown in Figure 4. The following equations indicate the importance of two parameters:

$$\text{Aspect ratio} = B/D \tag{2}$$

and

$$\text{Flexibility factor} = E_s d^3/E_c t^3 \tag{3}$$

where

- B = cell thickness,
- D = cell diameter,
- E_s = Young's modulus of the soil material,
- E_c = Young's modulus of the cell material,
- d = diameter of the cell diaphragm, and
- t = thickness of the cell diaphragm.

In effect, the flexibility factor (F) is the ratio of soil stiffness to diaphragm stiffness.

Figure 4 shows that the stiffness of the cell diaphragm should be relative to the soil in which it is installed so that the cell registration can be approximately constant. Ideally, a flexibility factor less than unity should be used. Also shown is how registration increases as aspect ratio increases.

In practice, pressure cells are generally used in three-dimensional stress fields and hence the influence of stresses acting parallel to the diaphragm needs to be quantified. Fossberg (6) carried out finite-element analyses of axisymmetric situations around a particular free-diaphragm, pressure cell that has dimensions similar to the Nottingham instrument shown in Figure 1. Figure 5 shows the results of Fossberg's analyses that indicate that increases in the cross stress (σ_T) cause decreases in cell registration, but that the influence of flexibility factor is similar to the uniaxial stress case. For a stress ratio of zero, which is the uniaxial case, Fossberg's results compare favorably with those of Tory and Sparrow (5).

Most of Fossberg's calculations were carried out under conditions of zero strain in the soil parallel to the cell diaphragm, i.e., K_o conditions. He also considered the case of no lateral restraint using the zero stress ratio. However, an induced lateral tensile stress, which could clearly not be transmitted to the

Figure 1. Nottingham pressure cell.

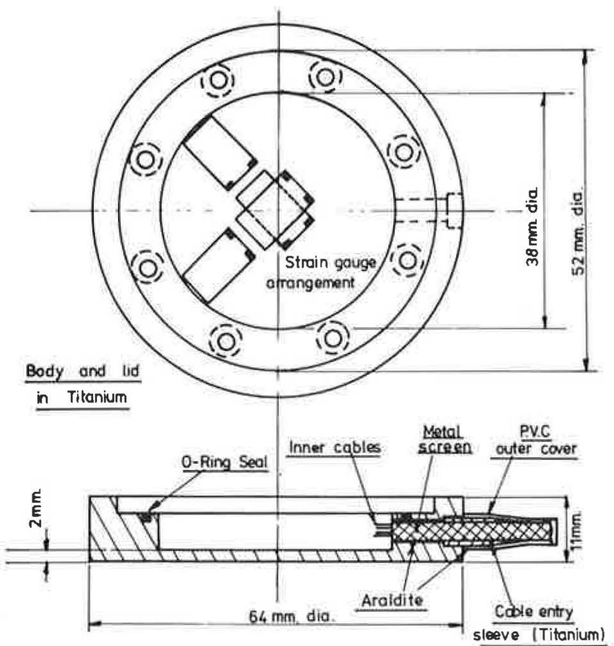
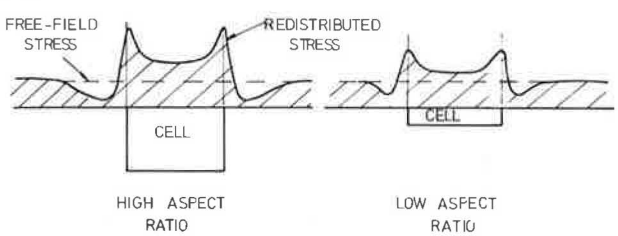


Figure 2. Redistribution of stress because of presence of a pressure cell.



cell, was indicated; therefore, an appropriate correction was made to eliminate the stress. Hence, the basic assumptions became similar to those of Tory and Sparrow (5).

A more extensive theoretical investigation has been reported by Collins and others (7). They evaluated cell registrations relative to stresses both normal and parallel to the diaphragm. These were defined as follows:

C_N = stress acting normal to diaphragm/free-field stress (4)

and

C_T = stress acting normal to diaphragm/free-field cross-stress (5)

Hence, for a pressure cell subjected to free-field stresses (σ_N) that are perpendicular to the diaphragm with σ_T in the two perpendicular directions the following equation is used.

$$C = (C_N \sigma_N + 2C_T \sigma_T)/\sigma_N = C_N + 2C_T (\sigma_N/\sigma_T) \quad (6)$$

As shown, both C_N and C_T depend on the aspect ratio and the elastic properties of the soil and the cell.

The major difference in basic assumptions between the work of Collins and others (7) and Fossberg (6) is that the former made no assumptions concerning lateral strain conditions and their cell was a homogeneous inclusion having the shape of a spheroid. Both Fossberg and Tory and Sparrow took account of the diaphragm deflection in modeling an actual pressure-cell situation. Hence, the theory by Collins and others is relevant to

Figure 3. Arrangement for bench calibration of Nottingham pressure cell.

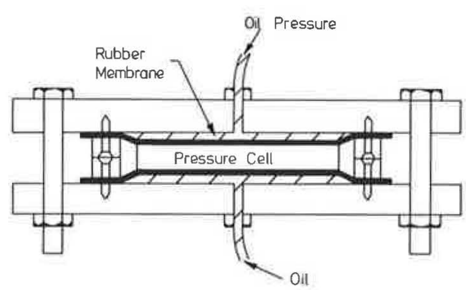


Figure 4. Theoretical pressure cell registrations.

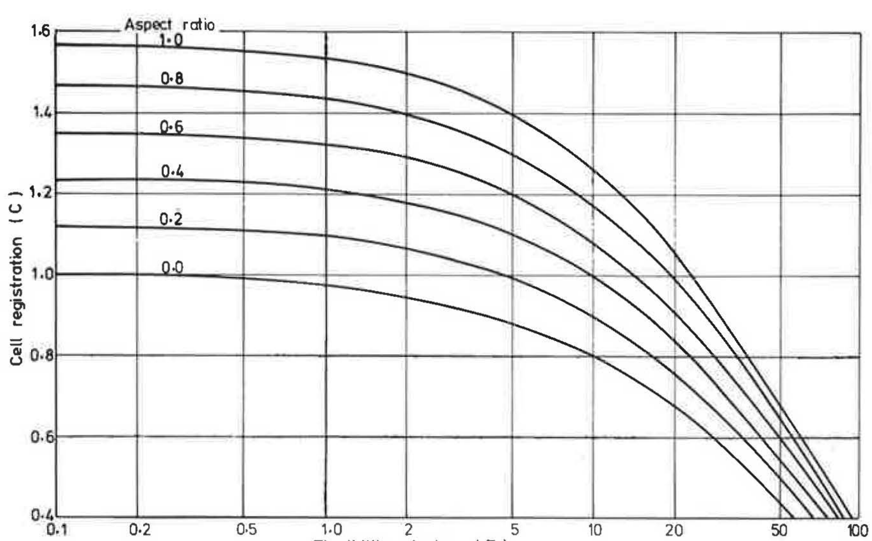


Figure 5. Theoretical cell registration for Nottingham cell based on Fossberg's theory.

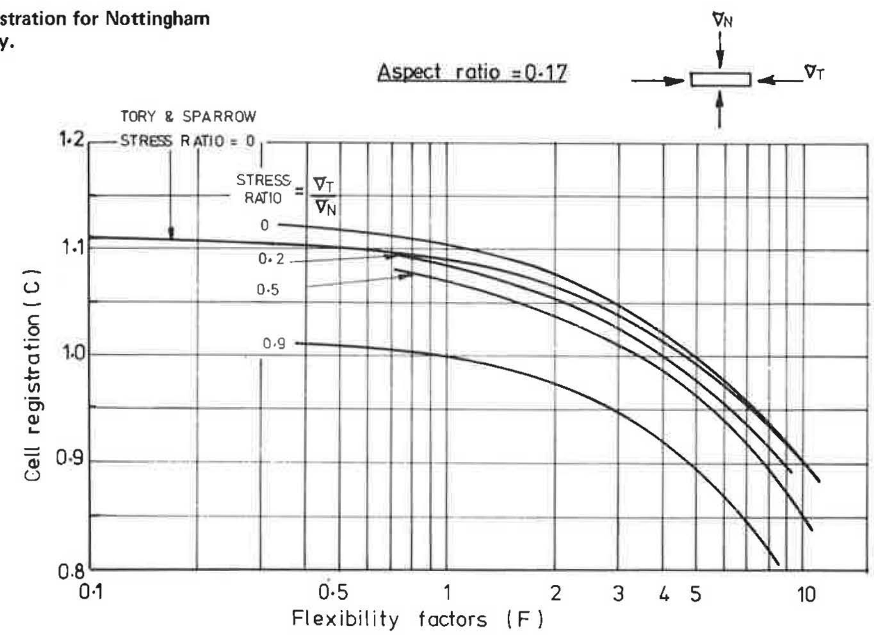


Figure 6. Comparison of theoretical pressure cell registrations for zero stress ratio.

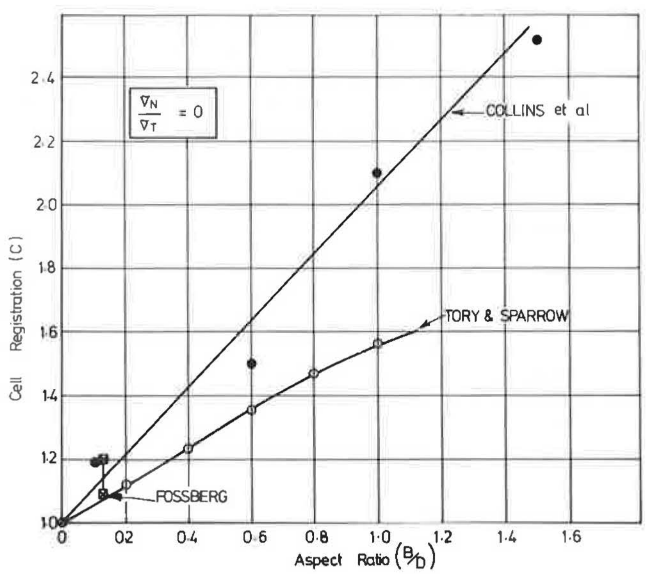
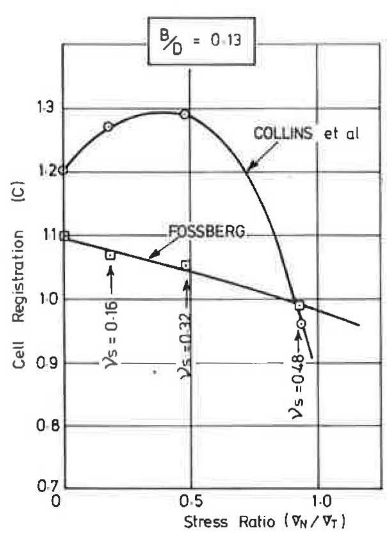


Figure 7. Comparison of theoretical pressure cell registrations at various stress ratios.



pressure cells with restrained diaphragms while the other theories are only applicable to free diaphragms. For conditions in which the diaphragm is very stiff, relative to the soil ($F \leq 1$), it is possible to compare the three sets of results. Figure 6 shows a comparison of these results for the zero stress ratio case, which is the only one dealt with by all three solutions. Collins and others (7) have shown significantly higher registrations than those shown by Tory and Sparrow. The discrepancy between both sets of registrations increased as the aspect ratio increased.

Fossberg's results were for only one aspect ratio (0.13), but he did consider lateral strains. With no lateral restraint and no correction for induced lateral tension, Fossberg's conditions were the same as Collins and others, and this agreement is shown in Figure 6. Figure 5 shows this same comparison but with Tory and Sparrow's results. Hence, it would seem that the discrepancy between Collins and others and Tory and Sparrow is because of the effect of lateral tension on the cell. Because this effect cannot be transmitted in practice, the latter results are more realistic in this particular case of zero stress ratio. Collins and others applied tensile free-field stresses in their analyses and hence the induced cross stresses were actually compressive. Both have been reversed in the above discussion for compatibility with the other solutions.

A comparison between the various stress ratios used by Collins and others and by Fossberg at the particular aspect ratio Fossberg used is shown in Figure 7. Fossberg generated different stress ratios by considering K_o conditions and varying Poisson's ratio (ν_s) for the soil. Agreement between the solutions only occurs at two points: One is the zero stress ratio previously discussed and the other is a stress ratio of approximately 1 and a Poisson's ratio of nearly 0.5. For these values, K_o conditions apply and both theories have the same assumptions regarding lateral strain. For the lower stress ratios and Poisson's ratios, the solutions by Collins and others involve the development of lateral strain and the possibility of associated tensile stresses.

This discussion has indicated that pressure cell registration is affected by the applied stress ratio and the lateral strain situation as well as the other factors noted above that are in relation to Figure 4. Of these various factors, the one that is the least well defined is the lateral strain condition. In the ground, a pressure cell measuring vertical stress is likely to be in a K_o situation while an instrument measuring horizontal stress could experience some lateral strain. The former situation is predictable with some confidence from theory while the latter presents two difficulties. In addition to the poorly defined lateral strain condition, stress ratios greater than unity are likely to be applied.

It would seem prudent at this stage in the understanding of soil-cell interaction to try and design cells in such a way that the effects of both stress ratio and lateral strain conditions are minimized. This approach implies reducing C_T to zero in Equation 6, which has been suggested by Mills and others (8). Figure 8, derived from Collins and others (7), shows how this may be done by choosing an aspect ratio appropriate to the particular Poisson's soil ratio. Unfortunately, the required aspect ratio is sensitive to Poisson's ratio and as the latter is difficult to specify with accuracy and could also vary with stress conditions, this approach can, at best, only be approximate. Also shown is the range of aspect ratios that can be used for a particular Poisson's ratio for values of C_T between -0.05 and +0.05, which seems to be a reasonable range.

Design Considerations

The foregoing theory provides some guidelines for the design of pressure cells and an assessment of their likely registration. There are, however, a number of other design considerations, some of which have resulted from experimental investigations while others are concerned with practicalities. These considerations are outlined below and detailed information follows.

Peattie and Sparrow (9) showed that the diaphragm should not occupy more than 45 percent of the total area of the cell face. If the above limitation is observed, the high stresses shown in Figure 2 that occur at the edge of the cell would be confined to the annular ring around the diaphragm.

A stiff annular ring is also required to minimize cross sensitivity, so while Peattie and Sparrow's recommendations were aimed at free-diaphragm cells, the use of these rings would also seem advisable for restrained diaphragms. It is important to distinguish between this mechanical cross sensitivity and the effects produced by various stress ratios, as previously discussed.

The overall dimensions of the cell should be related to the soil particle size. While large particles can be kept away from the diaphragm during installation, the soil in contact with the diaphragm should not be allowed to vary greatly from that in the surroundings, otherwise further redistributions of stress are likely. Kallstenius and Bergau (10) have suggested that the diaphragm diameter should be at least 50 times that of the largest soil particle. Instruments that rely on indirect measurement of diaphragm deflection or strain are likely to be less affected by the individual point contacts of large particles than those that rely on direct measurement such as the cell in Figure 1.

In the case of free diaphragms, the requirement that a stiff diaphragm should be used conflicts with the need for an adequate electrical signal from the transducer. In these circumstances, an appropriate strain gauge or other transducer must be selected to provide an electrical output of adequate size for the available monitoring equipment.

In establishing the maximum stress that a pressure cell can be used to measure, two criteria must be considered. First, the central deflection of the diaphragm should not exceed $\frac{1}{2000}$ of its diameter (11), and, second, the maximum tensile stress in the cell material should not approach the yield value too closely. This maximum stress occurs in the radial direction at the built-in edge of the diaphragm on the outside of the cell.

Both diaphragm deflection and stress are dependent on the material from which the cell is manufactured. It is important that corrosion should be avoided, particularly in long-term installations, and, for this reason, three metals such as aluminium alloys, stainless steel, and titanium have been chosen most often by various investigators.

Two important practical considerations are that the cell should be waterproof and that cable entries should be strong enough to resist the stresses imposed during installation. The arrangement shown in Figure 1 has generally been satisfactory in practice but has been improved recently by screwing the cable entry into the body and by covering the cable with an additional strengthening sleeve where it passes into the metal cable entry (12).

The selection of a particular type of pressure cell will depend on various factors that will include the peripheral equipment available to drive and monitor the cells. Those cells with a simple, strain-gauge bridge only require a power pack, which balances circuitry, and a recorder for dynamic work. More expensive cells also tend to require more expensive ancillary equipment. However, the other instrumentation envisaged for a particular experiment should be taken into account in the planning stage.

Laboratory Calibration Tests

The foregoing discussion has indicated that a pressure cell will in general not register the exact field stress; however, with well-designed instruments, the error may not be very large. Experience with controlled calibration tests has often indicated errors larger than those predicted by theory. Perhaps these errors are because of the difficulty in precisely modeling the in situ conditions, particularly those resulting from placement technique.

Thus, it is clearly desirable to calibrate pressure cells under controlled laboratory conditions that reproduce, as closely as possible, the field situation. This situation implies that attention be paid to moisture content and compaction of the soil generally and in particular around the instrument; that the same installation technique is followed as on site; that the cell is subjected to the range of stresses in all anticipated directions; and that this is done at the appropriate rate of loading.

Two kinds of tests have been used for pressure cells, both employing large-diameter (225 to 950 mm) cylindrical samples with the cell installed centrally. The samples have been either tested in a rigid cylindrical container reproducing K_o conditions (2, 6, 13, 14) or as triaxial samples (15, 16, 17, 18) when the vertical and lateral stresses can be varied in different combinations.

When a pressure cell is used in a particular soil both the stress ratio and the flexibility factor can change as the stress conditions change. The magnitude of the resulting changes in cell registration has been evaluated for the U.K. Transport and Road Research Laboratory/linear variable differential transformer (TRRL/LVDT) cell (Figure 9) and the Nottingham cell (Figure 1) in two different soils, a silty clay and a fine crushed stone under a variety of stress conditions (19). The range of registrations from theoretical considerations was less than 10 percent, which, from a practical viewpoint, falls within the scatter band obtained in most experimental work. In comparing experimental results with

Figure 8. Curve for limiting cross sensitivity.

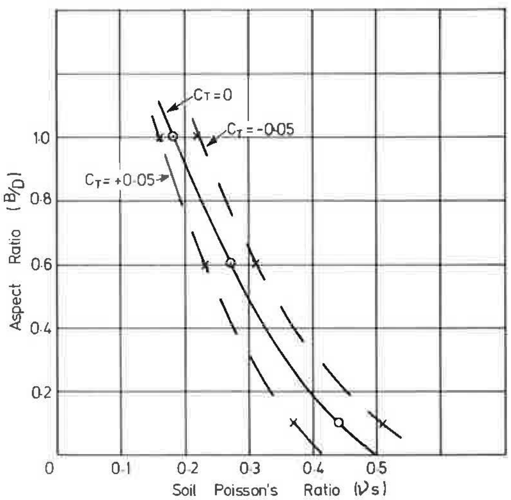
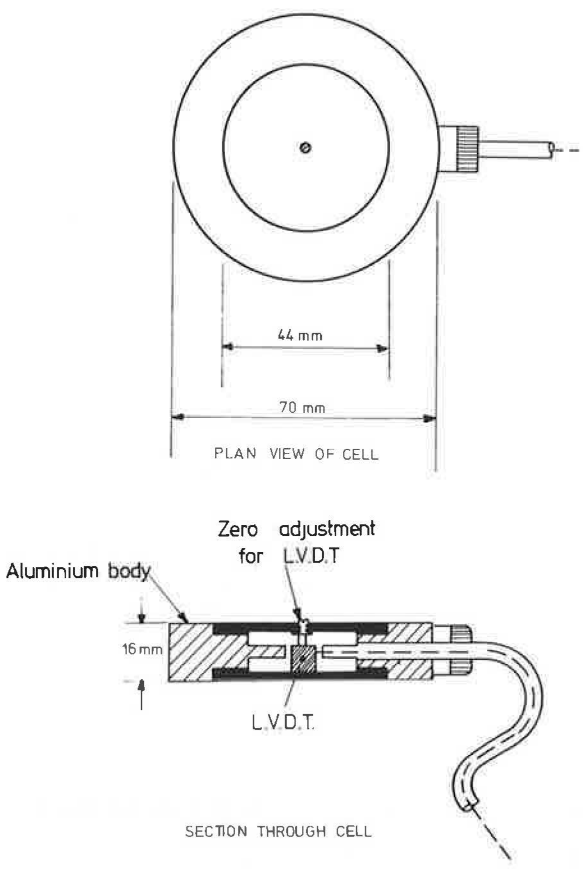


Figure 9. TRRL/LVDT pressure cell.



theoretical predictions, average registrations over the chosen stress range in individual calibration tests were compared with the average theoretical values. Although there was considerable scatter in the experimental cell registrations, good correlation was obtained between the mean values and those predicted from theory. Best comparison was obtained when more than six experimental results were available, which implied a fairly reliable mean value.

Hence it was concluded that the performance of pressure cells with flexible diaphragms can be predicted with some confidence, provided the anticipated stress conditions and corresponding values of soil modulus are known. It was also clear that registrations from laboratory calibration tests should be based on a reasonably large number of tests, in view of the scatter of results caused by placement technique, even when using experienced personnel. Therefore, it is even more important to obtain as many duplicate readings in a field situation as possible.

Installation Techniques

The calibration work previously summarized emphasized the need for reliable installation procedures. Experience suggests (13, 20, 21) that, for clay, a pressure cell measuring vertical stress should be installed with the diaphragm up in a precut recess in the soil surface. A trench should be provided for the cable. Care should then be taken in placing selected soil over the diaphragm to ensure that no large particles are included. After hand compacting a thin layer of such soil, the next layer of soil may be compacted by whichever site method is being used. For loose sand, Ingram (13) found that the best results were obtained by tamping the cell into the surface of the soil with a rubber-ended rod and then gently compacting the soil around the cell with a rod and a metal plate.

Details of Instruments

The instruments described in the following have been selected because they are representative of the various kinds used by different investigators; however, there are many other kinds available.

Nottingham Pressure Cell

The Nottingham pressure cell (16, 19, 20, 21) shown in Figure 1 is basically a titanium-recessed disc, the bottom of the recess forming a 2-mm thick diaphragm, with the lid enclosing the cavity. A 4-arm, active, strain-gauge bridge is bonded to the diaphragm: The gauges are arranged to reduce cross sensitivity and to give maximum output from the tension-compression characteristics of the diaphragm. The bridge is supplied by 10-V direct current (DC) and the output is fed to a galvanometer of an ultravoilet recorder. Potentiometric balance is provided across chosen arms of the bridge, and a 500 kΩ calibration resistor can be switched across one arm to simulate a fixed stress input.

The TRRL/LVDT Pressure Cell

The TRRL/LVDT pressure cell incorporates a LVDT displacement transducer set between two diaphragms that are screwed to each side of a thick annular ring, as shown in Figure 9. The core fitted to one diaphragm can be screwed to its null position in the LVDT body attached to the other diaphragm. The cell is then sealed and maintains this position under zero pressure. The cables pass through a tube with enough clearance to allow dissipation of pressure buildup in the gauge cavity. Thus, any pressure on the diaphragm is registered by the LVDT and any cross stresses are reduced by the stiff outer ring.

The TRRL Piezoelectric Pressure Cell

The TRRL piezoelectric pressure cell (22, 23) (Figure 10) uses the piezoelectric properties of quartz crystals. There are four, X-cut crystals positioned on either side of a central web (two on each side) that are connected to

Figure 10. TRRL piezoelectric pressure cells.

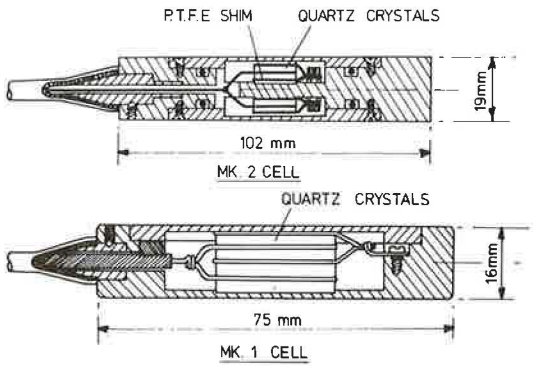


Figure 11. Kyowa pressure cell.

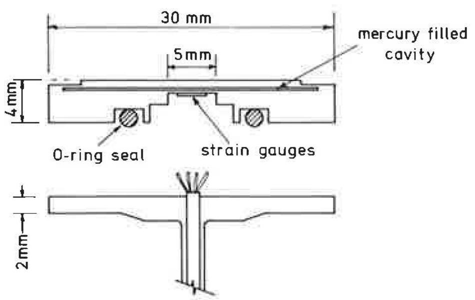
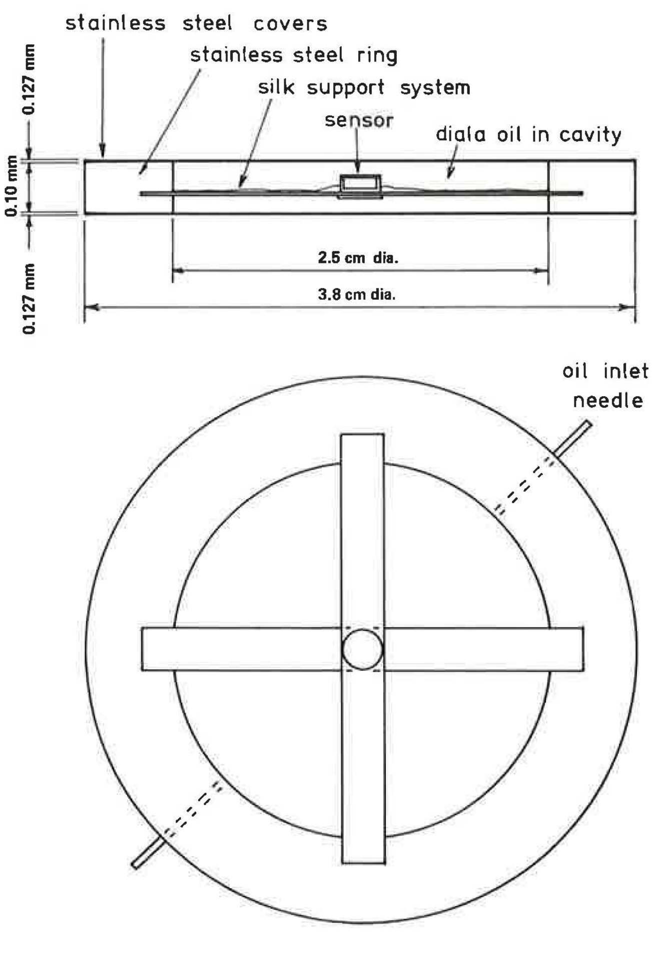


Figure 12. URS free-field stress gauge.



a thick annular ring. Two diaphragms are screwed to the ring in such a way that they are slightly arched by the trapped crystals. Copper shims are used to collect the charge generated across the surfaces during dynamic loading and the output is transmitted by means of a coaxial cable that is glued through a hole in the annular ring. A polytetrafluoroethylene (PTFE) sheet is inserted between the copper shims and the diaphragms to reduce the distortion caused by transmission of shear.

The Mk 1 and Mk 2 pressure cells are available to this design, the latter being of a much stiffer construction design to reduce mechanical cross sensitivity. Both cells are shown in Figure 10. The Mk 1 is only recommended for measurement of vertical stress because of its cross sensitivity. The quartz crystals of this cell only respond to changes in pressure; therefore, this cell can only be used for dynamic measurements.

Kyowa Cell

A cross section of the Kyowa cell (24) with a thin, mercury-filled cavity is shown in Figure 11. The pressure is determined by a strain-gauge bridge attached to the back of an inner secondary diaphragm with a 5-mm diameter, which is considerably smaller than the 27-mm outer diaphragm. A shortcoming in practice is the centrally situated cable entry emerging opposite the diaphragm. This arrangement has been shown to be unsatisfactory because it causes considerable disturbance to the stress regime around the cell (7). However, a normal radial edge cable entry could be incorporated without much difficulty. This cell is similar in principle to, though smaller than, the Plantema cell (25) that has an edge cable entry and the Waterways Experiment Station (WES) cell described below.

United Research Service Cell

The United Research Service (URS) cell (26) shown in Figure 12 was developed by the URS research company for the Federal Highway Administration of the U.S. Department of Transportation. It consists simply of two stainless steel discs separated by an annular ring. The central void is filled with oil and a piezoresistive transducer is mounted on crossed webbing within the oil. This cell has the advantages of low aspect ratio (0.03) and high stiffness. It is suitable for long-term static or dynamic applications. However, the cost is likely to be high.

WES Cell

A number of WES cells (29) have been developed and used by the U.S. Army Engineers at the Waterways Experiment Station over the years. These cells have varied in diameter from about 5 to 60 cm. The 15.2-cm diameter cell (27, 28, 29) that has been used successfully on a number of projects is shown in Figure 13. This cell uses the indirect diaphragm principle having a cavity filled with mercury. Details of a smaller cell (13) that incorporate twin diaphragms carrying semiconductor strain gauges are shown in Figure 14.

Summary

The above discussion about earth pressure cells was an attempt to outline the current state of the art in theory, design, and use of these instruments. A summary of the particular instruments described above is given in Table 1. This summary includes important dimensions, characteristics, usage, and relative cost of the cells and their peripheral equipment.

In general, strain-gauge bridges are suitable for

Figure 13. WES soil pressure cell.

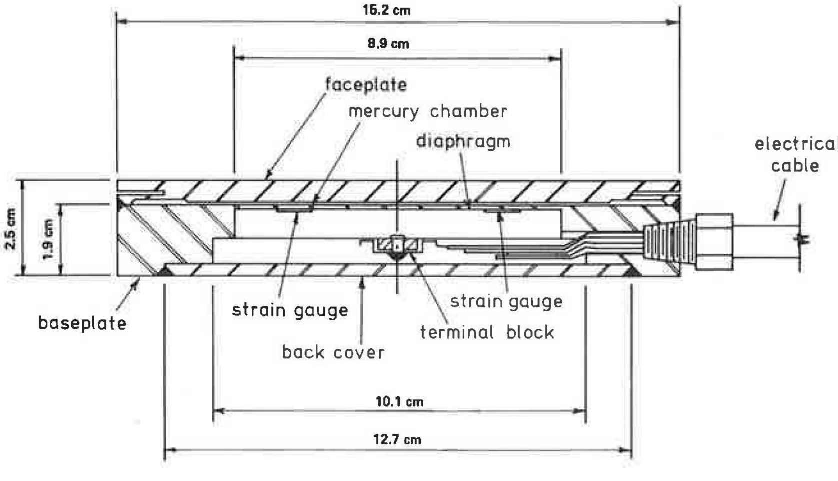


Figure 14. WES soil stress gauge.

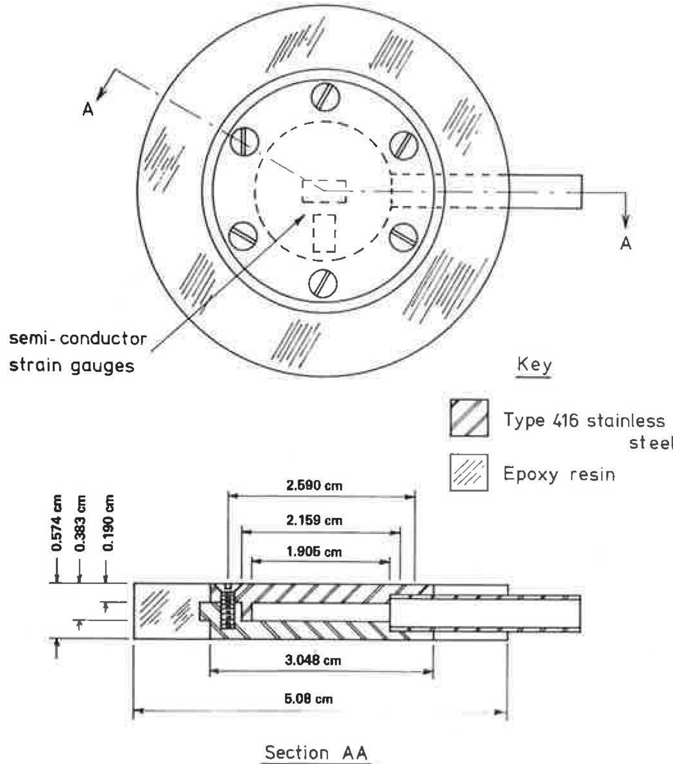


Table 1. Characteristics of various earth pressure cells.

Pressure Cell	Material	Diaphragm	Transducer	Usage	Relative Cost of Cell	Relative Cost of Peripheral Equipment	B (mm)	D (mm)	t (mm)	d (mm)	B/D	Area Ratio $=(d/D)^2$
Nottingham	Titanium	Free	Foil gauges	D, SS	Low	Low	11	64	2	38	0.17	0.35
TRRL/LVDT	Aluminum	Free	LVDT	D, SL	Medium	Medium	16	70	1.3	44	0.23	0.40
TRRL Piezo. Mk 2	Aluminum	Restrained	Quartz crystals	D	High	Medium to high	19	102	–	32	0.19	0.10
Kyowa	Steel	Indirect	Foil gauges	D, SS	Medium	Low	6	30	0.5^a 0.1	27^a 5	0.2	0.87^c
URS	Stainless steel	Restrained	Semiconductors	D, SS	High	Low to medium	1.5	38	0.13	25	0.04	0.43
WES 1	Stainless steel	Indirect	Wire gauges	D, SS	Medium	Low	25	154	4.5^b	146	0.16	0.90
WES 2	Stainless steel and epoxy	Free	Semiconductors	D, SS	Medium	Low to medium	5.7	51	1.9	19.1	0.11	0.39

Note: D = dynamic, SS = short-term static, and SL = long-term static.

[a]Outer and inner diaphragms respectively. [b]Inner diaphragm thickness varies. [c]Collar added to reduce this to 0.45.

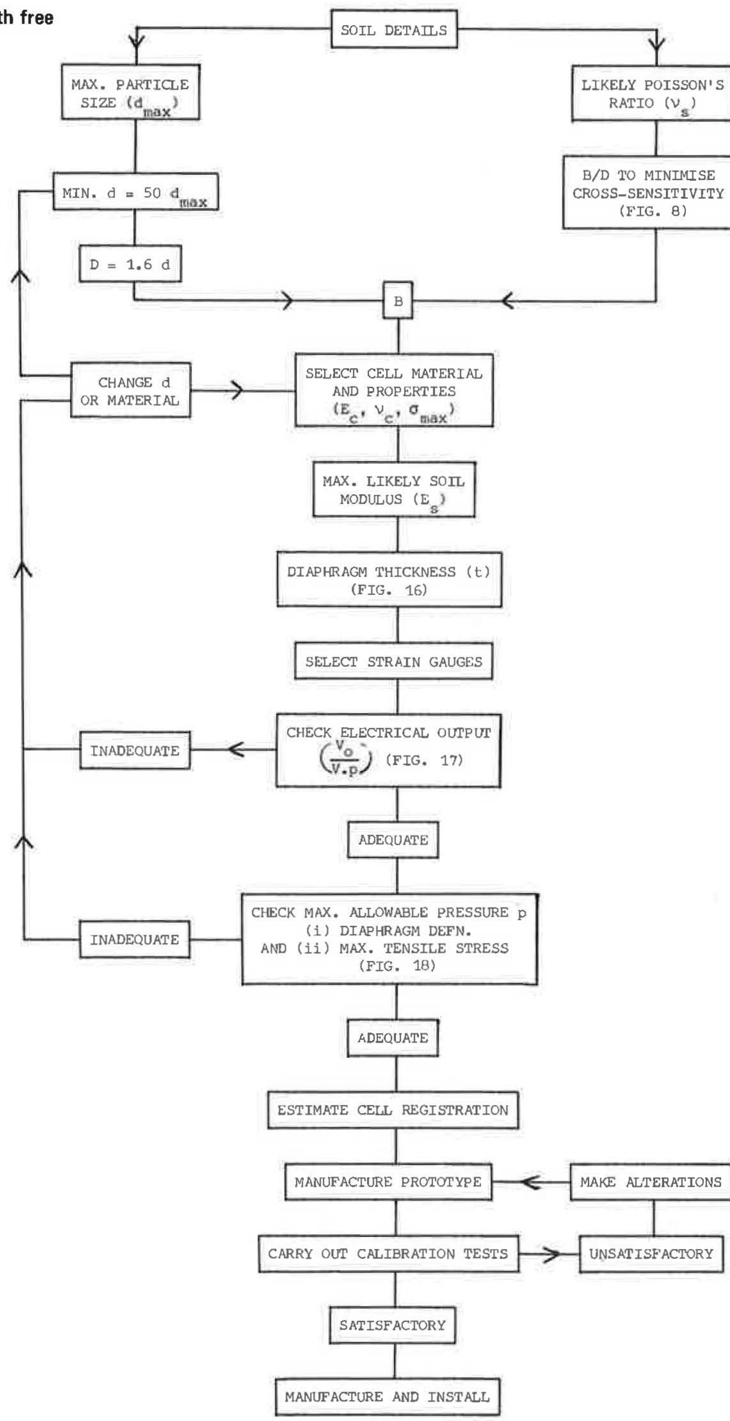
both short-term static and dynamic applications. They are not, however, so suitable for long-term static measurements because of possible zero drift. Temperature changes contribute to this drift, but this effect can be minimized by careful matching of the resistances of strain gauges, particularly of the semiconductor type.

Temperature changes in situ will generally not be large but should not be ignored, particularly if small changes of stress are envisaged. For dynamic measurements, temperature effects and other causes of slight zero drift are not of importance, provided either a four-arm active bridge is used or dummy gauges are provided to effect temperature compensation.

Most of the cells described are not readily available through normal commercial channels. These cells were developed for particular projects, which emphasizes the need to design instruments to suit particular site situations. However, detailed procedures and design examples are given in the following for the free-diaphragm kind of cell. This cell is generally the least expensive to make and it operates for short-term static or dynamic applications.

Almost all the experience of in situ stress measurement has involved cells in soils, little work has been reported on measurements in asphalt or granular materials (21, 30, 31). The basic principles of design are the same for these materials as for soils, but, in the case of asphalt, higher stiffnesses are involved and

Figure 15. Design procedure for earth pressure cells with free diaphragms.



the instrument and cable will need to be resistant to the high temperatures at installation.

Design Procedure for Free-Diaphragm Earth Pressure Cells

A summary of the design procedure is presented in Figure 15. A series of graphs have been prepared and these are referred to at the appropriate points in the flow diagram to facilitate the calculations.

Thus, a desirable diameter for the diaphragm is established by considering maximum soil particle size or, in the case of fine-grained soils, factors related to the practicalities of manufacture. An initial diaphragm thickness can then be obtained by using Figure 16. This figure is based on the suggested maximum flexibility factor of unity, knowledge of the maximum soil modulus and the cell material. Aluminium, stainless steel, and titanium have been used in this graph and other graphs because they are the three most commonly used metals for pressure cells. The lines in Figure 16 are described by Equation 3, which defines the flexibility factor; Equation 3 can be rearranged as follows:

$$(d/t)^3 = (E_c/E_s)F \qquad (7)$$

Figure 16. Determination of d/t from soil modulus and cell material.

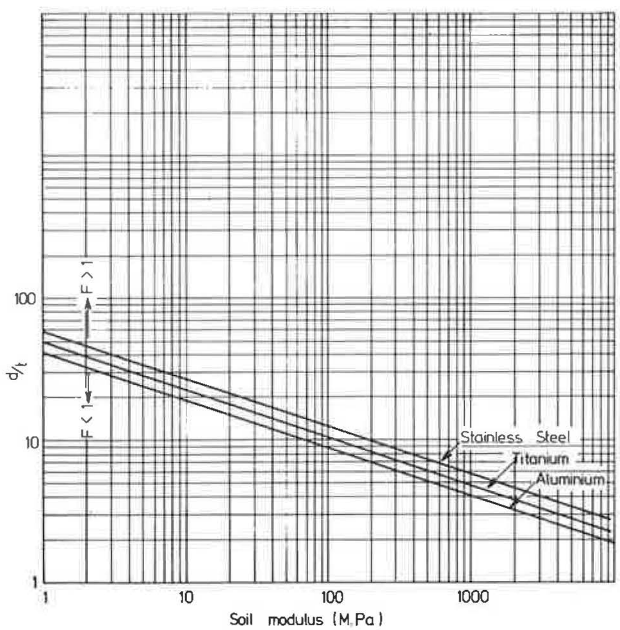


Figure 17. Determination of electrical output from d/t, cell material, and gauge factor.

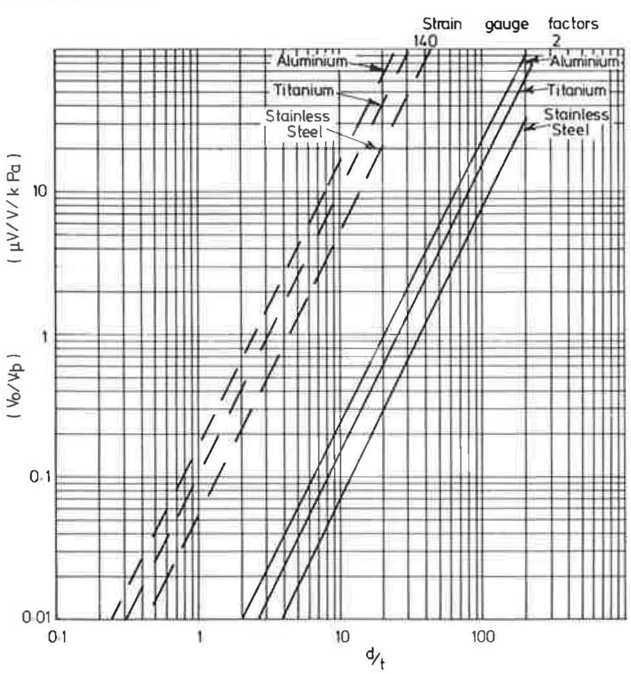


Figure 18. Determination of maximum allowable field stress from d/t and cell material.

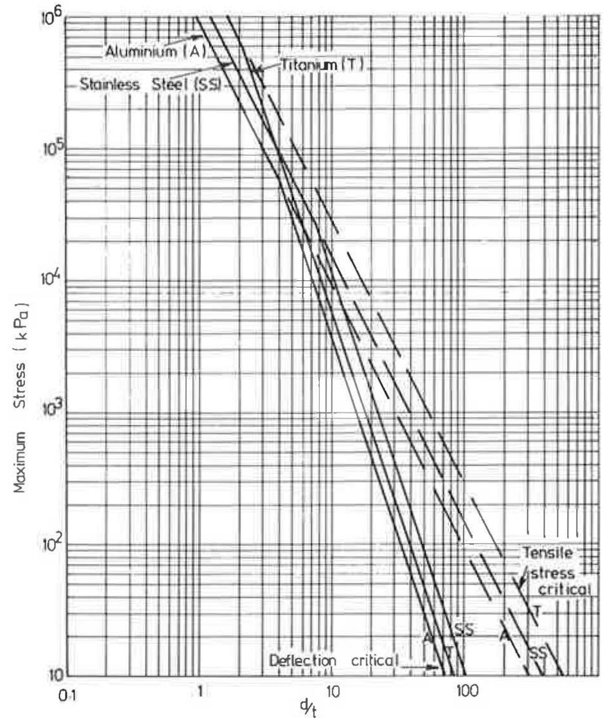
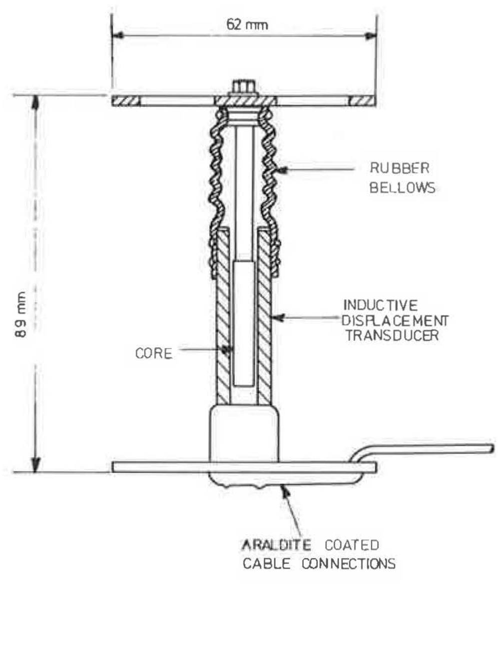


Figure 19. TRRL strain cell.



As shown in Figure 17, the electrical output to be expected from the cell can be determined in relation to the bridge voltage and stress being measured. Examples are given of foil strain gauge bridges that have gauge factors of 2 and of semiconductor bridges that have gauge factors of 140. Other lines could be established by using the following equation:

$$(d/t)^2 = (V_o/V_p)[32E_c/3G(1-\nu_c^2)] \quad (8)$$

where

V_o = output voltage,
V = bridge voltage,
p = applied stress,
E_c = Young's modulus,
ν_c = Poisson's ratio of the cell metal, and
G = strain gauge factor.

The decision as to the acceptability or otherwise of a particular bridge output will depend on the minimum stress to be measured and the sensitivity of the monitoring equipment. The procedure for determining stress and sensitivity is illustrated in the design examples below.

The maximum stress to which the pressure cell can be subjected is determined from Figure 18. Thus, the diaphragm deflection and the maximum tensile stress criteria are brought together. For limiting the deflection to a diaphragm diameter of $1/2000$, the maximum pressure is determined by the following:

$$p(d/t)^3 = E_c/[23.4(1-\nu_c^2)] \quad (9)$$

On the assumption that the maximum stress in the metal should not exceed half the yield stress (σ_y), this criterion gives the following:

$$p(d/t)^2 = 2.67\sigma_y \quad (10)$$

Figure 18 shows that the deflection criterion is critical except for cells with relatively thick diaphragms. The deflection criterion is only relevant to the performance of the cell in situ but the maximum stress criterion is also applicable during the so-called scragging process carried out after strain gauging and before the instrument is used. This process involves the cyclic application of stresses that at least covers the range expected in practice so that the stresses built into the metal during manufacture can be relieved.

Once a satisfactory cell has been designed, it is desirable that calibration tests be carried out in the soil involved in the investigation. A theoretical estimate of cell registration may also be obtained from Figure 4 or from the following equation based on C values for $F \leq 1$.

$$C = 1 + 0.56(B/D) \quad (11)$$

Strain Gauge Arrangement

A satisfactory arrangement of strain gauges on the cell diaphragm to provide a four-arm active bridge is indicated in Figure 1. This arrangement will result in approximately equal tensile and compressive strains from the gauges. The equation for radial strain is as follows:

$$\epsilon_r = (3a^2p/8t^2E_c)(1-\nu_c^2)[(3r^2/a^2)-1] \quad (12)$$

where

a = diaphragm radius ($d/2$) and
r = radius to the particular point.

From Equation 12, it can be shown that the compressive strain at $r = 0.82a$ is numerically equal to the tensile strain at $r = 0$. Since the strain gauge measures the average strain over its gauge length, this equality will occur for a gauge length of 0.36a when the arrangement of Figure 1 is used. This figure is reasonable for many strain gauges. The perpendicular arrangement of both pairs of gauges is to minimize mechanical cross sensitivity. Circular strain gauge arrangements specially designed for diaphragms are available as an alternative, but the calculation procedure would differ from that indicated above.

DESIGN EXAMPLE 1

The soil data include silty clay with a maximum particle size of 0.1 mm, a maximum E_s of 100 MPa, and a ν_s of 0.4. The material to be used is titanium. As shown in Figure 8, B/D is 0.2, which minimizes cross sensitivity. However, the minimum d is 5 mm (50 × 0.1), which is impracticable. Therefore, for adequate cable entry, it is assumed that the minimum B is 6 mm, D is 30 mm (6/0.2), and d is 18.8 mm (30/1.6). As shown in Figure 16, maximum d/t is 10.5; therefore, t is 1.79 mm. By using conventional strain gauges (G = 2), Figure 17 shows the electrical output as 0.17 μV/V/kPa. It is assumed that the minimum resolution on the monitoring equipment is 10 μV, the minimum stress to be measured is 3 kPa, and the required bridge voltage is 19.7 V [10/(0.17 × 3)]. Because the maximum allowable current through most strain gauges is 20 mA, the bridge current will be 40 mA and the gauge resistance will be 492 Ω [$19.7/(40 \times 10^{-3})$]. Thus, for instance, 600 Ω gauges and a 20-V supply are used. As shown in Figure 18, the maximum stress that can be measured is 4500 kPa, and the maximum allowable stress during scragging is 25 000 kPa. The cell registration is then estimated from Equation 11 as C = 1 + (0.56 × 0.2) = 1.11.

DESIGN EXAMPLE 2

The soil data include sand with a maximum particle size of 2 mm, a maximum E_s of 500 MPa, and a likely ν_s of 0.2. The material to be used is stainless steel. As shown in Figure 8, B/D is 0.9, which minimizes cross sensitivity. However, the minimum d is 100 mm (50 × 2); therefore, D is 160 mm and B is 144 mm. As shown in Figure 16, the maximum d/t is 7.3; therefore, t is 13.7 mm. As shown in Figure 17, V_o/V_p is 0.037 μV/V/kPa. For a V of 24, V_o/p is 0.89 μV/kPa. For a minimum resolution of 10 μV, the minimum p is 11.2 kPa. However, if this is unsatisfactory, then semiconductor strain gauges are used. As shown in Figure 17, V_o/V_p is 2.8 μV/V/kPa for a G of 140 and this is satisfactory. As shown in Figure 18, the maximum stress is 13 000 kPa. The cell registration is then estimated from Equation 11 as C = 1 + (0.56 × 0.9) = 1.5.

SOIL STRAIN CELLS

Basic Principles

Stress gauges need to be stiff for reliable performance; however, strain cells need to be of low stiffness so that their operation does not reinforce the soil or impede its deformation. The instrument must move with the soil and provide a minimum of interference. Deformation is measured over some known gauge length to determine strain. This implies that the instrument must determine the relative movement of two points in the soil.

Figure 20. Bench calibration of strain coils.

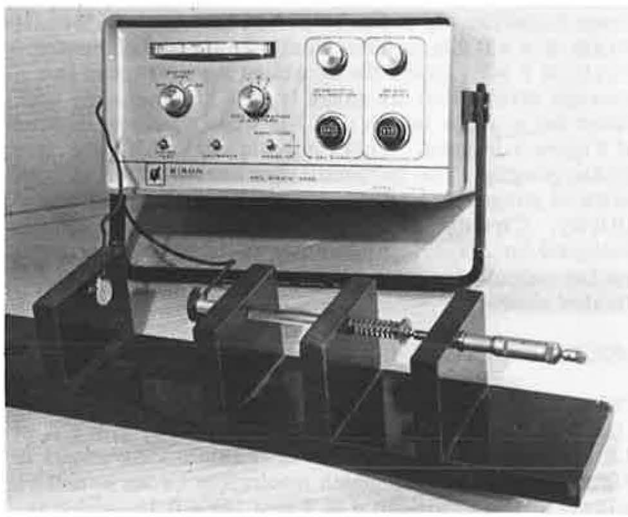
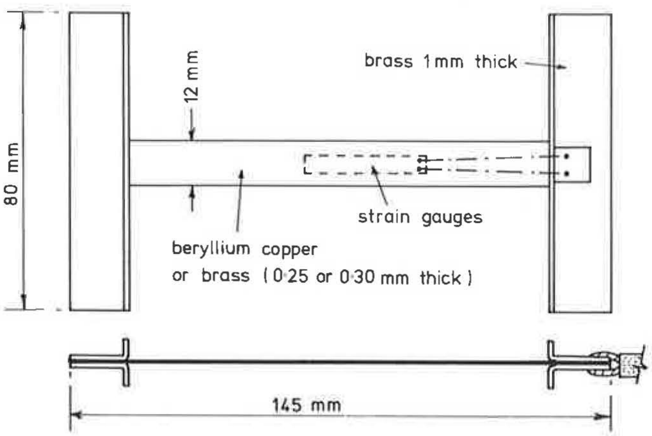


Figure 21. Strip gauge used by NIRR.



Relatively little attention has been given to soil strain measurement but some satisfactory instruments have, none the less, been developed.

Instruments

Basically, two kinds of instruments are available. One works on the principle of the TRRL version shown in Figure 19 in which the two end discs move relative to each other; the movement being determined by a built-in displacement transducer. This kind of instrument relies on a satisfactory shear break developing to provide a transition from the uniform deformation in the soil between the end plates and the concentrated movement of the instrument at one end. This movement is achieved by greasing and particularly by using the rubber bellows over the parts where relative movement takes place. The bellows also prevent soil from inhibiting free mechanical movement. The soil core between the end plates is prevented from being compressed unduly by using one end plate with an open section, which is shaped like a steering wheel.

The main shortcoming of this instrument is the mechanical linkage between the ends of the gauge length. This linkage causes problems of installation and friction that inhibit free movement (15). These problems are overcome in the other kind of instrument that consists of a pair of strain coils (32).

Generally, the two wire-wound induction coils are placed, coaxially but they can be used in a coplanar or orthogonal mode. An alternating current (AC) set up in one coil induces a current in the other coil, the magnitude of which depends on the coil spacing. The coils and the operating equipment are available commercially from Bison Instruments and field use has been reviewed by Selig (33).

Coil spacing can be up to 4-coil diameters and various sizes of from 2.5 to 35.6 cm in diameter have been used in a variety of projects. This instrument is suitable either for dynamic or static work and long-term stability is good. They have been used in asphalt materials as well as soil (21, 34, 35).

A problem does arise with strain coils when they are used near metal objects, which interfere with the flux linkage between the coils. This interference is particularly important when the metal moves such as when a wheel is over a test pavement and it comes within about five times the gauge length of the coils. Attempts have been made to overcome this difficulty by shielding the coil with a layer of aluminium foil on the pavement surface (35). However, this interference problem only affects dynamic measurements.

The coils are relatively inexpensive, but the electronic unit required to monitor a single pair of coils is quite expensive. For static measurements, switching between pairs of coils overcomes this restriction, but, if simultaneous dynamic readings are required, then several units are needed. For dynamic measurements, strains 0.003 percent can be resolved and for long-term measurements the percentage is about 0.1 (33).

The bench calibration of strain coils is carried out in an apparatus of the kind shown in Figure 20 wherein the spacing of coils can be accurately related to the electrical signal. If the medium in which the cells are to be used is likely to contain ferrous metal ions, special calibration may be required by placing the coils in samples of the material. An indication of the need for this can be obtained by placing a sample of the material between the coils when they are set up in the calibration apparatus shown in Figure 20 (21, 36). The coils are fairly tolerant to errors caused during installation or subsequently thereafter, which involve movements in directions other than the one in which measurements are being taken (33, 36).

The installation of coils in soil is a relatively easy process. An electrical technique can be used to position a second coil over a first coil that is already buried. The coil is moved until a maximum output is recorded, i.e., when exact coaxiality is achieved (33).

STRAIN GAUGES FOR BOUND LAYERS

The strain measuring devices that have been used in bitumen or cement-bound pavement layers are of three types: foil-strain gauges cemented to carrier blocks or directly placed on an exposed surface; strip gauges (24) of the type shown in Figure 21; and the strain coils previously described. When working in bituminous layers, high temperature resistance is required of both the instruments and the electrical cables, if placement is to be undertaken during paving operations, as is generally the case.

Care should be taken to ensure that carrier blocks have a stiffness that is less than the material in which they are to be placed so that the blocks do not reinforce the layer, which would cause low strains to be recorded.

Foil Strain Gauges

Foil strain gauges (37, 38, 41) may be used for measuring either vertical or horizontal strains and experience has been confined to bituminous layers. Horizontal strain at the bottom of a bituminous layer can be successfully measured by a strain gauge cemented to a carrier block. This block is let into the underlying layer so that the surface carrying the gauge is flush with the top of this layer. Subsequent paving over this arrangement results in the gauge adhering to the bottom of the bituminous layer. Care is taken to remove large aggregate particles from the mix placed immediately over the strain gauge.

Vertical strain gauges have to be placed on carrier blocks and good results are obtained by sandwiching the gauge between two blocks, for protection, and then placing the block on the surface before paving. This surface can either be the underlying layer or an intermediate bituminous layer.

Strip Gauges

The TRRL version of the strip gauge (23) consists of two 6.3-mm square steel bars connected by a thin strip of aluminum that carries a foil strain gauge on either side. The South African version of the strip gauge used by the National Institute for Road Research (NIRR) (24) is shown in Figure 21. Protection of the gauges can be provided by molding polyethylene around each gauge before installation or simply by wrapping each gauge with polyvinyl chloride tape.

The instrument is laid on the surface below the bituminous or cement-bound layer and paving takes place over that layer so that a measure of horizontal strain at the bottom of the layer may be subsequently obtained. The instrument may alternatively be cast into a block of the bound material that is then placed face down on the surface before paving.

These gauges are rather stiff and this would seem to violate the basic principle of in situ strain measurement. In view of this, it is surprising that hardly any relevant calibration tests seem to have been performed with these gauges. Bohn (as related through private conversation) has shown from tests with various gauges placed at the bottom of asphalt beams that their stiffness relative to the asphalt is very important and should be minimized. He used some gauges with a plastic strip having a modulus of elasticity 25 times lower than that for aluminum, but even these tended to underregister the true strain, even when the asphalt modulus was relatively high. Calibration tests with this type of strain-measuring device are therefore strongly recommended before installation in a test pavement.

Strain Coils

When used in bituminous material, the coils may be attached to an intermediate layer by using a tack coat or they can be mounted on carrier blocks. In the latter case, care should be taken to ensure that the block is not moved unduly because the mix is compacted above and around the block. Hand compaction of material around the carrier block before paving can help. An alternative procedure (36) for placing coils slightly below the current level of construction is to cut a circular hole and place the coil in a hot mastic mix. A similar technique can be used for placing a pair of horizontally aligned coils.

Intereference by moving metals is particularly marked for coils that are to be used in surfacing layers. In addition, the minimum resolution of about 0.003 percent strain could be a problem in stiff bound layers.

DEFLECTION GAUGES

Measurement of transient surface deflection of pavements is carried out extensively in connection with overlay design. However, the standard methods involving the Benkelman beam or Lacroix deflectograph involve slow speeds and equipment at the surface, which does not provide particularly accurate measurements. It is an advantage, therefore, in full-scale trials to have in situ, deflection-measuring equipment that can provide not only surface measurements but also interface deflections. Three basic kinds of equipment appear to be available for this purpose.

Displacement Transducers

The principle of the method of displacement transducers (23, 29, 33) is that a rod is driven into the subgrade at a sufficient depth to be beyond the zone of influence of wheel loads (about 2 m), and an LVDT or similar transducer attached to the top of the rod registers movements of the particular level in the pavement relative to these data. Alternatively, the datum could be at an interface; therefore, deflection of one or more layers above this point could be determined. The disadvantage of this method is that a hole has to be made through the pavement to accommodate the rod, and the hole has to be lined so that the rod is free from the surrounding material; otherwise, it would reinforce the pavement and make the datum ill-defined.

An advantage is that the displacement transducer can be screwed into the top of the rod when measurements are required and replaced afterwards by a blank plate at the surface. In addition, both permanent and transient deflections can be determined.

Optical Method

An optical method has been developed by Hofstra (private conversation) in which a 1.5-mm laser beam was used. This beam is passed through a thin rectangular metal tube (4 by 5 mm) cemented in an indentation on the asphalt surface. The beam is partly intercepted by a thin blade positioned vertically in the tube beneath the wheel track. Application of a wheel load changes the blade position and hence affects the intensity of light reaching the other end of the tube. The intensity of light is measured by a photoelectric cell and can be related to the surface deflection after suitable calibration.

This arrangement has yet to be used on a full-scale trial but a similar system has been used successfully in Holland (39). A light beam was projected along a tube to two photoelectric cells located in the road surface. The output from the cells was changed by their movement under passing wheel loads and the deflection determined from prior calibration.

Accelerometers

The use of accelerometers is attractive because installation is simple and no rods or tubes are required, only the usual electrical connections. Electronic integrators are available to convert the acceleration measurements to deflection though this process requires that the output is zeroed before each wheel pass, which could present a problem if a train of wheel loads is involved. This technique would seem to be better for the determination of peak deflections than for defining the shape of the deflection bowl and only applies to transient measurements.

OTHER INSTRUMENTS

Equipment for Wheel Load Determination

The loading applied to a test pavement is an important parameter; therefore, correct evaluation is essential. If the experiment is to be loaded by using special trucks with a known wheel load, then no special provision is required for monitoring loads during testing. However, if tests are to be conducted on a public road using actual traffic, measurements of wheel loads are essential. Two basic kinds of equipment have been used for this purpose: One is the dynamic weighbridge (40), which is a major permanent installation, and the other is a portable, axle-weight analyzer (41).

The weighbridge developed by the British TRRL consists of a rigid platform supported by load cells and set so that its top is flush with the road surface. Its width (in the direction of the traffic) has to be sufficient to support the largest anticipated tire contact area and its length will depend on whether wheel or axle loads are to be determined. The arrangement must be rigid to prevent resonance interfering with the load cell signals.

The electronics associated with a weighbridge can count the numbers of loads in a series of load ranges, which produces an axle load spectrum. The active part of the weighbridge can be designed to be removable so that a dummy platform may be installed when measurements are not required.

The axle-weight analyzer developed by the South African NIRR has been designed to be portable so that information can be obtained from a variety of sites. It consists of a thin rubberized pad that contains two layers of metal foil separated by a soft rubber. This arrangement acts as a capacitor, the capacitance depending on the pressure applied by the wheel load.

The analyzer is stuck to the road surface by using hot bitumen and has a thickness of about 7 mm. A flat road surface is required for best results and care has to be taken over calibration. Detailed information on this piece of equipment has been described by Basson and others (41).

When taking in situ measurements of stress, strain, or deflection, it is important to know the position as well as the magnitude of the load, and various techniques have been used for determining these. Again, the procedure is easier if special loading trucks are used. For those cases, a metal detector strip is set in the pavement surface and can be used in conjunction with a pair of pickups on the truck, which are a simple visual guide for the driver. Alternatively, a row of photoelectric cells can be used to detect reflected light from the white marks on the pavement surface. For real traffic, a triggering mechanism is located in line with the instrumentation so that wheels proceeding down this line will register on the instrumentation.

Pore Pressure Transducers

Earth pressure cells register total stresses; therefore, it is desirable to be able to evaluate pore pressures so that effective stresses can be calculated. The measurement of long-term changes in pore pressure is relatively straightforward and has been done in earthworks by using piezometers of various kinds for many years. For the pavement test section application, a simple instrument has been developed at the Waterways Experiment Station (29). A porous stone allows the pore fluid to enter a small cavity that is protected from the influence of effective stresses by a strong surrounding. The changes of fluid pressure in the cavity, and, hence pore pressure, are monitored by a small pressure transducer. With modern technology, it should be possible to produce an instrument smaller than the one currently used that is based on the same principles.

The WES instrument was used to measure general changes in pore pressure during the test period, but the system has the potential for measuring transient changes caused by individual wheel loads. There are many problems in measuring these changes satisfactorily but the principal one is the need for a very stiff measuring system to reduce flow into the cavity to a minimum. The pore size of the filter element has to be small enough to prevent blockage by soil but large enough to allow adequate flow (20). These problems are particularly marked in fine-grained soils but dynamic pore pressure measurement has not been developed to the stage in which it can be reliably used in full-scale trials.

Temperature Transducers

When dealing with asphalt materials, it is important that the in situ temperature conditions be accurately determined. This parameter influences the behavior of the asphalt and, hence, often that of the entire pavement. Fortunately, temperature can be easily measured with thermocouples (42) or thermistor probes (29). These instruments can be placed after construction by drilling and filling the hole with bitumen, but less interference to the structure results from installation during construction. In the latter case, high temperature resistant wire is needed.

Soil Suction Measurements

In partially saturated soils occurring in regions with low water tables, the evaluation of soil suction has a significance exactly analogous to that of pore pressure measurement in saturated or nearly saturated soils. Satisfactory results can be obtained by using the psychometric technique (43, 44, 45, 46).

This method is used for measurements in situ or on samples. The soil suction (the measurement includes any osmotic contribution as well as capillary contributions) is determined from measurements and an empirical calibration curve. Continuous recording is not possible with the psychometric technique but repeated measurements may be made at intervals as short as 15 min. A variation of this technique called the Dew Point Method has been developed commercially and permits continuous measurement and recording.

When the instrument is in equilibrium with the soil, an accuracy of about 100 kPa over the range 0 to -5 MPa is normal. The wide range makes this instrument particularly useful in measurements related to pavement studies in most areas with low water tables.

Limitations of the method are that independent measurement of solute suction (osmotic contribution) is needed if measurements are to be related to pore pressures. The calibration is temperature dependent, and diurnal soil temperature changes prevent in situ operation within about 300 mm of the surface. The relatively low absolute accuracy is acceptable in pavements where soil suction is a significant factor and considerable practical use can be made of the technique (47).

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Field Observations of Rutting and Their Practical Implications

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Observation of a series of full-scale road experiments in the United Kingdom indicates that, after an initial period of deformation, reflecting compaction, and moisture changes, permanent deformation and rutting can be related to ranges of cumulative equivalent standard axles of 82 kN (18 000 lb). Cracking of structural significance seldom occurs until ruts have developed to a depth of 10 mm (0.4 in). After the cracking occurs, deformation behavior is more difficult to predict; continuity of the relation of the cumulative equivalent standard axles is most likely on stronger pavements. The marked influence of temperature and subgrade strength on deformation is demonstrated by results from the AASHO Road Test in the United States and from road experiments in the United Kingdom. Essentially similar behavior was observed in both countries, and differences can be related to differences in climatic conditions. Accelerated pilot-scale testing under controlled conditions of wheel load and temperature in a circular road machine has quantified the contributions of these two factors to deformation behavior. The link demonstrated between this type of testing and actual road behavior indicates its potential for developing and validating predictive models of deformation behavior.

Road deterioration under the action of traffic takes two main visible forms: cracking of the road surface and deformation in the wheel paths along which the great majority of heavy vehicles pass. The appearance of either form is not necessarily accompanied immediately by the other. Cracking at the pavement surface is normally a fatigue phenomenon originating either in the surface itself or in a cement- or bituminous-bound base beneath. Cracking that originates in the surface is associated with underdesigned pavements having bituminous materials of the asphalt concrete type or thin rolled-asphalt surface layers. Once cracking has become general, rutting will occur because the lower layers of the pavement or the subgrade or both are consequently overstressed and because those elements of the road are weakened by the ingress of water. Prediction of road behavior after general cracking has taken place is difficult, and in many cases the onset of general cracking must be taken as the effective end of the life of the road without structural maintenance.

Rutting can develop over many years without cracking taking place, particularly if the rutting is associated