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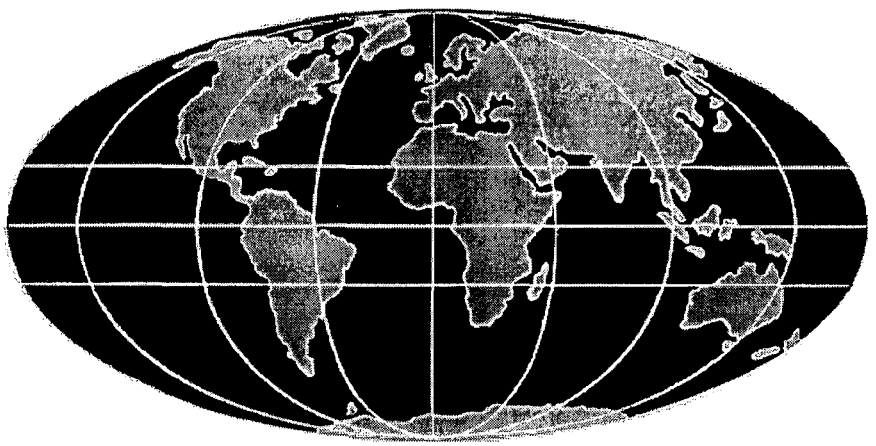
TITLE: Expansive clay road embankments in arid areas: moisture - suction conditions

by: M J O'Connell and C S Gourley



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EXPANSIVE CLAY ROAD EMBANKMENTS IN ARID AREAS; MOISTURE-SUCTION CONDITIONS.

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ABSTRACT This paper describes the importance of the moisture-suction condition on the behaviour of expansive soils and its significance to road engineering in an arid climate. The Transport Research Laboratory has developed instrumentation and techniques to measure both the moisture and the suction beneath roads. An example is given of some early results where the moisture and suction have been measured below a new road in an arid area. The results indicate that transient moisture-suction conditions as well as the equilibrium conditions may be important to the road design engineer. The techniques can be easily used to evaluate the moisture and suction conditions beneath roads.

INTRODUCTION

Expansive clays are normally excluded as an engineering construction material because of their potential to change in volume with a change in the moisture or suction condition of the soil. Volume change causes deformation and cracking in lightweight structures such as roads. However, expansive clays occur widely in arid climates and often in extensive plains where there is little alternative material for construction. This invariably causes a substantial increase in road construction costs because better materials must then be hauled long distances.

The moisture-suction condition of the soil in a structure can change after construction. The degree of change depends upon the complex interaction of the structure in which the soil has been used, the ground conditions and the climate. Where the relationship between these variables and the moisture-suction condition can be defined, there may be an opportunity to use these soils as engineering materials and to reduce construction costs. Good engineering design will account for both the mode and magnitude of change.

This paper describes a new instrument for the measurement of total suction and the use of a nuclear depth probe gauge to measure soil moisture content *in situ*. The techniques for the operation of both systems are given, including forming vertical access holes for the nuclear probe. Some results from measurements made in an expansive soil road subgrade are presented and discussed to demonstrate the value of the techniques.

THE NATURE OF EXPANSIVE SOILS

Origin of expansive soils

The formation of expansive soils depends on a complex interaction of a number of controlling variables, such as, weathering and erosion, prevailing climate, parent rock type, local topography and drainage.

Expansive soils have a world-wide distribution; their occurrence is not climate specific though they are particularly widespread in the dry tropics.

It appears that the primary source of residual expansive clay soils is the *in situ* weathering of basic igneous, metamorphic and pyroclastic rocks. Further erosion of these residual soils can lead to the development of areas of transported expansive soils. Other important sources result from transportation of clayey soils containing expansive minerals which are lithified into sedimentary mudstones and shales. Subsequent re-weathering of these sedimentary rocks leads to release of these expansive minerals back into the soil formation.

Clay-water interaction

Water that is bound to the solid part of the clay mineral takes two forms. These are:

(a) *Adsorbed water* of up to four molecular layers immediately adjacent to the surface of the clay mineral and which is relatively strongly bound.

(b) *Absorbed water* of variable thickness, located outside the adsorbed layers and which is less well bound.

The absorbed water, commonly referred to as the "diffuse double layer", contains exchangeable cations. It is the type of exchangeable cation and the variation in the thickness of this layer which causes the swelling and shrinking of clayey soils.

The ability of a clay mineral to adsorb and absorb water is an intrinsic property of the clay. It can be defined as "a property of the clay which results from its mineral composition and interaction with water"; it is not dependant on any particular condition of the soil that may exist at a moment in time.

It is possible to demonstrate that the volume change is dependant on the clay particle size and the thickness of the absorbed water. By comparison, the variation in thickness of the tightly bonded adsorbed water is small and is regarded here as remaining constant. Figure 1 shows the cross-section of the clay minerals montmorillonite and kaolinite and their respective bound water layers when their demand for water is satisfied. Montmorillonite and kaolinite have particle thicknesses of 10Å and 1000Å and total absorbed water thicknesses between adjacent particles of 400Å and 800Å respectively.

It can be seen that the ratio between the absorbed water and the particle thickness is 40 for montmorillonite and 0.8 for kaolinite. This indicates a theoretical potential volume change for montmorillonite of about 50 times that of kaolinite from completely dry to saturated conditions.

In clay-rich soils the solid particles are not in immediate contact due to the presence of the absorbed water. Volume change can occur by alteration of the thickness of the absorbed water without alteration of the particle arrangement. The amount of water in the absorbed layer, and thus the thickness of the layer, will be dependent on the stress state to which the soil is subjected. Increasing the suction will

remove water from the absorbed layer and cause shrinkage of the soil. Decreasing the suction will allow water to enter the absorbed layer, pushing the solid cores further apart and causing swelling.

Pore water composition

The composition of the pore water will also affect the absorbed layer thickness. Under otherwise similar conditions, a soil with a high salt content will have a lower void ratio than a soil with a low salt content. Where the water causing expansion of a soil is nearly salt-free, such as rainwater, the salt concentration of the pore fluid will tend to decrease as the water content increases. If the free water has a similar salt content to the pore fluid, as may be the case with wetting up due to ground water flow, then the salt concentration of the pore fluid will be unaffected. The soil wetted up with salt-free water will thus swell more than the soil in which the salt concentration in the pore fluid is maintained at a constant value.

Moisture content-suction

Moisture conditions beneath the ground surface are described by the moisture content and the pore water pressure. Where the pore water pressure is negative, it is usually referred to as the suction. Various factors will affect the moisture content and the suction, which are inter-dependent; a change in one will be associated with or will cause a change in the other. Partially saturated soil has an incomplete absorbed water layer. The total suction present in the soil comprises the effects of both the matrix and solute suction. The potential, or difference in energy level, between free water and the incomplete absorbed water layers is the cause of the matrix suction. In addition to this, there can also be a potential due to the presence of salts in the soil water which gives rise to the solute suction. It is the total suction which provides the driving force for moisture transfer and movement within the soil. It is the interaction between the availability of moisture and its ability to move through the soil, driven by suction, which determines the changes that will occur and thereby the volume change and bearing strength of an expansive soil.

EXPANSIVE SOILS IN ROAD ENGINEERING

During road construction it is of paramount importance that the expansiveness is adequately identified. The design engineer needs to address the influence of expansive soils both as naturally occurring undisturbed soils and as the compacted soils used in the road formation. It is necessary to identify the source of expected heave or shrinkage before selecting the design solution. Failure to correctly identify these soils and adopt appropriate engineering design could lead to failures and costly remedial works.

Volume change

For saturated soils only, the volume change of the soil will be equal to the volumetric moisture content change. In the partially saturated state, the relationship between moisture change and volume change of the soil will be affected by factors such as the fabric and structure of the soil and hysteresis in the moisture content-suction relationship.

Volume change of an intrinsically expansive soil is caused by a change in moisture content or suction. The soil volume increases with an increase in moisture content or a decrease in suction, and conversely a volume decrease occurs with a decrease in moisture content or an increase in suction.

Heave and shrinkage

Heave is the vertical displacement of a point in a soil mass that results from an increase in the volume of the soil. It is the parameter usually measured in the field and it is related to swell measured in the laboratory. However, the conditions in the field may differ from those used in the estimation of swell by empirical or laboratory methods and account must be taken of factors such as overburden and foundation stresses, and initial and final suctions or moisture contents.

Shrinkage is the vertical displacement of a point in a soil mass that results from a decrease in the volume of the soil. It may be as significant as heave in terms of potential damage to road structures.

Expansive soil movements can be broadly grouped into two categories. The first, monotonic heave, occurs where relatively stable moisture conditions are established under a covered surface. This is generally associated with the formation of a domed ground profile, with the maximum heave occurring near the centre of a structure or, for example, the centre-line of a road. The second, seasonal movement, which includes heave and shrinkage, occurs where alternate wet and dry seasons are a feature of the climate. Seasonal movement of this type causes heave at the edge of the sealed surfaces. With the onset of drying, the soil shrinks leaving the edge unsupported which may then drop and crack. Roads are intolerant of this alternating heave and shrinkage and ultimately the movement produces longitudinal cracking.

CLIMATIC FACTORS

Water is supplied by infiltration of rainfall, by a rise in the ground water level, and as a consequence of actions taken by man. These will be associated with a decrease in suction toward a value of zero. Acting in opposition to this is the removal of water from the ground by evaporation and transpiration, and by a depression of the groundwater level. These processes will be associated with an increase in suction.

The availability and sources of water must be investigated at design. A useful means of visualising the flow and sources of water at the site is shown in the block diagram given in Figure 2. If possible sources of water are not identified correctly, then it will not be possible to design for the likely changes in the moisture state that may occur during the lifetime of the road. Pronounced changes in suction in soils occur seasonally in many areas of the world. Evaporation exceeds precipitation in dry climates, leading to a water deficit and an increase in suction. It is important to know which point in the seasonal cycle coincided with the site conditions during any surveys.

The Thornthwaite Moisture Index (Thornthwaite 1948), TMI, provides a rational method for classification of climate. The TMI categorises climate on the basis of rainfall, temperature, potential

evapotranspiration and the water holding capacity of the soil. Negative values of TMI indicate dry climates.

Equilibrium suction under the road centre-line has been compared with TMI in several field studies of existing covered areas. The first relationship, published by Russam and Coleman (1961), Figure 3, was based on data obtained from various sites. The sites were all on sealed roads, at least 5 years old, in areas that were well drained and were not strongly influenced by vegetation. The roads were constructed on deep soil profiles that had a deep or non-existent water table. The data were obtained from a depth of 450mm beneath the surface of the road. Different relationships were attained between equilibrium suction and TMI for different soil types. Whereas the reference line provides a reasonable relationship between equilibrium suction and climate, in some cases suction data has not compared well. This is because the sites have not met the conditions used to derive the reference line. Site conditions which can modify the suction conditions beneath the road are:

(a) run-off from the sealed surface,
(b) lateral infiltration from ponded water and drains,
(c) leakage from culverts,
(d) presence of vegetation, and
(e) thermal and hydrostatic gradients within the soil.

Where any of these conditions apply, the equilibrium suction will not fall on the reference line.

INSTRUMENTATION

Suction controls the soil behaviour, volume and strength, and provides the energy potential for moisture movement. Where the moisture is available to the subgrade soil it will migrate until more stable suction conditions are established. In arid climates with deep or non-existent water tables, seasonal rainfall will provide a variable supply of water. The suction condition although more stable, may vary seasonally.

There is, therefore, a need to determine the availability and distribution of moisture and the suction beneath sealed surfaces if the behaviour of expansive soils is to be understood and used successfully in road design. In recognition of this, TRL have developed techniques and devices to measure *in situ* suction and moisture content.

Measurement of suction

The concept of using calibrated filter papers as suction sensors for soil samples in the laboratory has been used since the 1930's. The method measures the soil suction indirectly by determining the moisture content of a filter paper brought into suction equilibrium with a sample of soil. The technique has gained increased acceptance in recent years and has been successfully used to measure a wide range of matrix and total suctions in soil samples. The filter paper technique has been found to be convenient and economical and can be applied over a very wide range of suction (0 to 10^6kPa).

Whatman No.42 filter paper has been shown to be a suitable absorbent sensor because of it is robust in use, sensitive to moisture change, has a small uniform pore size distribution and is stable under heating to 110°C. The problem of hysteresis of the filter paper is avoided by using the material on the wetting cycle only. Drying the papers at 105-110°C will alter the absorption properties of the filter paper irreversibly and the papers must therefore be used once only and then discarded.

When air dry, the filter paper exhibits a high suction relative to the soil water which causes soil pore fluid to pass to the filter paper. The flow continues until the suction in the water in the filter paper and in the soil are in equilibrium. At equilibrium the filter paper and the soil are applying the same stress to the pore fluid i.e. the suction in the filter paper is the same as the suction in the soil. If the amount of water transferred to the filter paper is small and the sample of soil is large (relative to that amount of water) then the suction established in the filter paper will be nearly the same as the initial suction in the soil.

Where the filter paper is placed in contact with the soil, the moisture is transferred to the filter paper in the liquid phase, which includes dissolved salts, and the osmotic potential of the soil water is not determined. The suction recorded is therefore the matrix suction. Where there is no contact between the filter paper and the soil sample, the transfer of moisture to the filter paper is in the vapour phase and is therefore pure water. An osmotic potential will exist between the pure water transferred by the vapour phase to the filter paper and the salts within the pore fluid of the soil which will exert an additional component of suction on the water in the filter paper. The matrix and solute suction components will therefore influence the final suction condition of the filter paper and the suction determined is therefore the total suction.

TRL suction probe

A generalised sketch of the suction probe is given in Figure 4 with the main components identified. The probe provides a simple, robust and reliable technique for determination of soil suction and overcomes many of the limitations of *in situ* suction equipment such as tensiometers and gypsum blocks. The probe was designed to incorporate the filter paper in an inner assembly which is sealed against an outer assembly (see Figure 4) that is permanently installed in the ground.

An outer access assembly is driven into the ground using a technique based on the dynamic cone penetrometer. When the driving cone is displaced from the perforated sleeve, a section of soil is exposed close to where the filter paper sensor is located. The filter paper sensor is held in position by a retrievable inner assembly which seals into the outer assembly. With the inner assembly in the sensing position the filter paper is exposed close to the soil. The space within which the filter paper is contained is a chamber in the soil which is isolated from the atmosphere above the road by the outer and inner assemblies (see Figure 4). Within this closed system the relative humidity will reach an equilibrium with the pore fluid. The equilibrium will be dependent on the total suction which exists in the

soil water. The moisture content of the initially dry filter paper increases until it reaches a state of equilibrium with the relative humidity within the measuring chamber.

Calibration

To use filter paper for measurement of the suction in soil samples it is necessary to determine the suction-moisture content relationship of the filter paper being used. Where a suitable or appropriate calibration exists for the filter paper, as used under these conditions, it is possible to relate the measured moisture content of the filter paper to the total suction of the soil.

Where the filter paper is adequately calibrated from an initially dry condition, then a relatively simple measurement technique results. The sensing chamber is small enough to allow quick equilibration of the filter paper with the soil suction. A number of calibration curves for Whatman No.42 filter papers have been published in the literature (e.g. McQueen and Miller 1968 and Chandler and Gutierrez 1986).

The values of total suction determined using the probe are dependent on the ground temperature conditions and the length of time that the filter paper sensor is exposed to the soil. An extensive calibration experiment was carried out by TRL whereby the effect of temperature and equilibration time on the filter paper moisture content were determined and are incorporated into the calibration equation.

Measurement of moisture

The development of nuclear gauges has made it possible to obtain measurements of sub-surface soil moisture contents and to monitor the changes that may occur. The gauge consists of a single probe containing a nuclear source, radiation detector and electronic circuitry.

Principles of measurement

The diagram in Figure 4 shows how the gauge operates. The source emits high energy, fast, neutrons which collide with hydrogen in the soil causing them to slow down and lose energy. The neutrons are most sensitive to hydrogen, compared with the other elements normally present in the soil, because far fewer collisions are required to slow them down. Hydrogen present in the soil is assumed to be associated with water molecules. The low energy neutrons are then counted by the detector. The count of neutrons at the detector is directly proportional to the density of the soil moisture.

Most gauge manufacturers provide a calibration with the gauge and report a level of precision. For a typical count period of 1 minute many gauges are reported to have a precision of 0.24% at 24% volumetric water content. This equates to ±0.1% at 12% gravimetric moisture content at a soil dry density of 2.0Mg/m^3.

Many gauges also incorporate a gamma radiation source for the measurement of soil density. It is important to note that the density determined is the wet density which includes the density of soil particles and water. The radiation emitted from the gamma source collides with the soil and is scattered back to a detector located

close to, but shielded from, the source. The count of the radiation collected at the detector is, in this case, inversely proportional to the wet density of the soil. The typical reported precision for a one minute count is 0.01Mg/m^3 at a wet density of 2.0Mg/m^3.

If measurement of both moisture and soil density are made it is possible to determine both the gravimetric moisture content (per cent by weight of water relative to the weight of soil solids) and the dry density (the density of the soil solids alone). These measures are commonly used by road engineers.

To ensure that measurements and subsequent calculations are correct the gauge designers use a process of optimization to try to ensure that the volume of soil seen by both types of radiation is the same. The radius of the volume seen by the gamma radiation remains constant for the general range of soil densities. However, the radius of the volume seen by the neutron radiation decreases from twice that seen by the density source in completely dry soil, to the same as that seen by the density source in saturated soil. The relationship is not linear and is weighted towards a mass of water closer to the detector. Completely dry soil is rare in practice even in an arid area but the difference in the volume seen by each type of radiation has implications in layered soil with different moisture contents. If these circumstances arise, the difference in the resolution of the two methods of measurement could produce errors in the result.

For soils that remain at a constant dry density, changes in measurements using the gamma (wet density) source indicate a change in moisture density. However, this alternative method of measuring moisture density cannot be applied to expansive soils because a change in moisture will result in a change in the dry density.

The augering system

The gauge is lowered within a pre-formed access hole to the required depth as illustrated in Figure 4. The hole is normally lined with a thin walled tube of a material which is virtually transparent to radiation, such as aluminium. The recommended installation technique using hand augered holes is not suitable for hard compacted soils. Alternative powered systems were not available for the dimensions of the access tubes required. TRL has developed an auger system that can be coupled to a powered auger to form good quality access holes through most materials and soils.

The auger system cuts a hole slightly undersize for the tube which is then driven into position. The tube shaves the sides of the hole and ensures close contact between the tube and the surrounding soil. The system has proved suitable for installing tubes to a depth of 3 metres using a 7HP auger. The tubes are sealed at the bottom and a removable cap is fixed to the top.

In use, the gauge is positioned over the access tube and the probe is lowered to the measurement depth using its electronic cable. A suitable counting time is selected and the measurement taken.

INSTALLATION CONSIDERATIONS

The selection of access tube and suction probe positions and their installed depth will determine the information that it is possible to collect on the range, mode and cause of possible changes that may occur.

With reference to Figure 2, information would be valuable at a number of positions under a sealed road from the centre-line to the edge, with additional measurement positions outside the sealed area extending to positions remote and uninfluenced by it. Measurements also need to be taken to a depth which allows discrimination between modes of moisture change, for example, from rainfall and evaporation or from ground water. For the soil suction installations, where measurement depths are preselected, depths should be chosen on the same criteria as outlined above.

EXAMPLE OF RESULTS

The road selected in this example is a new construction located in the north east of Kenya, through an area of expansive clay with a poorly drained topography. The annual rainfall is 320mm and the potential evaporation is about 2110mm per annum. The rainfall occurs in one minor season from April to May and one major season from November to December. The Thornthwaite Index calculated for a climatic station nearby with a similar rainfall and temperature pattern is about -50. This classifies the region as arid. The road is on an embankment where the expansive clay soil was used to form the fill and subgrade layers. The subgrade layer is distinguished from the fill because it provides support for the pavement and receives the stress from traffic loading. The pavement consists of a 175mm sub-base and a 125mm roadbase, both are graded crushed stone which is permeable. The carriageway has a width of 3.25m and a 2.5% crossfall and was sealed using a triple surface dressing. The shoulder has a width of 1m and a 4% crossfall and was sealed using a double surface dressing. The sideslope does not have a cover material placed over the expansive clay and was finished to a slope of 1 in 4. The road was constructed without drainage ditches. A number of culverts and turn-out drains were built to remove any surface water from the vicinity of the road embankment.

The pavement was designed to carry 0.5 million equivalent standard axles over a period of 15 years. This required a long term strength in the expansive clay subgrade of between 7 and 13% CBR (California Bearing Ratio). These values were achieved on un-soaked specimens.

The clay was found at a natural moisture content of about 13% to 16% which is low compared with the optimum moisture content for compaction of about 28 per cent using the BS 2.5 Kg rammer method. Water resources in the region are scarce and the clay was compacted in the fill and subgrade at the natural moisture content. The densities achieved were adequate compared with the specification required for the design strength. *In situ* strength tests showed that a CBR of greater than 30% had been achieved with the clay at its constructed moisture content and density.

Immediately after construction the road was instrumented with an array of nuclear gauge access tubes and suction probes at positions

consistent with both the criteria described previously. The suction probes were positioned close by and spaced only to ensure that one measurement method did not influence the other.

Data collected immediately after construction showed initial moisture contents of 12-16% and corresponding suctions of 10-12MPa. In Figure 5 the suction and moisture content results taken 7 months after construction have been contoured. The depths at which the measurements were taken are indicated on the Figures. It is clear from the contours that below the centre-line of the road, and for a large area at a depth of greater than 600mm from the surface, no changes have occurred.

The moisture and suction contours clearly show an increase in moisture and a decrease in suction at the shoulder and sideslope of the road. A wetting front can be seen progressing downwards and inwards towards the centre of the road. The wetting extends across the subgrade, to a depth of about 600mm from the surface.

Deep below the road, particularly on the left hand side, is an area of lower suction and higher moisture content which could indicate a migration of moisture upwards. However, it also coincides with the edges of an old track which was removed prior to placing the new embankment but where the ground was stripped to accommodate the new embankment. In this area it was noted that the newly exposed ground was wetter.

The results indicate the distribution of moisture under the road and the corresponding suction results show the potential for further migration into the body of the embankment. The results complement each other in indicating both the degree and potential for further change.

Whilst the results have been presented primarily as an example of the techniques of measurement, it would be of interest to briefly discuss the ingress of water that has occurred. In the 7 month period after construction, the rainfall was 250mm. It is clear that the major wetted zone is adjacent to the edge of the sealed shoulder and that it is progressing laterally under the seal. The ingress appears to be associated with the water running off the road surface with some contribution from direct precipitation onto the sideslope. The water available at this position could be considerably greater than the precipitation because of the run-off from the 4.25m wide sealed surface on each side of the road. The pavement is permeable and, with the pavement thickness and sideslope angle, a strip about 0.5m wide of pavement material is exposed. It would appear that water is penetrating through this into the subgrade.

The road is not in suction equilibrium because it is at an early stage in its life and because of the ingress of the surface water run-off. It is, therefore, not correct, for the given TMI, to compare the suction data with the reference line given by Russam and Coleman (1961). Further changes may well occur during the early years. The fact that the moisture and suction changes have occurred in the expansive clay implies that a volume change has also occurred. This will have an effect on the shape of the road resulting in deformation. If fluctuations in the moisture-suction conditions also occur then longitudinal cracking could develop.

The results given in this example demonstrate the importance of the transient state of the road in the early years, rather than the equilibrium, in determining the soil suction condition for design. It would also indicate that the behaviour of roads with permeable pavements in arid climates are likely to be more dependant on the direct ingress of water from run-off of rainfall than the soil moisture balance in the ground.

It is intended that the information collected will be used in conjunction with other methods of evaluating road performance to determine the influence of suction and moisture on the engineering behaviour of the soil. This will provide useful design information for road engineers.

SUMMARY

It is not yet possible to predict with a high level of confidence the long term pore water pressure or suction beneath a covered area. The reference line for "heavy" clays first published by Russam and Coleman (1961) appears to be representative of sites that are in a state of equilibrium where the pore pressures are dependent primarily on climate, and as such have:

(a) uniform deep soil conditions,
(b) no impeded drainage,
(c) no infiltration or entrapment of water,
(d) deep water table,
(e) vegetation with a normal water consumption.

Deviation both above and below the reference line is possible if any of these conditions are varied.

The suction and moisture distribution beneath a road is affected by both the climate and the road itself. A small body of data exists which demonstrates, qualitatively, the influences of climate and road design. More data is required before a full quantitative assessment of moisture conditions beneath roads in dry climates can be made. The importance of the transient condition as well as the equilibrium condition on the road structure has been discussed.

Two systems have been developed and used by TRL to increase the available information on moisture and suction distribution across the road width and over a range of depths.

The suction probe was developed for the monitoring of suction in subgrade soils and embankment fills on road pavements in developing countries, though it is now being used on a number of soils investigation projects around the world. The system developed allows monitoring of the total suction in the soil at the same position.

The development of a powered auger system for nuclear gauges that use a single probe has enabled hard compacted materials to be quickly augered to depths suitable for the detailed examination of sub-surface moisture conditions. Access tubes can be installed for rapid repeat measurements. The measurements can help to differentiate between modes

of moisture ingress in structures such as roads. The system described here has now been used for the installation of about 300 two metre tubes. The maximum depth tested has been 3m.

The techniques described can be easily used to evaluate the moisture and suction conditions beneath existing roads, where this information may be useful for cost effective road design.

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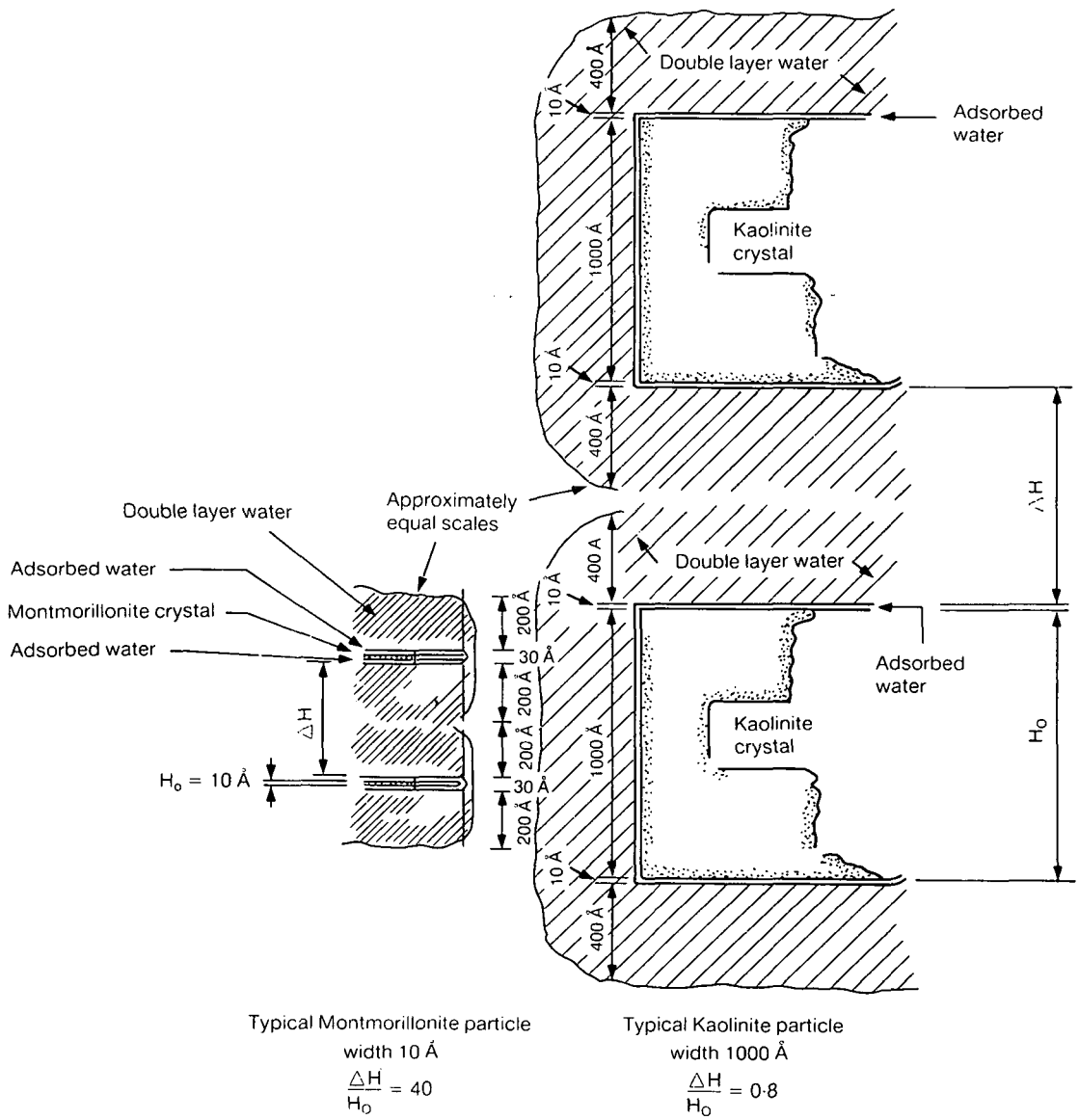

Fig. 1 Theoretical potential volume change for montmorillonite and kaolinite

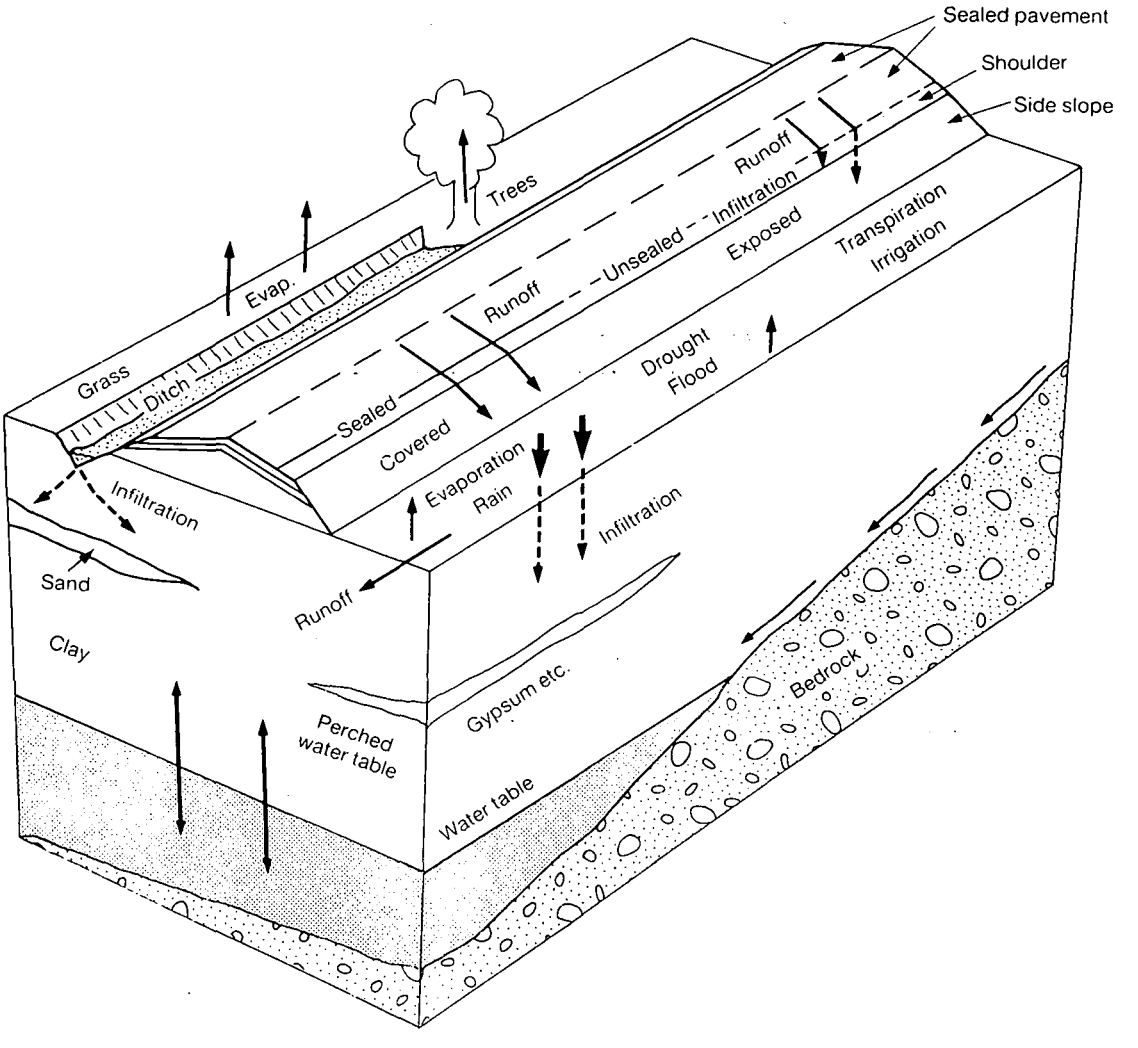

Fig. 2 Block diagram showing some moisture movement mechanisms

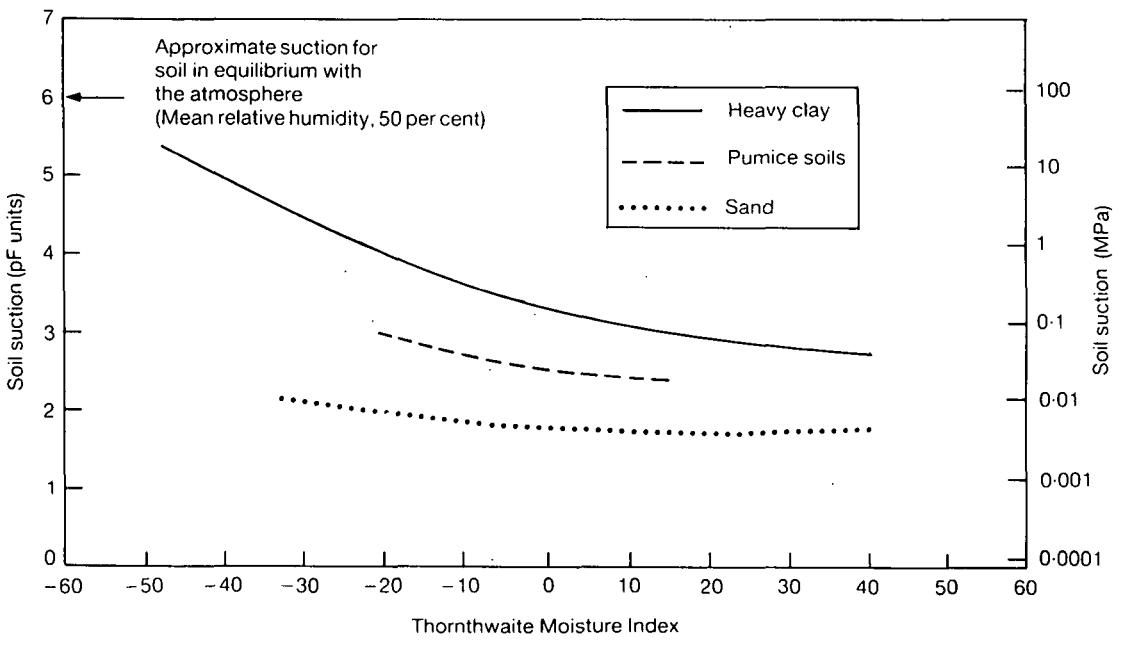

Fig. 3 Variation of the soil suction of road subgrades with Thornthwaite Moisture Index (TMI), (Russam and Coleman 1961)

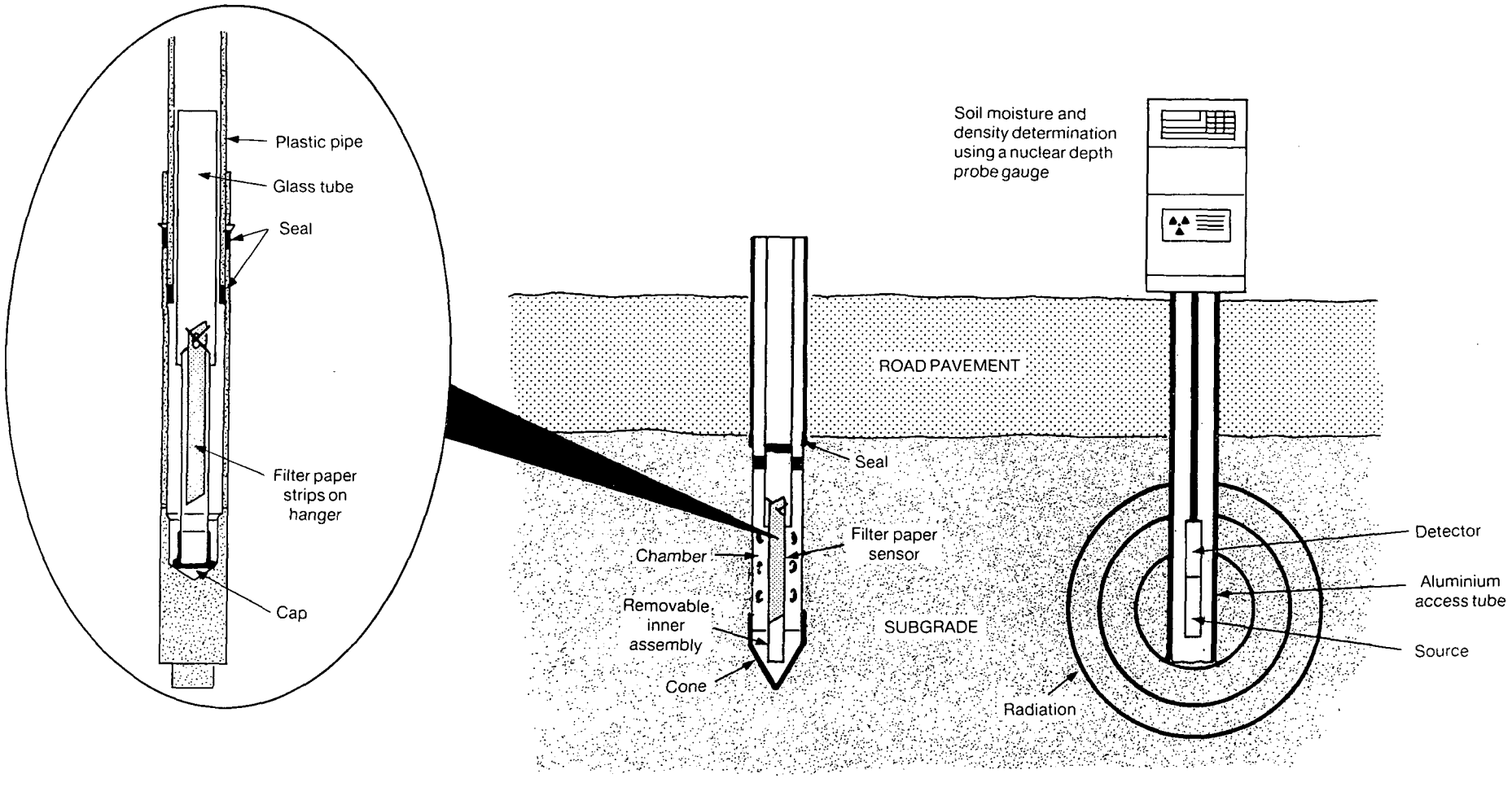

Fig. 4 Diagram showing soil suction probe and nuclear depth gauge in place

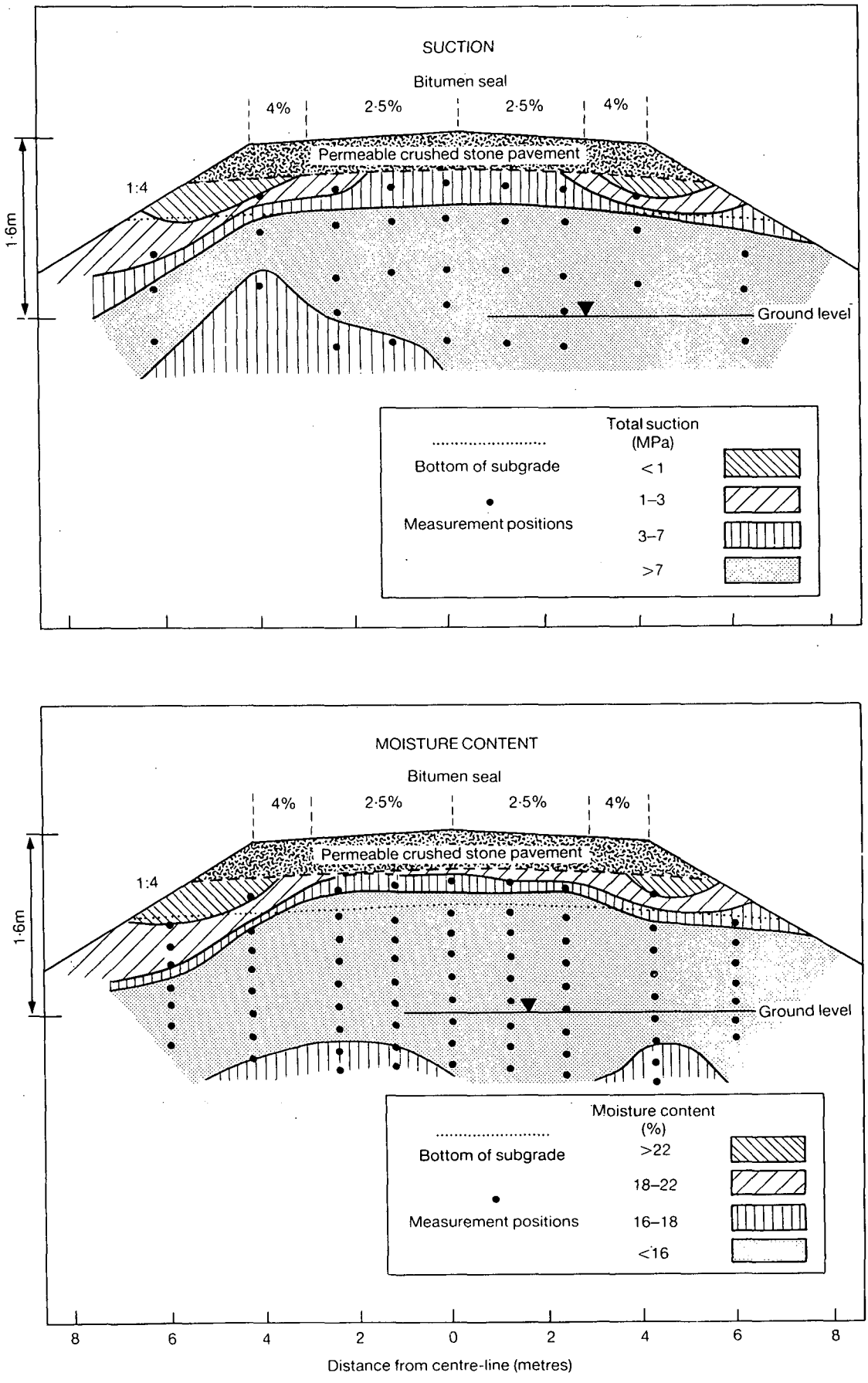

Fig. 5 Soil suction and moisture content contours; 7 months after construction