CHAPTER 3

Time - Dependent Behavior of Earth Materials

Creep in Rocks

Time-dependent behavior in earth materials is commonly referred to as creep. In fact, creep is dependent on other factors also besides time such as temperature, pore pressure, and the ambient stress level. The effect is usually pictured as a strain–time curve representing the deformation of the material at constant stress. Idealized creep curves for a rock take the form shown in Figs. 3.1(a) and 3.1(b). After the initial component of instantaneous elastic

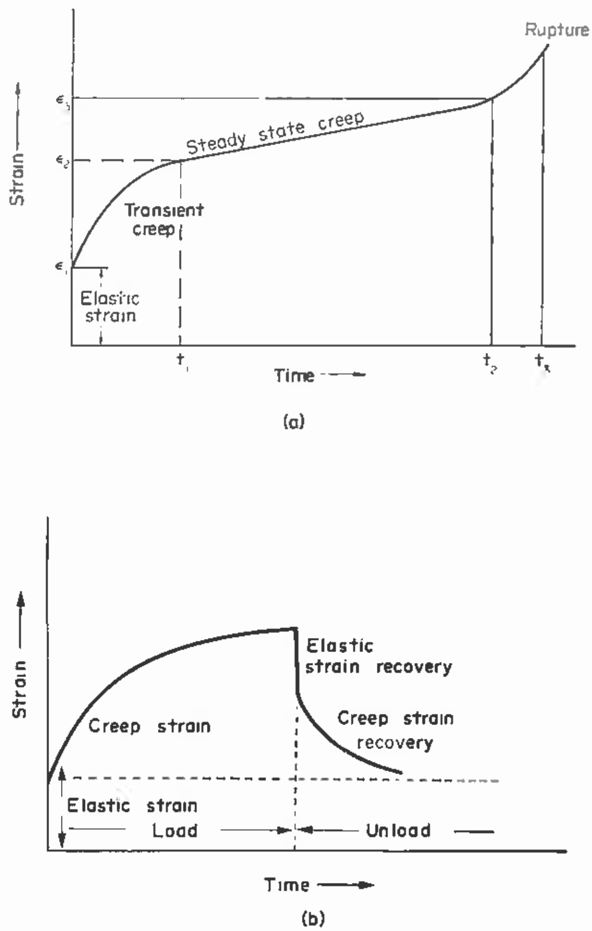

Fig. 3.1(a). Idealized creep curve for a rock material,
(b) Time-dependent creep and recovery in a rock material.

response to load the strain–time relation becomes curvilinear, with decreasing slope or strain rate over the length of time t_1. This is termed the primary or transient creep. If the stress is removed during this period the elastic component of strain is recovered immediately, and the creep strain is recovered by a time-dependent process, at a decreasing strain rate.

The transient creep phase is followed by a secondary stage of creep, at constant strain rate. This steady-state creep occurs over the time t_1 to t_2, and the deformation during this time is permanent. It is not recovered if the applied stress is removed. If the stress level is sufficiently high the secondary creep phase may be followed by a tertiary phase, displaying an accelerating creep rate as the rock loses strength at the approach to rupture, over the time t_2 to t_3. From a practical engineering viewpoint, when considering the stability of earthworks such as tunnels, underground support structures, and rock and earth slopes, the tertiary creep stage is of little importance. Our interest then lies mainly with primary and secondary creep.

If the deformation process has reached the tertiary stage, the situation, from an engineering point of view, has gone beyond control. The rock mass is approaching failure at an accelerating rate, and usually the engineer can do little else but watch things happen. Unless there is some radical change in one or more of the operative factors, complete collapse is inevitable. Sometimes such a change does occur, as for example in a rock mass that is moving under the influence of gravity. During a period of heavy rainfall an earth or rock slope may accelerate in movement and threaten to slide, but a change in the drainage characteristics or a climatic change which lowers the fluid pore pressure, or otherwise dries out the mass, might allow at least a period of temporary stability to be resumed. The acceleration period would thus only be of limited extent. It would be followed by a period of deceleration lasting until the secondary creep phase was resumed.

In general one may expect the stronger, fine-grained igneous and metamorphic rock to creep very little at the magnitudes of stress and the ambient temperatures that will prevail during conventional engineering operations. Sedimentary rocks such as sandstones and limestones may display some creep when exposed in shafts and tunnels, or in rock cuts, and the engineer will need to take this into account when constructing the support linings of shafts and tunnels, and when considering the stability of his rock cuts and slopes. Creep is liable to be very considerable indeed, even at low stress levels, in rocks such as the saline evaporites and the more porous sediments, particularly when water or other fluids are present in the rock interstices (see Fig. 3.2).

Creep Laws in Rock Materials

The total strain at time t is then given by Griggs' relationship

$$\epsilon_t = A + B.\log t + Ct$$

where A represents the instantaneous elastic strain,
$B.\log\ t$ represents the primary, or transient, creep,
Ct is the secondary or steady-state creep.

$$\frac{d\epsilon}{dt} = \frac{\sigma}{\eta}$$

where η is the coefficient of viscosity. ϵ_t is the total fractional deformation equal to $(L_t{-}L_0)L_0$ where L_0 is the gauged length at zero time and L_t is the length at time t.

The constants A and B are estimated from graphical plots of the creep surve on semi-log ordinates. The slope of the line drawn through early values of ϵ gives B, and the intercept of

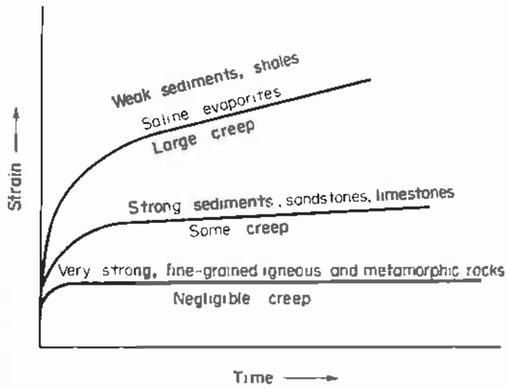

Fig. 3.2. Comparative creep characteristics for the same stress level in different types of rock.

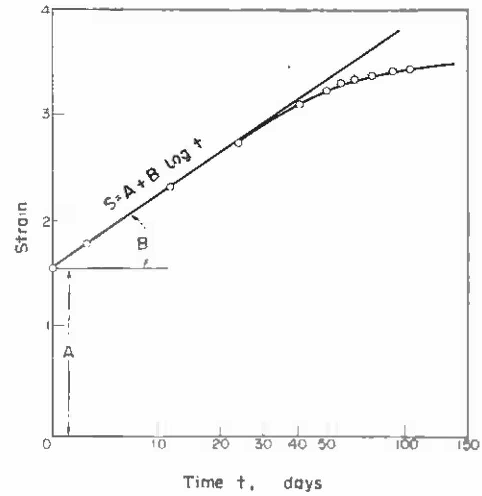

Fig. 3.3. Determination of the creep constant from the strain-time curve.

this line with the strain axis gives A, while C is the strain rate during the secondary creep stage (see Fig. 3.3). The strain rate generally decreases with decrease of ambient stress level. Typical curves observed by Price on sandstone are shown in Fig. 3.4. Price also shows the relationship between the rate of deflection and the applied load as a percentage of the instantaneous failure load, and demonstrates a linear relation between the strain rate and the applied load during secondary creep.

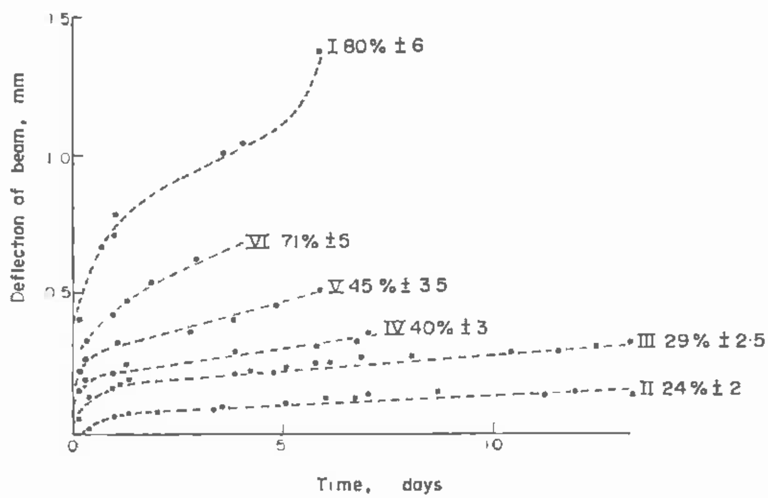

Fig. 3.4. Time-deflection data for beams of Pennant Sandstone (Price).

A number of investigators have observed the steady-state creep component to be relatively small, compared with transient creep, and sometimes negligible, or absent altogether. The viscosity coefficient for rocks is so high, at the temperatures that are relevant in geotechnology, that the secondary creep constant C becomes insignificant compared with transient or primary creep.

Several investigators also have observed the creep of rocks under constant stress to follow a power law, such that

$$\epsilon_t = A + Bt^n.$$

At first sight it may appear that the question as to whether the creep in a rock material follows a logarithmic law or a power law is of academic importance only, but it has some significant practical implications. Considering the mechanism of creep deformation as one of progressive dislocation and transverse sliding within and between the mineral constituents of the rock, if temperatures are low and the stress level is well below the instantaneous fracture level, dislocation and sliding will begin only at the weaker points in the material. As deformation proceeds, the resistance to further deformation will build up because progressively stronger energy barriers must be overcome. The material, in fact, becomes "work-hardened". The deformation process continues, but at a decreasing rate.

However, if the temperatures and stresses are higher, the build-up of resistance due to work hardening may be overcome, with the result that the dislocations and slip planes "climb up" or "pile up" on one another in quick succession. If this happens the work-hardening effect that helped to produce the logarithmic creep law is partially lost. Creep is then likely to take place more rapidly, and to follow a power law.

The practical implications of this are important in relation to strata control in mining, and the support of excavations in mining and civil engineering. If the conditions are such that a logarithmic law prevails, at a low strain rate, the chances of maintaining the walls of an excavation in a sound condition will be much better than would be the case when a power law holds and the strain rate is higher. In the latter case the development of dislocations may lead to the aggregation of discontinuities, general loosening of the grain structure, and ultimately to large fractures and ground movement. At the same time it must be borne in mind that some types of rock will creep extensively, even at low stress levels, during which they display steady-state creep. If the stresses remain active over a sufficiently long period of time the rock may ultimately fail, not because the ambient stress levels are high, but simply because the rock material can no longer sustain the extent of the resultant deformation. Such conditions are not uncommon in porous sediments, particularly when the energy levels to be overcome in the dislocation process are reduced by the presence of moisture or other pore fluids.

The Effect of Stress on the Strain Rate

During the transient creep phase the strain rate may follow a power law in relation to stress, such that

$$\epsilon \text{ (approx.)} = \frac{1}{t}\left(\frac{\sigma_1 - \sigma_3}{2G}\right)^n$$

where G is the Modulus of Rigidity and $(\sigma_1 - \sigma_3)/2$ is the maximum shear stress.

Observed values of the exponent n in various rocks at room temperature range from around 1 to 5.

The effect of increased stress, relative to the fracture strength of the rock material, is to accelerate the strain rate. Conversely, the rate of creep of the walls in a rock excavation can be reduced in two ways: (1) by reinforcing or otherwise increasing the strength of the wall material, (2) by reducing the ambient stress in the immediate rock walls.

Practical Implications of Creep in Earth Materials

The characteristics by which the imposition of constraining forces will increase the strength of a particular earth material have a critical influence on the effectiveness of strata-reinforcement techniques such as rock bolting and tunnel lining. Layers of relatively weak ground can be bound together and secured by the elastic tension that is exerted by a rock bolt stretched between its anchor and the surface plate through which it is bolted, or by the direct compression that results from lining a tunnel with materials that are more rigid than the rock. By making the rock, or other lining reinforcement, of a high elastic modulus relative to that of the rock mass, the deformation of the reinforced ground is reduced. In this manner the imposed constraint on the rock walls increases the inherent strength of the rock, assuming that fluid pore pressures do not also increase within the rock material.

But if the stress levels are so high, relative to the strength of the rock, that significant time-dependent deformation exists, then it may not be possible to impose the necessary degree of constraint, by reinforcement or lining, that would be required to achieve permanent stability of the rock walls. In that event a rational design for the support system could only be made if the time-dependent deformation characteristics of the rock, and the state of stress within the rock walls, were known. The important parameter, which must be determined by experimental observation, is the creep constant, i.e. the slope of the time-strain relationship during the transient creep phase. Since this is a function of the stress level, the experimental tests to determine the creep constant must cover a range of stress values comparable with those that are expected to exist in the field. Field observations of the *in situ* stress level are then needed, to complete the required design data.

The rational design of strata-reinforcement and tunnel-lining structures is at an early stage of evolution. The usual method of procedure is still, very largely, intuitive, although theoretical concepts may be applied as a first approach to design. The aim of the engineer is to increase the strength of the rock walls around his excavations, by the application of direct reinforcement, and sometimes also by employing "pressure-relief" techniques, so that the rocks will support themselves over the length of time that the excavations are required to stay open. The object of direct reinforcement is primarily to increase the effective stress or effective confining pressure on the immediate wall rocks, where lateral constraint is largely removed by the excavation. This increases their yield strength and so also reduces the time-dependent deformation in them. The object of pressure relief is to deflect the imposed loads to a zone further within the rock mass, where lateral constraint is more effective. This also reduces the loads imposed upon the immediate wall rocks, from within the rock mass, and hence also reduces time-dependent deformation of the walls.

Pressure-relief technique in elastic and near-elastic rocks

The pressure-relief technique is one that has been handed down through generations of miners, wherever they are or have been involved underground at depths where support problems exist due to the existence of high strata pressures. For example, when mining a sedimentary deposit the excavations commonly take the form of tunnels of rectangular cross-section, and a network of these running at right angles to each other forms a system of "rooms" separated by supporting pillars of rock. The pillars are required to carry the weight of the overlying strata and there is an extra load imposed by the excavation of rock material from the rooms, as compared with that which existed before any mining was done. Consequently there is a redistribution of stress around the excavations, and if the excavated material is strong relative to the rock above and below it, the edges of the pillars form zones of concentrated stress to an extent which may cause the rock material in the immediate walls of the tunnels to yield and fracture.

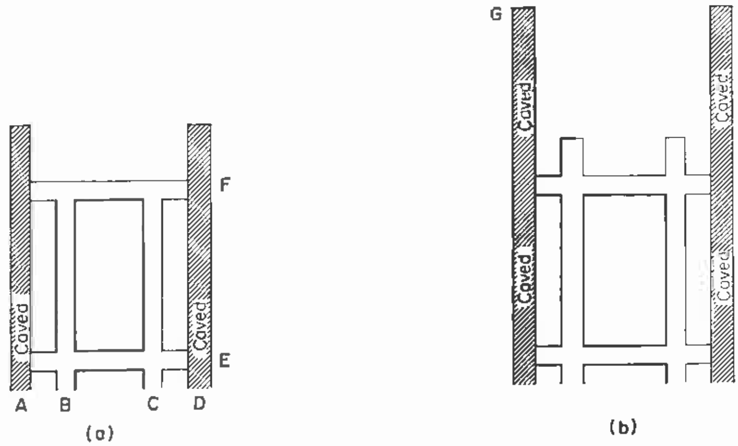

Fig. 3.5. Stress-relief and the yield-pillar technique
(a) A and D advance, B and C halted. (b) A and D halted and caved. B and C advance.

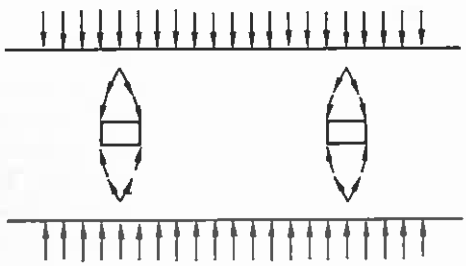

Fig. 3.5. (c) Construction of tunnels A and D in a high stress field.Stress concentrations on tunnel walls.

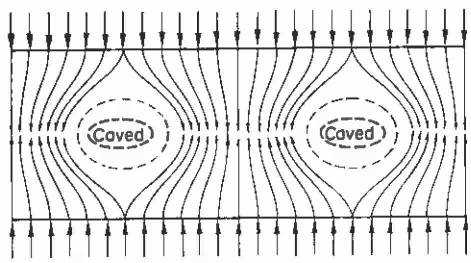

Fig. 3.5. (d) Caved ground around A and D throws stress concentrations into sides and on central pillar.

The result may take one or more of several forms.

(a) High shear stresses along and parallel with the tunnel walls may cause shear fractures along the pillar edges. The roof of the tunnels is pushed downwards, and the floor pushed upwards, relative to the pillars. From within the tunnels the general appearance is that the pillars have been pushed into the roof and floor – an occurrence which the old miners call a "thrust".

(b) If the floor strata are relatively weak, as is usually the case in coal mines – particularly if water is present – the floor strata moves plastically from underneath the pillars and into the tunnels.

The floor of the tunnels is then observed to "heave". In either case, whether it be "thrust" or "heave", the net result is that the cross-sectional area of the tunnels, or rooms, is progressively reduced. Ultimately they may close altogether, unless the broken and moving ground is excavated from within them.

The old miners were not slow to observe that if, after a tunnel had thus closed, it was recovered or reopened by making another excavation coaxially with or adjacent and parallel

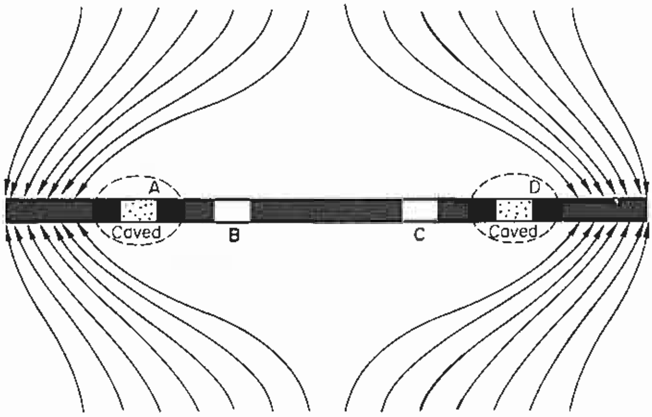

Fig. 3.5(e). Construction of tunnels B and C and yield of pillars A–B, B–C, and C–D deflect major stress concentrations further into the side zones. The central zone in which B and C must be maintained is now largely relieved of stress.

to the first, then this second excavation was usually much easier to support and maintain. In fact, very often it remained quite stable over the length of time that it was required to stay open. Arising from this there evolved the practice of constructing "pressure-relief" chambers or "caving chambers", alongside the tunnels whose stability it was desired to ensure. There are various modes of application of the technique, which vary in detail, but the general principle is common to all. It is that of deflecting the stress concentration zones away from the periphery of the tunnels and into the solid ground over, within, and beneath, the interior of the supporting pillars.

A typical example is shown in Fig. 3.5, in which four tunnels A, B, C and D are being driven parallel with one another, B and C being those whose permanent support is desired. The tunnels are connected laterally, at intervals, by "cross cuts" E, F, and G. In Fig. 3.5(b) the tunnels A and D are being driven in advance of the cross cut F and when they reach the appropriate distance to the next cross cut G they are stopped, all supports, struts, etc., within them are withdrawn, and they are allowed to collapse and close. In so doing they become "caving chambers" and the broken ground around them is partially relieved from the weight of the overlying strata. Stress concentrations are thus deflected into the solid ground on either side of tunnels A and D and towards the middle of the ground between A and D. (see Fig. 3.5(d)). However, when construction of tunnels B and C is resumed, to advance from cross cut F towards G, the ground between A and D yields slightly under the added stress concentration zones produced by excavations B and C. In so doing, the stress concentration zone around the middle of the central pillar between B and C is also deflected into the flanks on either side of A and D (Fig. 3.5(e)). The net result that is aimed at by this construction of "caving chambers" combined with "yield pillars" is to reduce the stress levels in the walls of the tunnels B and C to a point at which the rock walls will remain intact, with negligible time-dependent deformation.

A similar result is achieved, when difficulty is experienced in maintaining a narrow excavation at depth, by widening the excavation and "back filling" on either side to the finished dimensions of the tunnel. The back fill may consist of broken rock, packed sand, or poured concrete, and it has a finished strength considerably less than that of the original rock. The fill therefore yields under the weight of the overlying ground, and while continuing to support the strata immediately above and below the excavation, deflects the major strata pressures into the solid ground on either side (see Fig. 3.6).

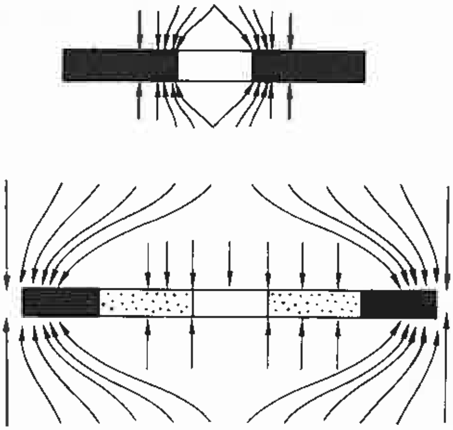

Fig. 3.6. Pressure relief by widening and backfill. (a) Narrow excavation. Stress concentrations close to sides. (b) Wide excavation backfilled. Stress concentrations thrown into solid ground. Central excavation relieved of stress.

Creep in plastic rocks

The assumption of elasticity in saline evaporite rocks, such as rock salt and potash, is only valid if the shear stresses in the material do not exceed a limiting value – the shear strength of the rock. If this limit is exceeded then plastic deformation occurs. The consequence of creep in the material is to reduce the principal stress difference $\sigma_1 - \sigma_2$, until, ultimately, the shear stress τ falls below the shear strength of the rock, at which point an elastic regime is regained. Baar maintains that strain hardening does not occur in salt rocks at depth, with the result that the deformations around underground excavations in deep potash and rock salt mines are dominated by creep, because the shear strength of the walls remains low (around 100 psi – or 689.5 kN/m^2).

Following this argument it is apparent that high stress differences cannot persist for very long around newly made excavations in salt, and a zone, which Baar terms the "stress relief creep zone", extends deep into the solid around any such opening. Within this zone the salt behaves plastically, to redistribute the stresses generated by the imposed loads, until local stresses in excess of the shear strength have been eliminated.

The initial stress relief creep may be completed within a period of hours around a new opening, but occurs over a longer period of time when a change of load takes place due to some cause, such as a change in mining conditions resulting in surface subsidence or the re-loading of earlier stress-relief creep zones, due to pillar extraction. Over a long term the creep rates of the wall rocks become constant if the loading conditions do not change, and a condition of steady-state creep maintains constant stress gradients within the walls.

The Effects of Temperature on Creep

The effect of increase in temperature is to increase the magnitude of the constants in the creep equations, and also to decrease the viscosity. However, these effects are seldom of any practical importance in engineering situations, when temperatures below 100°C are to be expected. The effects might be significant in abnormal situations, such as could exist, for example, on the occurrence of fire in a mine or tunnel. They also reach practical significance at normal working temperatures in rocks such as the saline evaporites, and they will certainly have to be taken into account when dealing with frozen earth materials.

In experiments to observe creep in model pillars of Saskatchewan potash, King observed that the increase in temperature associated with an increase in depth of mining from 3400 to 4500 ft (1036.3 – 1371.6 m) can be expected to have approximately the same effect on creep behavior as would be produced by an additional 1000 psi (6.895 MN/m^2) vertical stress on the pillar. This effect was considerably intensified when seams of clay occurred in the roof and floor strata. Under these conditions very large creep deformations can be expected to occur when mining potash by conventional methods at depths over 1400 m from the surface.

Creep of ice and frozen ground

The movement of glaciers and ice sheets demonstrates the existence of creep in ice. The dependence of strain rate upon the ambient stress in ice becomes weaker as the stress level decreases and it has been suggested that at low stresses, between 0.1 and 0.5 kg/cm^2, which are representative of the conditions in glaciers, the ice may demonstrate linear viscous behavior.

However, Mellor and Testa, on the basis of evidence provided by the results of uniaxial compressive tests on fine-grained polycrystalline ice, show that the strain rate during secondary creep is proportional to $\sigma^{1.8}$, where σ is the applied stress.

All flow processes in materials arise essentially from the thermal activation of their atomic structure and, consequently, temperature has an effect on creep. It is found experimentally that the creep strain rate bears a relationship to temperature, such that

$$\text{Strain rate } \delta\epsilon/\delta t \qquad \propto \qquad \exp\left(\frac{-Q}{\kappa t}\right)$$

where κ is a constant and Q is the activation energy.

Mellor and Testa observed an activation energy for ice, of 16.4 kcal/mol at temperatures below −10°C, and at higher temperatures the creep rate of polycrystalline ice became progressively more temperature-dependent. A single ice crystal displayed a more rapid strain rate, at all stages of creep, than did polycrystalline ice, and it is apparent that creep of ice at 0°C is influenced strongly by grain growth and crystal reorientation during the deformation process.

Creep in Soils

Creep of rock detritus and soil is frequently to be seen on hilly terrain. The motive forces in this case are almost entirely gravitational, although lateral stresses generated by expansive forces due to swelling ice and clay in the interstices and crevices of the material, and by forces due to heat and shrinkage, are sometimes important. The effects are distributed throughout the surface layers of material, to a depth through which the influences of atmospheric temperature and moisture can penetrate.

The deformation mechanism is essentially one of plastic flow, in which a slow downslope movement of the whole mass is combined with a vertical movement of fragments through the moving layer. The creep rate is not constant through the layer, but decreases with depth. Material at the base of the layer becomes compacted, while tension cracks open up at the surface. These openings form access paths and lodgement for water during periods of rainfall, so that in wet seasons the hydrostatic pressures increase within the interstices of the soil, to reduce its cohesion and increase the creep rate.

If clay minerals are present there may be considerable shrinkage in the intervening dry periods, so that desiccation cracks open up to provide further access for water in the succeeding wet season. Water soaking through the surface layers reaches the compacted sub-surface layers, which are relatively impervious, and conditions are set up that are conducive to a sheet slide, representing structural failure of the detritus material.

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