Creep and Progressive Failure in Snow, Soil, Rock, and Ice

Fluage et rupture progressive dans la neige, le sol, le roc et la glace

R. HAEFELI, *Professor of Snow Mechanics and Avalanche Research, Swiss Federal Institute of Technology, Zurich, Switzerland*

SUMMARY

One of the most astonishing phenomena which mark the mechanical behaviour of granular and solid materials (snow, soil, rock, and ice) is the correlation (owing to stress metamorphosis) between creep processes and variable states of stress. Depending on the character of this relationship, this change may result either in a stabilization of the system or in an unstable equilibrium in which the slightest external disturbance is sufficient to start fracture. The example of snow cover serves to demonstrate on the one hand how a continuous change (metamorphosis) of the state of stress goes hand in hand with the measurable process of snow creep, resulting in stabilization, and thereby reducing the danger of avalanches. On the other hand, a loss of the creep capacity (resulting, for example, from a drop in temperature) may result in an aggravation of the state of stress or even in a fracture, the progressive character of which is demonstrated in the snowslab avalanche.

An initial attempt to generalize the laws and relationships present in the layer of snow leads to a new concept of the state of equilibrium and of slope deformation which appears very interesting inasmuch as it is also applicable to creeping media which, like snow, soil, and ice, for example, do not obey Hooke's law. The Rankine state of stress figures in this theory of creep as a special case whose importance with respect to the limit of equilibrium is well known. An obvious example of a progressive two-phase fracture is the formation of fissures on the surface of a bed of clay, a phenomenon which, in rock mechanics, is comparable to the formation of fissures (perpendicular and parallel to the surface due to changes of temperature).

The *Bergschlag* (popping) is regarded as an analogous phenomenon, the mechanism of which can be defined as progressive fracture in several phases. During the construction of the Mont Blanc Tunnel this phenomenon presented particular problems, which could only be successfully combated by the development of the modern anchoring technique. A phenomenon similar to *Bergschlag*, but much less dangerous, has been observed in cold ice tunnels (Jungfraujoch).

It remains only to mention the rheological problems of the large ice caps of the Arctic and Antarctic, whose fracturing processes are among the most spectacular of phenomena. Finally, the importance of a more thorough study of the process of creep and progressive fracture is emphasized by the recent catastrophes.

SOMMAIRE

Un des phénomènes les plus étonnants qui marquent le comportement mécanique des matériaux granulaires et solides (neige, sol, roc et glace) est la correlation (due à la métamorphose de tension) entre les processus de rampement d'une part et les états de tension variables de l'autre. Selon le caractère de cette variabilité, ce changement cause ou une stabilisation du système ou bien, au contraire, un équilibre labile auquel le moindre dérangement extérieur suffit pour déclencher la rupture. L'exemple de la couche de neige sert à démontrer d'une part comment un changement continu (métamorphose) de l'état de tension va de pair avec le processus mesurable de rampement de la neige, qui cause une stabilisation et par cela une réduction du danger des avalanches. D'autre part, une perte de la capacité de rampement (e.g., résultant d'une diminution de température) peut mener à une aggravation de l'état de tension ou même à une rupture, dont le caractère progressif est démontré à l'exemple des plagnes de neige.

Un premier essai pour généraliser les lois et les rapports trouvés dans la couche de neige mène à une nouvelle conception de l'état d'équilibre et de déformation de talus qui semble être intéressante dans ce sens qu'elle est aussi appliquable à des médiums rampants qui, comme neige, sol et glace, n'obéissent pas à la loi de Hooke. L'état de tension de Rankine figure dans le cadre de cette théorie de rampement comme un cas spécial dont l'importance concernant la limite de l'équilibre est bien connue. Un exemple évident d'une rupture progressive à deux phases est la formation de fissures à la surface d'une couche de limon, phénomène, qui, dans la mécanique du roc, est comparable à la formation de fissures (perpendiculaire et parallèle à la surface dues aux changements de température).

Le *Bergschlag* est considéré comme un phénomène analogue dont le mécanisme peut être défini comme rupture progressive en plusieurs phases. Pendant la construction du Tunnel du Mont Blanc, ce phénomène est entré en évidence d'une façon spécialement impressionnante. Il n'a pu être combattu avec succès que grâce au développement de la technique d'ancrage (*Verankerung*) moderne. Un phénomène analogue au *Bergschlag*, mais beaucoup moins dangereux, a été observé dans des tunnels de glace froide (Jungfraujoch).

Reste à mentionner les problèmes rhéologiques des grandes calottes de glace de l'Arctique et de l'Antarctique, dont les processus de rupture font partie des phénomènes les plus grandioses. Enfin l'importance de l'étude approfondie des processus de rampement et de la rupture progressive est soulignée en vue des grandes catastrophes récentes.

AN OLD TRUTH says that man perceives the things of this world by discerning their differences. To distinguish means to compare. Comparing incites us on the one hand to look for the common fundamentals. On the other hand it moves the polarities of the species into a brighter light and helps us to discern their originality and multiplicity. In the time of Homer the gods are said to have talked to men and inspired their thoughts. The first independent thought may have been expressed by the audacious phrase of Tales that all was born from the water. Encouraged by this connection established some 2000 years ago we have dared to place water, the symbol for change and movement, in the centre of our scheme. Water is also a link between the four materials—

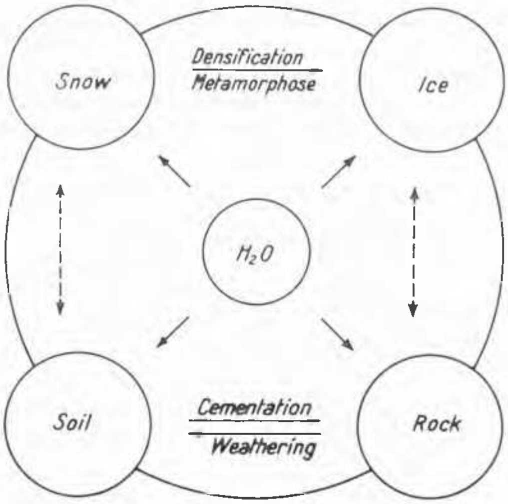

FIG. 1. Scheme of interplay between: snow, soil, rock, and ice with void ratios of 0.5–30, 0.2–10, 0–0.2, and 0–0.1 respectively.

snow, ice, soil, and rock—of which we shall compare the continually changing mechanical behaviour (Fig. 1). As "soft" water constantly dropping wears away stone, the softest and lightest among these four materials—snow—produces the most lasting effects on the other three; through metamorphosis and densification, snow, which has a void ratio up to 30, turns into ice, bursts the rock, creates the mighty forms of erosion and contributes finally, through the development of the moraines, to the formation of soils.

FIG. 2. Hôtel des Neuchâtelois on Unteraar Glacier, where Agassiz and his collaborators had their base camp.

FIG. 3. Unteraar Glacier (Mittelholzer, 1934).

Before studying the creep and failure phenomena of these four materials let us remember a man who was among the first to measure exactly the creep processes of ice as exemplified in glacial movement. He not only measured these movements, but he confined himself in them, constructing with his friends about 1842 the famous Hôtel des Neuchâtelois on the tongue of the Unteraar glacier as an accommodation and a laboratory (Figs. 2 and 3). With genuine team spirit, spade work was done there during the summer as well as during the hard winter with an enthusiasm and a devotion that remains unique. For the first time, it was ascertained that because of the lubricating effect of the greater quantity of melting water in the warm season the tongue of a glacier moves more quickly in summer than in winter. This man who at the peril of his life let himself down 80 m by rope in a whirlhole to measure the temperature of the ice in the interior of the glacier is Louis Agassiz (Portmann, 1962). Professor von Muralt has dedicated the following words to him:

Louis Agassiz, born on May 28, 1807, at Môtier, Switzerland, was one of the most important naturalists of the last century. In 1846, a lecture tour led him to Boston where he felt so attracted by the atmosphere in which research was being done at Harvard University that he moved for good to Cambridge (Mass.). There he became the heart of the biological research projects and soon realized the need to found a national academy of sciences as a centre for the intellectual efforts of the whole country. On March 3, 1863, President Lincoln put his signature to the law by which the Academy of Sciences in Washington was born. A beautiful oil painting, which still hangs in the Academy of Sciences, shows to the right of President Lincoln the smiling Louis Agassiz, who in its first years rendered the Academy great services as a co-founder and foreign secretary. (My translation)

VARIOUS KINDS OF CREEP

The experimental bases for an investigation of the creep processes which developed on the one hand in the laboratory, and on the other hand *in situ*, that is, on the natural strata formation, are rather more advanced with regard to snow and ice than with rock and soil. The most progress has probably been made in research into the creep of ice because it is similar to the creep of metals near the melting point. For rock, creep research on concrete may have an inspiring influence.

Flow Curves

The flow curve shows the strain rate of a sample plotted against the sheer stress. It can be expressed either by the rate of change of an originally right angle or by a specific change of length per unit time. The conditions are simplest with a cube of ice exposed to pure shearing stress (Fig. 4). For each shearing stress a constant strain rate sets in after

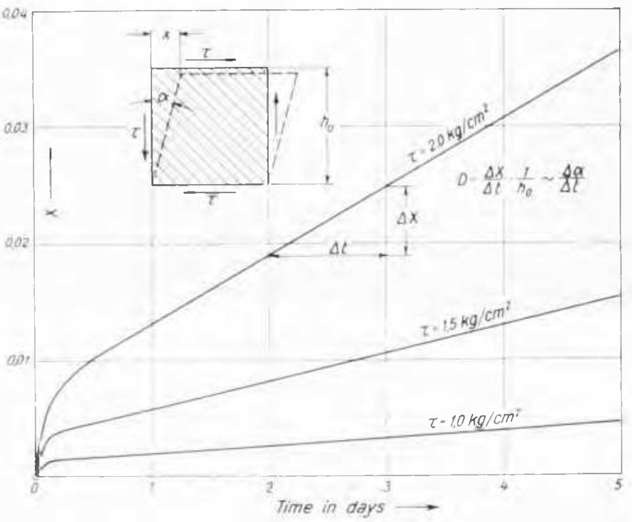

FIG. 4. Time displacement curves of ice for three different shear stresses.

some time. Fig. 4 shows the rectilinear time–displacement curves for three different shear stresses (1, 1.5, and 2 kg/sq. cm.). To each shearing stress, there corresponds, under a given temperature, a certain strain rate D which is independent of the rate of the hydrostatic pressure simultaneously in effect. If we plot this strain rate against the shear stress, we obtain the flow curve of ice the formula of which is (Glen, 1952, 1955; Steinemann, 1958; Haefeli, 1961a, 1961b)

$$D = k_1\ (\tau/\tau_1)^n \text{ (Fig. 5)} \qquad \tau_1 = 1 \text{ kg/sq.cm.} \qquad (1)$$

For $\tau = \tau_1$ kg/sq.cm., D is identical with the parameter k_1 which only depends on the temperature of the ice and represents that angular rate which appears when the deformation of a cube of ice takes place under the unit of the shear stress (1 kg/sq.cm.). Fig. 5 shows the deformation of two cubes of ice submitted for a year to a constant shear stress of 1 kg/sq.cm., one at -1.5 C, the other at 0 C.

As even the smallest shear stress causes a continuous deformation of snow and ice, both materials belong, from a mechanical point of view, to the liquids (Fig. 6). Since their viscosities (tan u^*) are not constant at an unchanged temperature but depend on the shear stress, their behaviour, from a rheological point of view, is "pseudoplastic." Only under a small stress can the viscosity of snow be considered constant. In the case of the natural creep of ice appearing as glacial movement occurring relatively near the melting point, the deformation processes are closely related to those in the

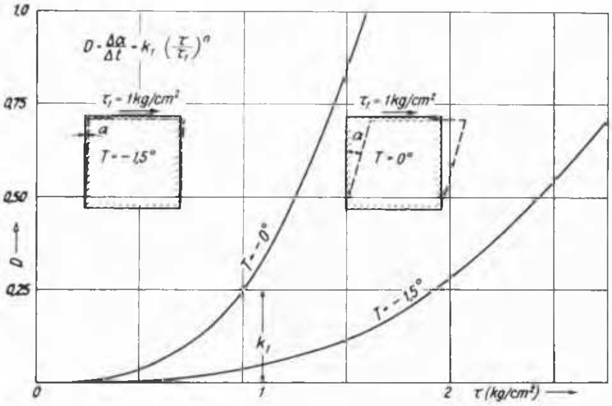

FIG. 5. Flow curves of ice for two different temperatures. The two ice cubes indicates the real deformations in one year under a constant shear stress of 1 kg/sq.cm. (dashed line).

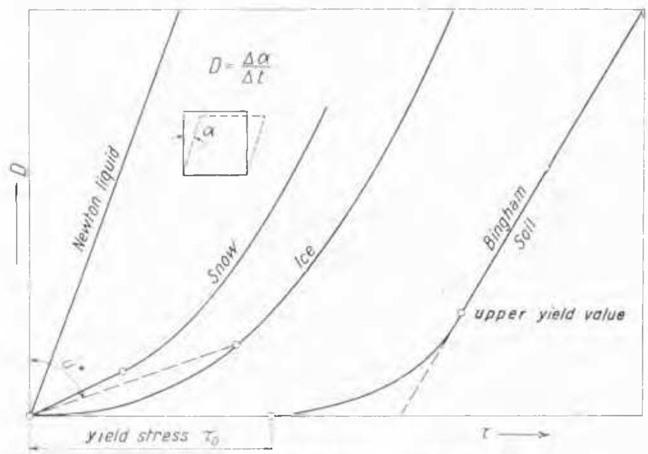

FIG. 6. Flow curves for snow, ice, and soil.

deformation of warm metals. Because ice behaves, on the other hand, like an elastic body under stresses of very short duration, but like a viscous liquid under long-term forces, we can also speak of the visco-elastic behaviour of ice.

In contrast to that of snow and ice, the creep of the soil begins as a rule only beyond a certain yield stress, unless it is in a liquid state (Geuze and Tan Tjong-Kie, 1963; Haefeli, 1954). Its rheological behaviour places it among the Bingham solids (Fig. 6). The very existence of quick clay, which liquefies itself upon disturbance of its structure, proves that this rheological behaviour depends not only on the type of soil and its water content, but also, above all, on structural and chemical conditions.

Densification and Secondary Settlement as Internal Creep

The densification of various non-cohesive materials under the influence of constant external stresses depends on different factors.

1. In the case of snow, it is the destructive metamorphosis which alters the snow crystals into snow grains, reducing their surface and thus mutually approaching the centres of gravity of the different grains.

2. With regard to the fine-grained, saturated, cohesive soils, the consolidation settlement governed by the pore water pressure is succeeded by the secondary settlement. This secondary settlement is proportional to the logarithm of time

and can be explained by the visco-elastic behaviour of the bound water envelopes which are exposed to a high molecular pressure.

3. Densification in coarse-grained, non-cohesive materials, depends mainly on the intensity of the weathering which weakens the highly strained points of contact between the grains and thus renders possible their failure and the plastic deformations that would explain the mutual approach of the grains. On the other hand the failure process in the contact points between the grains involves a statistical problem.

The densification processes of the fine-grained soils can generally be understood as an internal creep due to internal shear stresses between the individual grains. We could also speak of a pseudoplastic flow of the molecularly bound water envelopes which behave similarly to ice (Winterkorn, 1943). This, which is an internal creep, would also explain why triaxial densification proceeds normally even under a (general) hydrostatic pressure, that is without external shear stresses (Fig. 7).

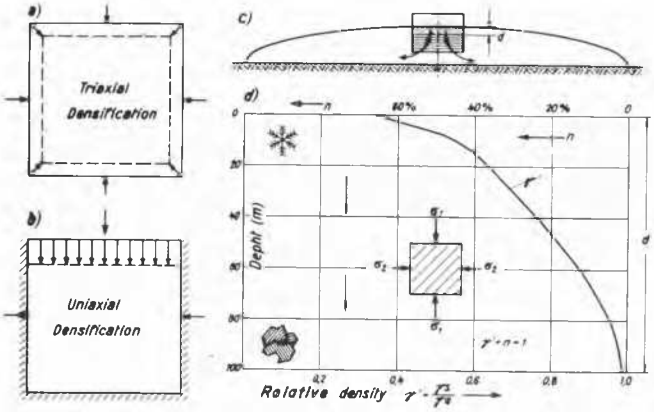

FIG. 7. (a) triaxial densifications; (b) uni-axial densification; (c) and (d) natural densification process in a firn layer on the top of an ice sheet.

As an example of uni-axial densification which, in soil mechanics, is similar to secondary settlement in the deltas of great rivers (for instance in the Netherlands) Fig. 7c shows the central zone of a mighty ice cap (Greenland or Antarctica). A névé, 80 to 150 m thick, covers the ice base which is 2000 to 3000 m thick. In this transition zone, a continual metamorphosis and densification is in progress from fine-grained polar snow at the surface through polar firn to polar ice and all at very low temperatures, that is without a liquid phase. Year after year, a new snow cover is laid down and slowly sinks with continually increasing overburden pressure through the névé cap until it is changed, after several centuries, into polar ice. The particular interest of this uni-axial densification is that all the characteristics of the strata, such as void ratio, density, pressure at rest, and viscosity, are a function of the depth z under the surface of the névé, that is, are independent of time as long as the climate remains constant.

Secondary settlement in soil mechanics, appearing as a slow, continuous phenomenon, can become a question of vital importance for the inhabitants of vast deltas. Let us try to explain this process of the fine-grained soil with a very simple model. For this purpose, the four cubes shown in Fig. 8a may represent the grains. Two grains at a time are connected with a small ice cylinder which represents the molecularly bound water envelopes. Under a constant grain-to-grain pressure each ice cylinder is exposed to the creep process shown in Fig. 8b. The transverse extension, being unhindered, causes a continuous decrease of the specific vertical pressure in the ice cylinder and consequently in its settlement rate. This process can be calculated on the basis of the flow law of ice of constant volume (Eq 1) and the following formula is obtained:

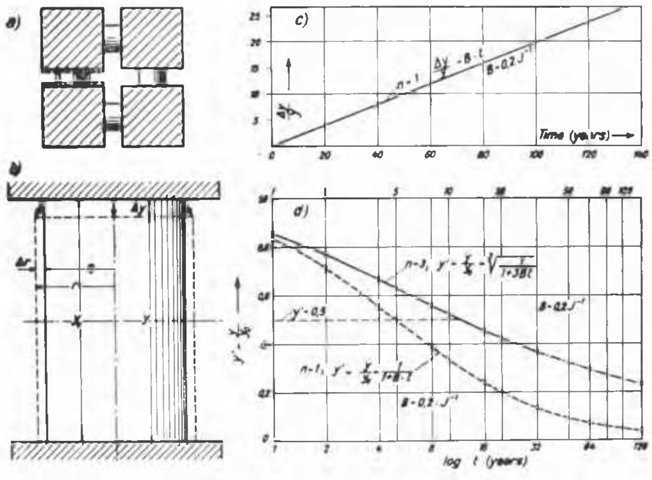

FIG. 8. Model for secondary settlement.

$$y' = \frac{y}{y_0} = \sqrt[n]{\frac{1}{1+nBt}}, \qquad B = \frac{2}{3}k_1\left(\frac{1}{2}\frac{\tau_0}{\tau_1}\right)^n, \qquad (2)$$

where y' = specific settlement at the time t; y_0 = initial height of the sample; y = height of the sample at the time t; k_1 = parameter of temperature in J^{-1}; $\tau_0 = \sigma_0/2$ = initial stress at the time $t = 0$; τ_1 = unit of stress (1 kg/sq.cm.); n = exponent of the liquid law of ice.

Supposing that $k_1 = 0.3\ J^{-1}$ (c. 0 C) and $\sigma_0 = 2$ kg/sq. cm., B is 0.2 J^{-1}. The function y' computed on these suppositions follows practically a straight line on a semi-log plot for $n = 3$ to $t = 40$ years. This would agree with previous measurements and theoretical investigations on the nature of secondary settlement. For $n = 1$ (Newton liquid), the settlement of the cylinder of ice would proceed so that the ratio $\Delta y : y$ shows a linear increase with time, conforming to the equation (Fig. 8c):

$$\Delta y/y = Bt \qquad (3)$$

The corresponding settlement curve on a semi-log plot is shown in Fig. 8d.

Steady and Unsteady Creep Phenomena

A *steady creep* process is present when the creeping speed is constant with respect to time and there is no change in either volume or shape in the mass undergoing creep. The steady condition is rare in nature. At the most one may speak of quasi-steady creep phenomena. Creep in rubble slopes and slope washes may be cited as examples. Apart from small variations these may maintain their same or similar speed for decades.

Fig. 9 illustrates the horizontal displacement of seven churches situated on a creep area of 40 sq. km. in Switzerland (Peiden). The area is composed of heavily weathered Bündner schist with stratification parallel to the slope. Over a period of 67 years the Peiden church has been displaced 15 m horizontally and 3 m vertically without suffering the slightest damage (von Moos and Haefeli, 1962).

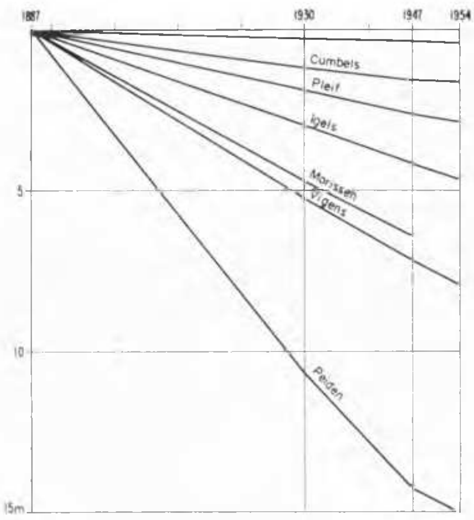

Abb. 9.9 Horizontale Verschiebung einiger Kirchen von 1887–1954

FIG. 9. Horizontal displacements of seven churches near Peiden (Switzerland, 1887–1954).

The leaning of old towers, high buildings, and pillars is a good example of *unsteady creep* processes. In these cases a gradual "vicious circle" process is involved that often stretches over centuries (Fig. 10). The eccentricity of the resultant forces, increasing with time, activates the creep process by increasing the edge pressure. Recent experiences in Switzerland have shown that this dangerous creep process may be reversed by the introduction of outside forces and the tower or pile straightened or the inclination regulated (Fig. 11) by creep.

Another example of unsteady creep is the anchored retaining wall which uses prestressed cables to keep the horizontal movement of the wall resulting from earth pressure as small

FIG. 10. Inclined tower of Pisa.

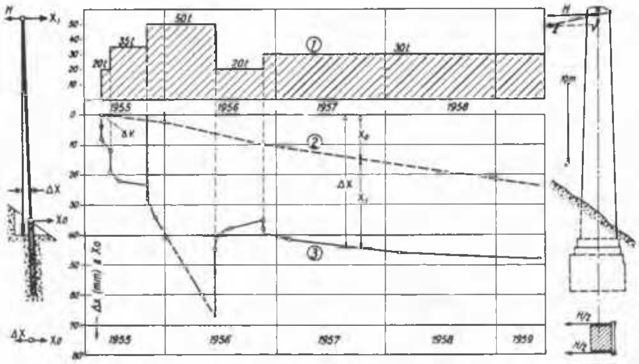

FIG. 11. Regulation of the inclination of a bridge pile by horizonal forces and creep.

as possible (Fig. 12a). Through prestressing, a known area of the earth mass which is to be stabilized will be subjected to a supplementary compression stress, to improve its mechanical properties. The soil responds to this excess pressure through internal and external creep. Thus the prestress is released progressively and will asymptotically approach a certain end value. The reduction in prestressing can be demonstrated with the aid of a consolidometer using calibrated springs to apply the pressure instead of a constant load. The springs then take over the function of the prestressing cables (Fig. 12b).

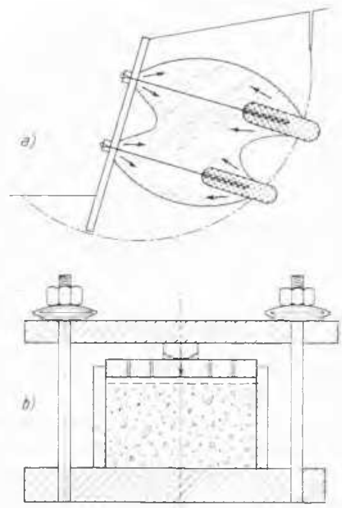

FIG. 12. Unsteady creep activated by prestressing.

The creep of a sloping layer of unconsolidated material belongs in particular to the group of unsteady creep processes which are related to a volume change of the mass undergoing creep (Fig. 13). Any settlement of such a layer, be it snow, clay, volcanic ash, or lake marl, is always associated with a horizontal component of movement. The so-called creep angle β between the surface of the slope and the creep vector decreases for any given slope with decreasing porosity. Let us call the route described by point A_0 during the creep process the *creep curve* (Fig. 13). If the point A_0, moving along its path (a hyperbola) with increasing consolidation and decrease of the creep angle, finally arrives at the point A_3, then the snow layer has been transformed into an ice layer of equal weight with a creep angle

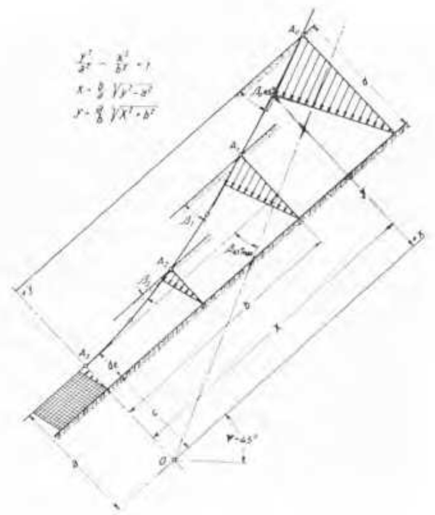

FIG. 13. Consolidation and self-stabilization of a sloping layer by creep.

of 0° (Haefeli, 1942). If on the other hand not only the variation with respect to time but also the spatial distribution of rate of creep is considered, a differentiation between continuous and discontinuous or sliding creep is recommended (Fig. 14). In most cases of natural creep phenomena a combination of both types of movement is found. This is particularly true of glaciers and wet snow.

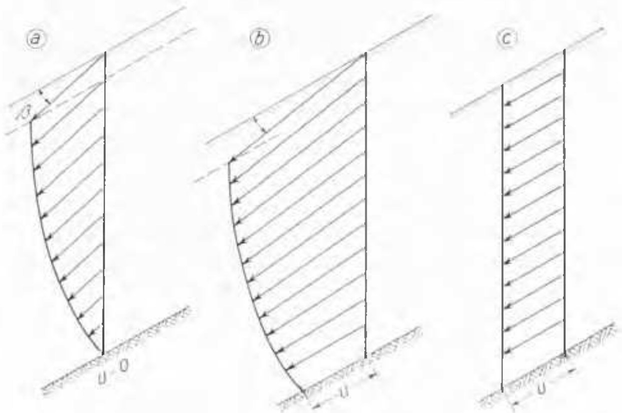

FIG. 14. (a) spatial continuous creep profile; (b) discontinuous creep with slip movement on the bottom; (c) translation (sliding).

Fig. 15 shows the folding pattern of a sliding snow cover and demonstrates pseudoplastic behaviour. Fig. 16 shows that nature had discovered the wheel long before man. In addition to the sliding creep phenomena there is a rolling creep. The snakelike winding of an icicle in a slowly deforming glacier crevasse shows the perfect plasticity of ice under constant pressure (Fig. 17).

Summarizing, the spatial continuous and discontinuous creep phenomena, including the slow slip processes, can be divided into three main groups:

1. Spatial continuous creep when exceeding a critical shear stress (creep limit) which is smaller than the residual shear strength.

2. Spatial discontinuous creep (slipping) on one or several discontinuous planes, when the residual shear strength is exceeded.

3. Internal creep when the grains draw nearer, that is to say when the volume of the creep mass diminishes. There are various causes of this consolidation process, for instance

FIG. 15. Folding of sliding snow cover.

FIG. 16. Rolling creep of snow cover.

FIG. 17. Icicles in a crevasse demonstrates the visco-elastic behaviour of ice.

changes of the shape of grains (metamorphosis of snow and névé), consolidation, secondary settlement, weathering, destruction of grains when, as a statistical phenomenon, the grain contact pressure is greatly increased. All three cases can occur in combinations of two or three.

Examining critically the third group, the fact of fundamental importance is that every consolidation process of the inclined layer is connected to a horizontally moving component. The same can be said of the settlement process of a compressible layer with a horizontal surface, but with an inclined bottom. Finally it must be pointed out that the well-known phenomenon of solifluction is also to be interpreted as an irregular creeping of the surface layers.

CREEP PROCESSES AND STRESS TRANSFORMATIONS

In the case of unsteady phenomena the creep process is related to stress changes which take place according to established principles. These changes may either improve or lessen the stability of the system.

Creep Profile and Stress Conditions

Most easily studied are the conditions in a sloping, laterally infinite, uniform snow layer in which the creep profiles are congruent (neutral zone). Here the direction of the creep vector is given by the creep angle β and the corresponding stress conditions are clearly determined as well. In the case of a triangular creep profile (Fig. 18) which has repeatedly proved to be characteristic for snow blankets, the direction of the principal stresses may be determined by the simple construction illustrated in Fig. 19. It can easily be seen that with a slight movement of P in the direction of the creep vector V the right angle DPE does not change. That means that in the direction of P–D and P–E, which coincide with the direction of principal stresses, the shear stresses are zero.

With a small modification this graphical method is valid for any desired shape of creep profiles as long as they are congruent and the creep vectors are parallel. For other unconsolidated materials which do not behave as viscous

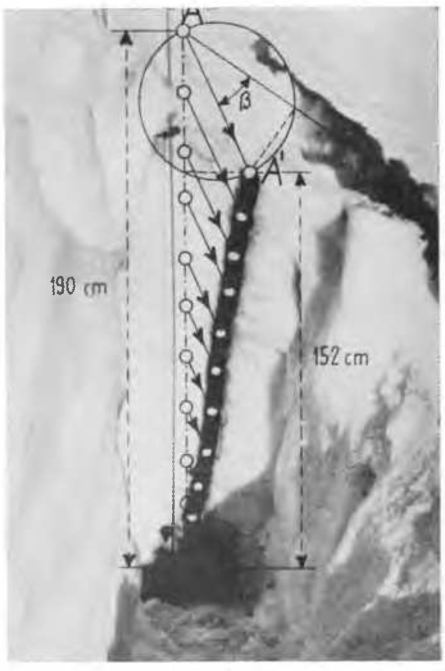

FIG. 18. Triangular creep profile of the snow cover without sliding on the bottom. Creep vector A–A′ measured in 66 days.

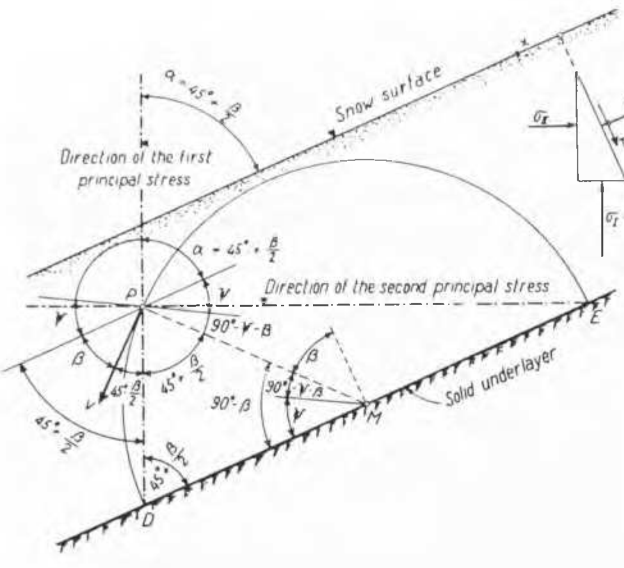

FIG. 19. Construction of the directions of principal stresses if the inclination of the creep vector is known.

liquids, but rather as Bingham bodies, that is, those in which the creep begins only after a measurable yield stress has been attained, the above construction is not strongly valid, but gives the most probable solution. The smaller the yield stress the more accurately the solution may be determined.

Stress Transformation (Stress Metamorphosis)

Let us examine a porous snow layer with a 30° slope and the maximum possible creep angle β. The corresponding minor principal stress is negative. With increasing consolidation β will be reduced, which induces a clockwise rotation of the principal stresses (Fig. 20). Thereby, the major principal stresses will finally be vertical and equal to the

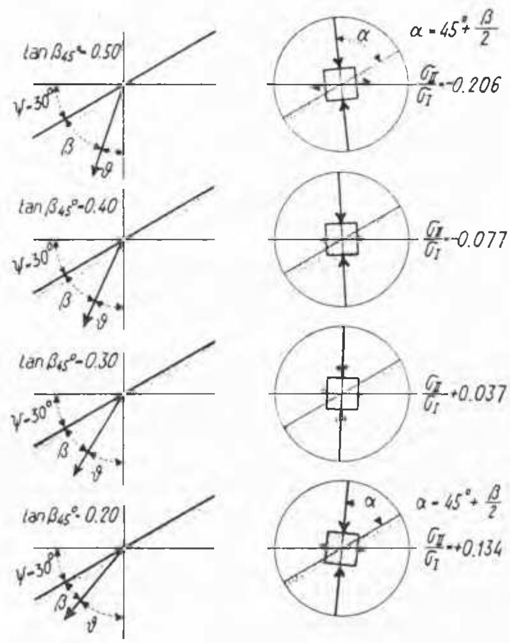

FIG. 20. Metamorphosis (transformation) of the stress state during creep and settling (densification) of the inclined snow layer (self-stabilization).

overburden pressure. At the same time the minor principal stress is reduced to zero.

We call this the critical case because its stability is still very delicate. With further creep and consolidation the minor principal stress becomes positive and then a stabilization of the snow layer sets in.

We speak in this case of a "stress metamorphosis" because the steady and regular transition of stress conditions, which makes itself known through the progressive changing of direction and magnitude of the principal stresses, is not only caused by the metamorphosis of the snow, but is also controlled by it. The speed with which the metamorphosis progresses or more precisely, the time required for the stabilization of the snow layer, depends primarily on the temperature. The lower the temperature, the slower the process of metamorphosis. For this reason the danger period for avalanches is longer in mid-winter (low temperatures) than in spring.

Three Special Cases of Creep

The *first* of the three special cases outlined below we have already noted and designated the critical case (Fig. 21a). The corresponding principal stresses are:

$\sigma_1 = \gamma z$	vertical
$\sigma_2 = 0$	horizontal
$\sigma_3 = \gamma z / m_2$	right angles to the plane of the figure

For each type of snow there is a related *critical slope* ψ_0 on which the critical stress conditions occur ($\sigma_2 = 0$) or, inversely, for every given slope there is a critical snow condition (Haefeli, 1965). It is understood that this critical state of stresses supposes a certain cohesion which increases in proportion to the overburden pressure or more precisely, the depth (Fig. 21a),

$$c \geqq \tfrac{1}{2}\,\sigma_1 \tan\left(\tfrac{1}{4}\pi - \tfrac{1}{2}\phi\right) \qquad (4)$$

The *second* special case (Fig. 21b) is the creep process and stress conditions of a layer of constant volume, which could be composed of ice or clay. Because the creep angle $\beta = 0$ in this case, the major principal stress according to the above-mentioned graphical construction, acts at 45° to the fall line. The major principal stress relates to the major so that (1 — tan) : (1 + tan). From Mohr's circle it is seen that in the case of cohesionless materials ($c = 0$) this set of stress conditions is only possible when the angle of internal friction ϕ is somewhat larger than the slope angle. The exact requirement is $\sin \phi = \tan \psi$. As mentioned above the critical stress condition in the case of ice ($\sigma_2 = 0$) will be attained when $\psi = \tfrac{1}{4}\pi$. The principal stress acting at right angles to the plane of the figure constitutes the pressure at rest, which for $\psi = \tfrac{1}{4}\pi$ and $m_2 = 2$ will be equal to half the overburden pressure.

The *third* special case is that of Rankine (Fig. 21c). It may only be made to agree with the outlined creep theory when the creep vectors are horizontally aligned. The creep angle β will thereby become negative and numerically equal to the slope angle ψ. This means that the creep phenomena lead to an increase in the porosity of the material or to a volume increase by shear. The internal friction angle ϕ in this case would be identical to the slope angle ψ and the major principal stress is known to be at an angle of $(\tfrac{1}{4}\pi - \tfrac{1}{2}\phi)$ to the slope line.

The conclusions concerning the stability of slopes in soil mechanics which these relationships lead to must be very carefully checked by further research. Interesting information may be expected concerning the values of pressure at rest in horizontal as well as sloping layers (Haefeli, 1965).

Example of Creep Pressure Measurement

Any rigid obstructions which stand in the creep path will be subject to creep pressure loading. The latter increases gradually with time and asymptotically approaches a maximum value. This value governs the design of the required construction. The peak value of the creep pressure can constitute a multiple of the active earth pressure but is only rarely equal to the passive earth pressure.

A primary practical application of the snow mechanics concept of creep pressure to analogous soil mechanics problems resulted from the consolidation of the Landquart bridge built by the famous engineer Maillart on the Rhätischen railway near Klosters, Switzerland (Fig. 22). In this case it was necessary to prevent further progress of the threatening destruction by the increasing creep pressure. The arch bridge, curved in plan, had its left abutment resting on creeping landslide material. A horizontal reinforced concrete compression member was constructed between the two abutments and was designed to resist a calculated creep pressure

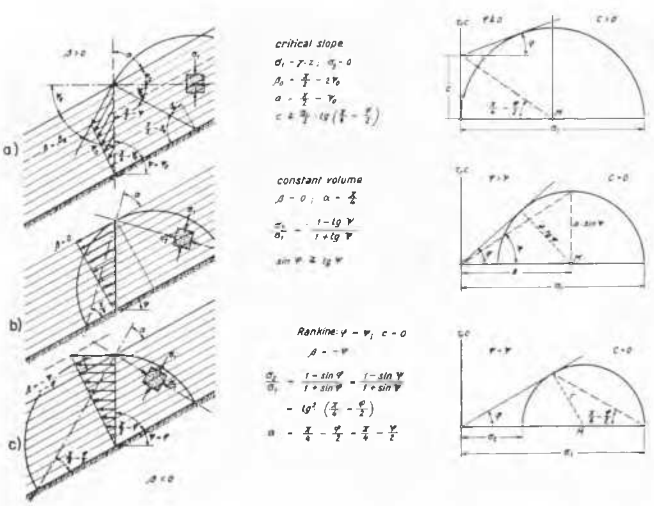

FIG. 21. Three special cases of creep and stress conditions: (a) critical slope; (b) constant volume; and (c) Rankine state.

FIG. 22. Landquart bridge (Klosters, Switzerland) constructed by Maillart (1930) with a horizontal beam to translate creep pressure from the creeping left to the stable right abutment.

from 1000 tons to a maximum of 1650 tons with an adequate factor of safety (Mohr, *et al.*, 1947).

Long-term measurements of the force in the compression tie, carried out by the Laboratory for Hydraulics and Soil Mechanics (Swiss Federal Institute of Technology), showed a slowly increasing compression force which in the course of six years reached approximately 1000 tons, the lower limit of the theoretically calculated value (Haefeli, *et al.*, 1953).

As expected this pressure increase curve (Fig. 23) had superimposed upon it yearly variations which were influenced by the seasonal temperature changes (Mohr, *et al.*, 1947; Haefeli, *et al.*, 1953). After the first six years of observations the pressure increased very slowly reaching a value of approximately 1200 tons in 1956, about 12 years after the beginning of measurements. This value is within the limits of calculated creep pressure.

PROGRESSIVE FAILURE AND RESIDUAL SHEAR RESISTANCE

In one of his latest articles, "Stability on Steep Slopes on Hard Unweathered Rock" (1962), Terzaghi defined progressive failure as follows:

> Failure of slopes on brittle materials starts at a point where the shearing stress becomes equal to the shearing resistance. As soon as failure occurs at that point, the cohesion of the rock at that point becomes equal to zero whereupon the stresses in the surrounding rock increase and the rock fails. Thus the failure spreads by chain action and the process continues until the surface of failure extends to the surface of the rock. This process is known as progressive failure.

In the fourth Rankine Lecture, Skempton (1964) showed by a series of examples how a substantial portion of the discrepancy hitherto existing between theory and practice in questions of slope stability, especially in preloaded soils, disappears when one considers the appearance of progressive failure in combination with the residual shear stress.

Example of Progressive Failure Processes

Progressive failure may occur in one or more phases with different stress conditions. The "snow slab" avalanche is a typical example of a multiple-phase failure process (Haefeli, 1954). The more the wind-packed layers of a snow slab lose their deformability as a result of hardening, the more the creep process in the tension zone will be slowed down by the longitudinal forces. The creep profile gradient (Fig. 24) is no longer adequate to activate the friction force in the sliding layer so that the full shear component of the overlying snow layer is transmitted to the ground layer. An ever increasing portion of the component of weight parallel to the slope is taken by tension in the wind slab. The avalanche is then "maturing" and only a slight disturbance is required to cause rupture in the weakest link of the chain. With a sharp detonation the tension crack A–B opens. It seems that the progressive rupture propagates itself at the speed of sound along the surface B–C parallel to the slope downwards, overcoming the head end resistance along the slip C–D.

We have, then, a progressive failure with three distinctly different phases which may occur successively or may overlap. First, the tensile strength of the snow slab (which is significantly smaller than the sum of the tensile strengths of the individual layers) is exceeded, then the shear strength of the sliding layer, and finally the compression strength at the head end parallel to the slope. With the formation of the tension cracks, the process in general is accelerated so that dynamic forces are also brought into play. Fig. 25 illustrates the marble-type structure of the rupture surface of the tension crack, and the grooved appearance of the sliding surface of a snow slab avalanche.

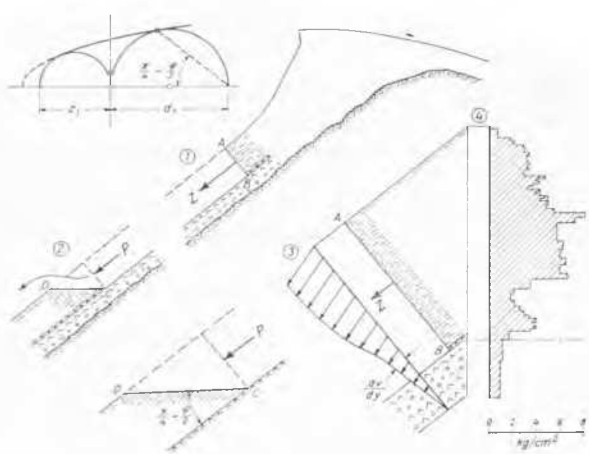

FIG. 24. Schematic diagram of a snow slab avalanche demonstrating progressive rupture in three phases.

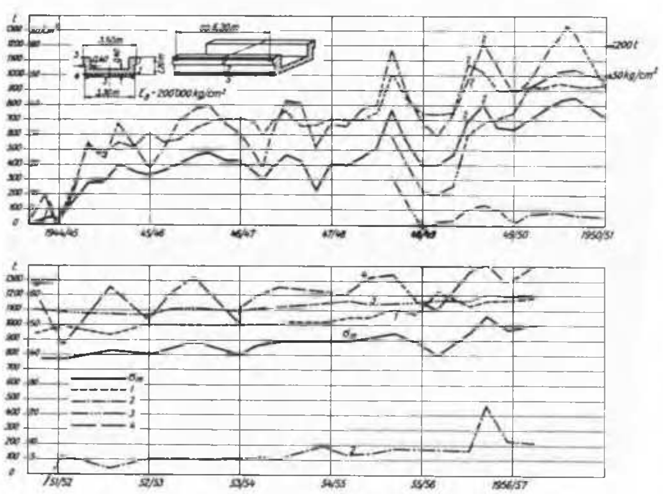

FIG. 23. Measurement of creep pressure *versus* time in the horizontal beam of the Maillart bridge at Klosters.

FIG. 25. Failure surface and sliding plane of a snow slab avalanche. (A. Pedrett, St. Moritz)

Progressive failure processes, in *one or several phases*, may also be observed in earth embankments composed of cohesive material. Fig. 26 shows an attempt to determine the principal stresses at various points of a logarithmic slip surface, admitting a $\Phi = 0$ material, in order to find the weakest link in the chain, in other words the element in the potential slip surface, which is under the least favourable loading. The Mohr circle, calculated for the case of four elements using the simplest assumptions allows the supposition that the critical point lies at the foot of the slope. At this point the element 13 is under failure conditions, that is the Mohr circle cuts the rupture envelope (horizontal line C). From here progressive failure may start and produce a slide surface, but only after a tension crack opens on the upper edge of the slope. The feared slide will only be avoided if the sum of the residual shear strengths, which depend almost entirely on friction, is enough to prevent the movement of the sliding mass. This last condition can be controlled with the aid of normal stability calculations.

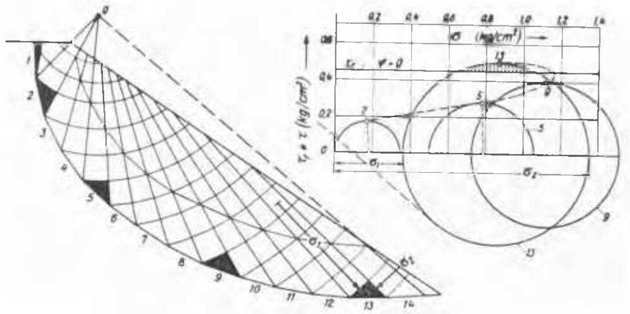

FIG. 26. Progressive failure in an earth embankment. It is assumed that in all points of the potential slip plane the major principal stress is inclined $(\frac{1}{4}\pi - \frac{1}{2}\phi) = \frac{1}{4}\pi$ to the potential slip surface.

Residual Shear Strength

Closely associated with the progressive rupture phenomenon and the resulting dangers is the "residual" shear strength, which can be defined as all the shear strength remaining along the slip surface after the loss of soil cohesion and it depends for the most part on friction.

In 1935 the *Swiss ring shear apparatus* (Haefeli, 1938) was fitted with a braking spring in order to allow determination of the residual shear strength after a complete halting of the sliding process (Fig. 27). Using this procedure a drained ring shear test may be outlined as follows. The three most important quantities, namely shear stress τ, horizontal movement x between the upper and lower surfaces of the sample, and the rate of shear v would be illustrated graphically *versus* time. The relatively long test duration of 8 to 24 hours permits continuous drainage and the reduction of pore pressures to zero.

After the linear increase of the shear stress with respect to time and after a definite horizontal displacement enough to overcome the peak value of shear stress (τ_f) is reached, the braking springs automatically become engaged. Simultaneously with the reduction of the sliding speed and the smoothing and polishing of the slip surface, the friction is progressively reduced until finally when the rest position is reached only the residual shear strength τ_r is left (Haefeli, 1951). The ratio between the residual shear strength and the maximum value of shear strength comparable with the sensitivity may be called the "residual coefficient." (This should not be confused with the factor defined by Skempton

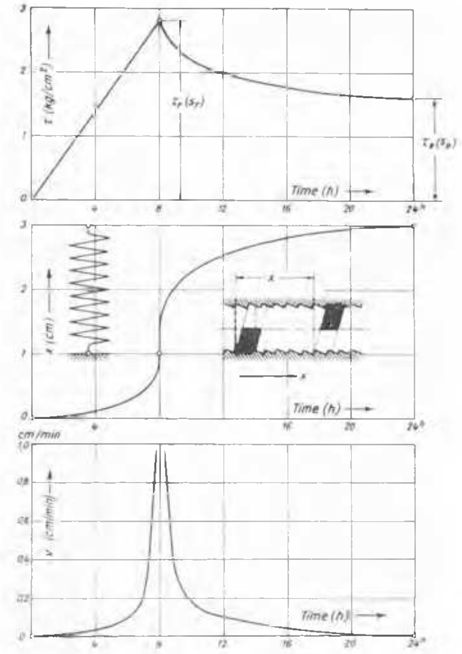

FIG. 27. Determination of peak and residual strength in the ring shear apparatus. Shear stress (τ), horizontal displacement (x), and rate of shear (v) *versus* time.

as the "residual factor" (Skempton, 1964).) Residual coefficient (Haefeli, 1957):

$$\lambda_R = \frac{\tan\phi_r}{\tan\phi_f} = \frac{\tau_r}{\tau_f} = \frac{\tau_f - c}{\tau_f} = 1 - \frac{c}{\tau_f}. \tag{5}$$

Residual factor (Skempton, 1964):

$$R = \frac{\tau_f - \bar{\tau}}{\tau_f - \tau_r} = \frac{s_f - \bar{s}}{s_f - s_r}. \tag{6}$$

The greater the proportion of cohesion c in the peak value of shear strength, the smaller the coefficient λ_R. It is for this reason that this coefficient is noticeably smaller for preloaded cohesive soil than for soils with no preloading. For cohesionless soil λ_R becomes 1. For fine-grained cohesive soils, in which the cohesion is directly proportional to the consolidation pressure, λ_R may be regarded as nearly constant. Fig. 28

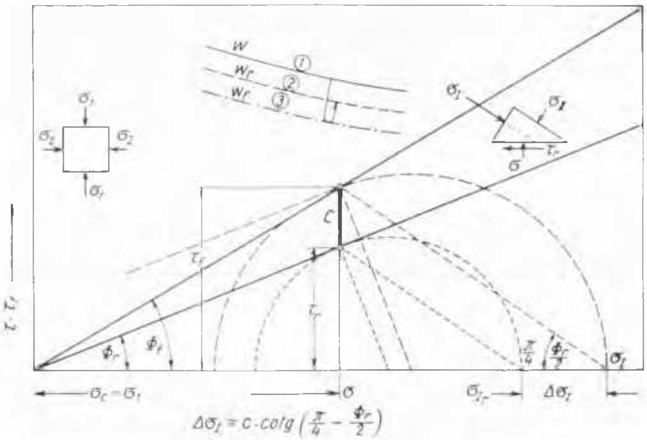

FIG. 28. Shear diagram with peak and residual shear strength. Change in water content, w, during the drained shear test.

shows clearly how much the Mohr failure circle will be reduced in size with the loss of cohesion c and the polishing of the sliding surface. The slow reduction of the major principal stress ($\Delta\sigma_I = \sigma_I - \sigma_{Ir}$) during the braking procedure is, in the case of a drained test under water, closely associated with an equivalent increase of water content (swelling).

Sheeting and Popping

Sheeting and popping may be considered as two related phenomena of relaxation, characterized by the formation of cracks more or less parallel to the surface and independent of the stratification. Let us now try to interpret this relaxation process as a multi-phase progressive failure.

As a comparison, Fig. 29 shows schematically the formation of fissures in a saturated clay layer exposed to desiccation at its surface and consequently to a shrinkage process. As a consequence of the loss of water by evaporation, a plane stress condition appears first, with horizontal, two-axial tensile stresses. By overcoming the tensile strength of the clay a network of fissures perpendicular to the surface is formed dividing the whole top layer into innumerable polygonal slabs. This first phase of cracking is accompanied by a radical change in the stress condition. The surface of the clay has been relaxed by the development of the cracks, but the tensile, compressive, and shear stresses (shown schematically in Fig. 29) are manifesting themselves in a plane parallel to the surface, leading to a second phase of failure (which is often facilitated by horizontal discontinuous areas such as the smallest sand layers). This second phase of a progressive failure causes cracks which are parallel to the surface and detaches the individual polygons from their base, their edges being strongly bent up (Fig. 30).

An analogous process with corresponding relaxation and cracking occurs when the surface of a rock mass is cooled, the only difference being that the "decrease" in volume and in the corresponding stresses are caused not by a loss of water but by a loss of heat. Therefore fissures which are parallel to the surface and due to a decrease of temperature can be also considered the result of a progressive failure, as well as the inverse phenomenon when a very strong heating of the surface of the rock takes place.

The system of fissures due to abrupt variations of temperature, perhaps intensified by frost action and fatigue, has a relatively narrow spacing and is mainly confined to that zone near the surface in which the short variations of both the outside temperature and the irradiation are perceptible. The fact that fissures which run parallel to the surface but which are completely independent of the stratification can be found at depths down to *ca.* 50 m normally excludes variations of temperature as a reason for this deep banking (Fig. 31). Conforming to Kieslinger (1958), this type of banking can be attributed to "residual stresses" which are considered a remainder of an overburden pressure from the respective pre- interglacial period. Tectonic forces may also be involved. Matthews (1930) came to similar conclusions in his famous and important studies of the morphology of the Yosemite Valley.

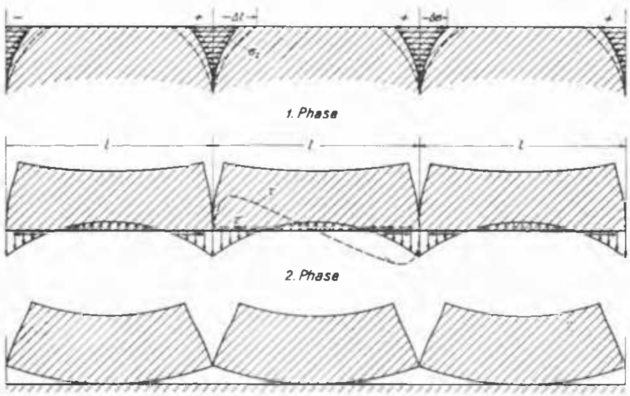

FIG. 29. Superficial shrinkage of a horizontal clay layer with two phases of progressive rupture.


FIG. 30. Polygonal fissures in a clay layer due to shrinkage.


FIG. 31. The Royal Arches of the Yosemite Valley (Matthews, 1950).

The question which now arises is how the mechanism of these deep relaxation phenomena described by Kieslinger occurs. Similar relaxation phenomena, but on a smaller scale, were observed during the construction of tunnels at some depth under the Alps (for example, the Simplon tunnel). This relaxation process described by Andreae (1950) and often referred to by Terzaghi (1946) is known as popping and is to be feared in mining and tunnel construction. Such relaxation phenomena occurred recently on a very impressive scale during the construction of the Mont Blanc Tunnel. An attempt shall therefore be made here to interpret, from the point of view of progressive failure and purely qualitatively, the mechanism of popping. This interpretation may be regarded as complementary to the fundamental considerations put forth by H. Kastner (1962) in his important book.

As Fig. 32 shows, the height of the overburden on the French side of the Mont Blanc Tunnel, more precisely in the zone of strong relaxation phenomena, was more than 2000 m, corresponding to an overburden pressure of *ca* 540 kg/sq.cm. For a circular tunnel profile, the maximum theoretical edge pressure would vary between 1100–1500 kg/sq.cm., whereas the compression strength of the parent Mont Blanc granite is estimated to be 1200–2400 kg/sq.cm.

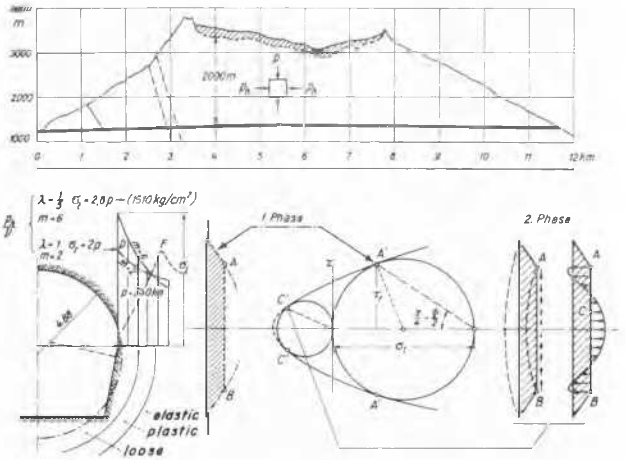

FIG. 32. Longitudinal profile through the Mont Blanc Tunnel with schematic diagram showing the mechanism of popping.

(Kastner, 1962). The natural relaxation processes, which take place immediately after excavation and lead to the formation of a ring-shaped plastic zone, cause a rapid decrease in these peak values of σ_t. The danger of popping related to these phenomena was successfully overcome thanks to the development and the application of the modern technique of rock anchoring. The iron consistency with which this fight against natural forces resulting from human intervention was carried through by French and Italian engineers deserves the greatest admiration.

In the first phase of progressive failure (Fig. 32), as soon as the compression strength of the rock at one or two neighbouring weak points, A and B, has been overcome (Kastner, 1962; Jaecklin, 1965) by the formation of local shear failures, the vertical pressure on the shaded zone situated between A and B is partially relieved. A corresponding elastic expansion is first hindered by the shear stresses becoming effective within the plane A–B. If these shear stresses were working and the slab was free, it would not only expand elastically, but deflect as outlined. Such a deflection is rendered impossible, however, by the stresses acting on the shaded slab along the plane A–B. The normal stresses shown schematically in the figure manifest themselves along the potential failure plane as new forcing stresses. In the centre of the slab horizontal tensile stresses are effective, while at its periphery (A and B) compressive stresses, as well as the shear stresses already mentioned, are effective. Under this unfavourable stress distribution, it is possible that the second phase of the progressive failure follows the straight line A–B, a thin rock slab splitting off with a sharp crack.*

When the excavation is immediately followed by anchoring, a horizontal compressive stress is superimposed on the stress condition of the second phase and consequently the tensile stress is decreased and the shear strength increased. Figs. 33 and 34 show the superficial marks of failure and the density of the anchors which were from 2 to 7 m. long.

FIG. 33. Sheeting and popping at P. K. 34225, French side (Lanterno, 1963).

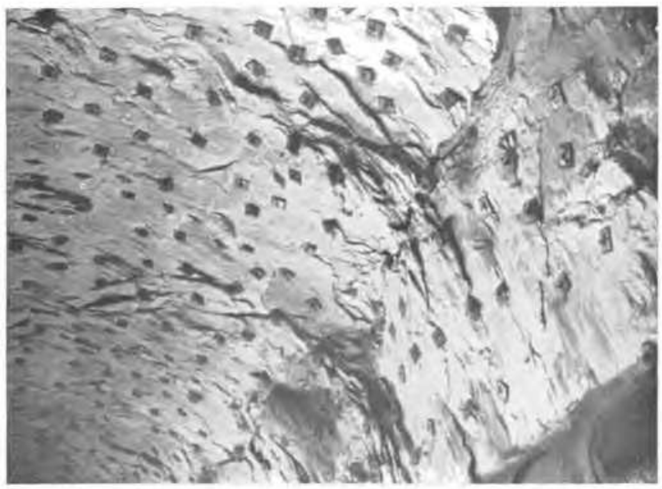

FIG. 34. Mont Blanc Tunnel, French side. Anchorage.

Creep and catastrophic events

As we have seen, we can distinguish two opposite kinds of interplay between creep and stability. In the first, harmless, kind creep produces a densification and consolidation of the material, a reduction of the peak and tensile stresses, and, as a consequence, an increase in the stability of the system. This natural consolidation process, as it occurs for example in the neutral zone of the slanting snow cover, manifests

*The late Prof. R. Staub has observed in a personal communication, that the rock falls in the high granite walls of the Bergell increase in frequency when the wall is exposed to intensive solar radiation. High overburden pressure combined with the pressure due to the increase of temperature of the rock surface can lead to a popping on free rock surfaces quite similar to the popping in tunnels.

itself as a decrease in the rate of creep. But in the second, very dangerous, kind of interplay creep produces a gradual concentration of the stresses in the relatively rigid elements of the system. This process is often initiated and intensified by the formation of sliding surfaces connected with the creep and leading to a local loss of cohesion and consequently to a decrease in the shear strength down to the residual strength. Here the residual factor, used by Skempton, is decisive.* Finally, the last resistances are broken down and progressive failure occurring in one or several phases often leads to a catastrophe.

Between these extremes lies the case of steady creeping and sliding, as observed, for example, in glacial movement or creep of sediments.

The Equilibrium and Deformation Condition of Ice Sheets

Probably the most phenomenal manifestations of the more or less steady creep processes of a visco-elastic solid material such as glacial ice are the great ice sheets, such as the Greenland inland ice in the north, and the Antarctica in the south (Fig. 35). Similar ice sheets covered the Canadian ice cap during that country's glacial periods. In view of the magnitude of the total mass of such an ice sheet and of the depth of ice in the centre (greater than 3000 m) we are confronted with the surprising fact that each ice crystal deposited at the surface of the névé, follows like a heavenly body, its prescribed orbit in the ice cake and is exposed in this way to a metamorphosis equally governed by natural laws (Nye, 1959; Haefeli, 1961b). Starting its journey near the centre, A, the ice crystal takes, in Greenland tens of thousands of years, in Antarctica hundreds of thousands, if not millions, of years, to reach the coast. The continuity of the sliding and creeping glacial movement which can reach rates of up to 30 m per day in the outfall fjords is only interrupted by calving, a catastrophic event comparable in power and grandeur, to large volcanic eruptions. In such cases ice masses with a volume of a cubic kilometer, and more, roll into the sea causing mighty tidal waves.

*On the other hand the effect of the rate of loading on the strength of clays and shales was studied by Casagrande and Wilson (1950).

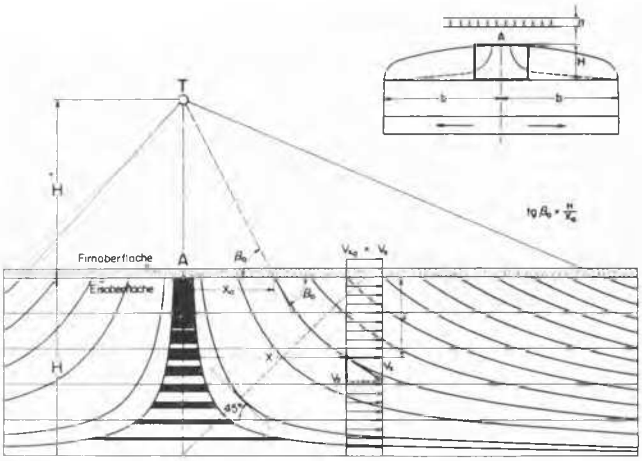

FIG. 35. Stream lines in the central zone of a strip-shaped ice sheet.

The Rock Slide in the Vajont Valley

On October 9, 1963, the world was shaken by a terrible catastrophe in the Vajont Valley in Northern Italy which claimed 1400 victims. Leopold Müller, who as an expert thoroughly investigated the circumstances which led to the greatest rock slide in historic times, made the following statements in his paper (Müller, 1964):

Until the last moment before the actual sliding the rock mass moved, creeping in its main part and with clearly distinguished parts, quite different from those of rock slide, like a glacier, in the other part with translatory motion. [Fig. 36] The extent of such movement was determined by the slight excess of driving forces, due to the joint water thrust or to the decrease in resisting forces, resulting from the buoyancy and softening of clayey substances during higher water levels. After the magnitude of creeping displacement had reached several meters, a progressive

FIG. 36. Vajont Valley rock slide (9 Oct. 1963). Photo: L. Müller [1964].

rupture occurred on the base of the moved mass. The resisting forces were thus again reduced by this rupture, until the remaining rock mass suddenly sheared off. Because of that a creeping motion changed within a few seconds into a rock slide. [Fig. 37]

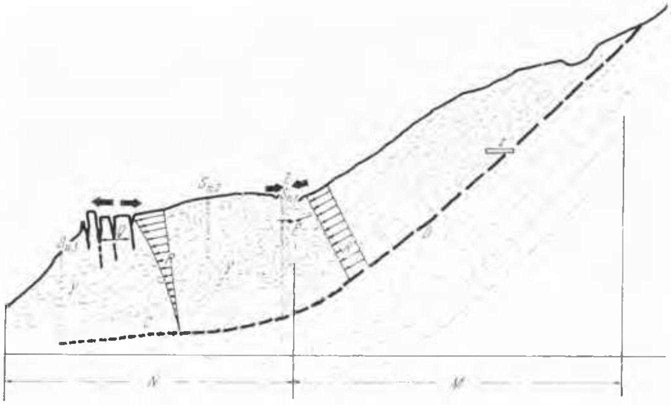

FIG. 37. Section through the Vajont valley rock slide (Mt. Toc) after L. Müller [1964].

It may be that, apart from the unfavourable effect of the buoyancy, the additional, perhaps even dynamic joint water pressures did play an essential role. We must take into account that the hydrostatic pressures in the joints can change rapidly as soon as the system of voids, partly filled with water, is compressed, so that the volume of voids increases or decreases.

The Avalanche on the Sherman Glacier in Alaska on March 27, 1964

As a last example I would draw your attention to a catastrophic event in which the interplay of four materials, rock, ice, snow, and moraines, provoked by a violent earthquake, caused a formidable avalanche. W. O. Field, to whom I am indebted for these data made the following statements with regard to this avalanche (Field, 1966):

Sherman glacier occupies a broad valley in the first range of mountains rising above the foreland fronting the Gulf of Alaska and immediately north of the mouth of the Copper River [Fig. 38]. It is within 25 km of shore, with a length of 12.6 km and an area of about 55 sq.km. The length of the avalanche along its axis of flow is approximately 7.7 km and its area is computed to be about 13 sq.km. One of the two branches of the avalanche started as a rock slide, and carried away with it a small hanging glacier. The volume of the rock would be about 10 million cubic meters with the total weight of the slide computed to be about 78 million tons [Fig. 38]. One of the unusual aspects of the avalanche was its flow characteristics over a gradient which on more than 2.4 km was as low as 3.7 per cent. This strongly suggests that the rock *débris* joined with snow as it fell to form a mixture which then behaved somewhat like a mud flow. (Katsumasa and Atsuyuki, 1965)

FIG. 38. Sherman glacier avalanche, Alaska (27 March 1964). Photo: National Geographic Society, 1965, p. 806.

Finally we must confess in all modesty that man is confined within narrow limits in dealing with and foreseeing the catastrophic events behind which the powers above are standing. Nevertheless we owe it to the victims of such catastrophes to overlook no avenue in order to understand and to more clearly foresee the reactions of nature to human intervention in its multiple hidden relations.

REFERENCES

ANDREAE, C. (1950). Gebirgsdruckerfahrung und Baumethoden im Schweiz. Tunnelbau. Internat. Gebirgsdrucktagung Loeben 1950. Wien, Urban.

CASAGRANDE, A., and S. D. WILSON (1950). *Effect of rate of loading on the strength of clays and shales at constant water content.* Harvard University, Soil Mechanics Series, No. 39.

FIELD, W. O. (1966). Avalanche caused by the Alaska earthquake of March 1964. Symposium of Snow and Ice Avalanches.

GEUZE, E. C. W. A., and TAN TJONG-KIE (1953). *Rheological properties of clays.* Delft Soil Mech. Laboratory.

GLEN, J. W. (1952). Experiments on the deformation of ice. *Jour. Glaciology*, Vol. 2, No. 12, pp. 111–14.

——— (1955). The creep of polycrystalline ice. *Proc. Royal Society*, A.V. 228, pp. 519–38.

HAEFELI, R. (1938). Mechaniche Eigenschaften von Lockergesteinen. *Schweiz. Bauzeitung*, Vol. 3, pp. 299–325.

——— (1942). Spannungs- und Plastizitätserscheinungen der Schneedecke. *Schweiz. Arch. für angewandte Wissenschaft und Technik*, Vol. 8, No. 9–12, pp. 3–45.

——— (1951). Investigation and measurements of shear strength of saturated cohesive soils. *Géotechnique*, June.

——— (1954) Kriechprobleme im Boden, Schnee und Eis. *Wasser- und Energiewirtschaft*, No. 3.

——— (1961a). Contribution to the movement and the form of ice sheets in the Arctic and Antarctic. *Jour. Glaciology*, Vol. 3, No. 30, pp. 1133–51.

——— (1961b). Eine Parallele zwischen der Eiscalotte Jungfraujoch und den grossen Eisschildern der Arktis und Artarktis. *Geologie und Bauwesen*, Vol. 26, No. 4, pp. 141–213.

——— (1966). Considérations sur la pente critique et le coefficient de pression au repos de la couverture de neige. UGGI Symposium on snow and ice avalanches at Davos, April, 1965.

——— CH. SCHAERER, and G. AMBERG (1953). The behaviour under the influence of soil creep pressure of the concrete bridge built at Klosters, Switzerland. *Proc. Third International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2, pp. 175–9.

JAECKLIN, F. (1965). Felsmechanik und Tunnelbau. *Schweiz. Bauzeitung*, No. 27, pp. 468–72.

KASTNER, H. (1962). *Statik des Tunnel- und Stollenbaus.* Berlin.

KIESLINGER, A. (1958). Restspannung und Entspannung im Gestein. *Geologie und Bauwesen*, Vol. 24, No. 2, pp. 95–112.

LANTERNO, E. (1963). Le tunnel sous le Mont-Blanc et le Museum de Genève. *Revue Musée de Genève*, No. 32–33.

MATTHEWS, F. E. (1950). *The Incomparable Valley.*

MATTHEWS, F. E. (1930). *The Geologic History of the Yosemite Valley.*

Mohr, C., R. Haefeli, L. Meisser, F. Waltz, and W. Schaad (1947). Umbau der Landquartbrücke der Rhätischen Bahn in Klosters. *Schweiz. Bauzeitung*, Nos. 1–3.

Moos, A. von and R. Haefeli (1962). Schweiz. Probleme auf dem Grenzgebiet von Bodenmechanik. *Geologie und Glaziologie.*

Müller, L. (1964). The rock slide in the Vajont Valley. *Felsmechanik und Ingenieurgeologie*, Vol. II/3–4.

Nye, J. F. (1959). The motion of ice sheets and glaciers. *Jour. Glaciology*, Vol. 3, No. 26, pp. 493–507.

Portmann, J. P. (1962). Louis Agassiz, pionnier de la glaciologie. Extrait des *Annales Guébhard.*

Skempton, A. W. (1964). Long-term stability of clay slopes. *Géotechnique*, Vol. 14, No. 2.

Steinemann, S. (1958). Experimentelle Untersuchungen zur Plastizität von Eis. *Promotionsarbeit ETH.*

Terzaghi, K. (1946). *Rock defects and loads on tunnel support.* Harvard University, Soil Mechanics Series, No. 25.

——— (1962). Stability on steep slopes and on hard unweathered rock. *Géotechnique*, Vol. 12, No. 4.

Winterkorn, H. (1943). The conditions of water in porous systems. *Soil Science*, pp. 109–15.

Katsumasa, Y., and D. Atsuyuki (1965). Fundamental study on mud-flow. *Bull. Disaster Prevention Research Institute*, Vol. 14, Part 2, No. 80.