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The σ_3-effect in the formation of rockslides

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Abstract Slopes composed of sedimentary rocks have different forms and internal structures, which are determined by the properties and occurrence of strata. Vertically-bedded slopes, dip-bedded slopes and horizontally-bedded slopes are common in nature. During and after the process of slope formation, the component forms and relative positions of strata are constantly changing and developing. In one case, deformation develops with time without variation in stress; in another case, there is no alternation in strain, but the stress decreases with time, i.e. relaxation. The former is the so-called rock creep deformation. There are many examples of slope failure due to rock creep deformation. This paper describes yielding break landslides in horizontally-bedded rock slopes caused by the development of rock creep under the long-term effect of the least principal stress (σ_3) gradient. Here the σ_3-effect is the process of landsliding due to such a mechanical mechanism.

YIELD BENDING PHENOMENA OF A COLUMN

Timoshenko & Gere (1972) found that the concept of yield bending in mechanics of materials is that theoretically a column may have a very small random deflection and a little lateral force would produce a deflection that will not disappear when the lateral force is removed. If a higher load is applied, the column will be destabilized and broken. This unstable phenomenon is called yield bending (Fig. 1), which tells us the following important things in mechanics of materials:

(a) the force that causes the yield bending is a compressive load, not the

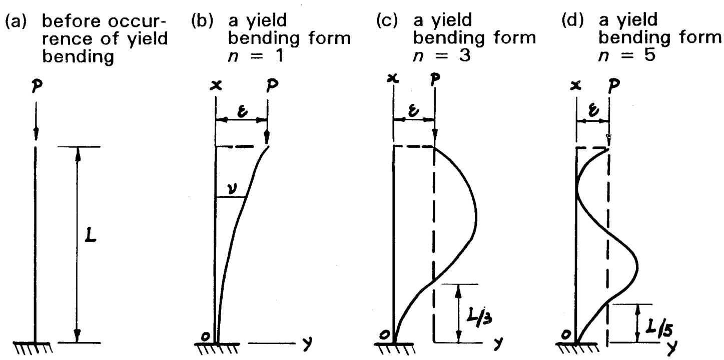

Fig. 1 An ideal slender column fixed at the bottom and free at the top.

weight of the column itself;

(b) theoretically there may be a randomly small deflection;

(c) the impact of a very small lateral force will produce an unvanishing deflection;

(d) finally under the effect of a critical load (*Per*) the column will be broken due to bedding and lateral deformation, not the direct compression.

In vertical-bedded or dip-bedded slopes of sedimentary rocks, as the thickness-length ratio of strata reaches an ultimate value, just like a column discussed in mechanics of materials, yield bending deformation similar to that of a column will occur.

YIELD BREAK LANDSLIDES IN STRATA OF DIP-BEDDED SLOPES

Yield bending phenomena of strata

When natural or manmade slopes during or after their formation have their structure, height, slope and rock strength reach a certain ultimate proportion, yield bending phenomena may take place in the strata due to the effect of gravity or load.

Gravity yield bending In the course of geological history most sedimentary rocks experienced yield bending deformation under the influence of geological tectonics, such as anticlines and synclines, which are different from the yield bending phenomena discussed here. Later these tectonic deformations were modified by neotectonics, erosion and human activities to become natural slopes and manmade slopes with different structural relations and forms. However, there is only one type of slope that can produce the phenomenon of gravity yield bending, i.e. natural or manmade dip-bedded slopes.

If the surface of a stratum and the slope surface incline in the same direction, and the dip angle of the stratum is equal to or a little higher than that

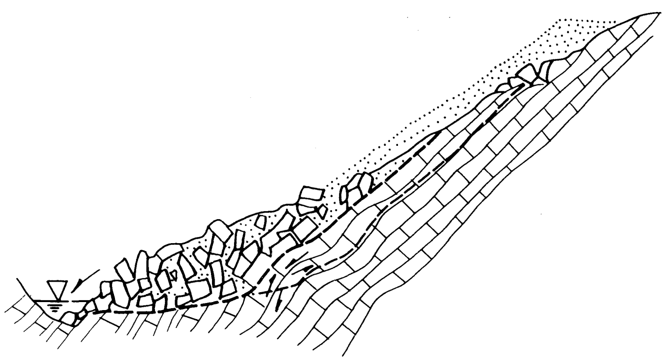

Fig. 2 A yield-break landslide at Bawangshan, Yalong River.

of the slope, gravity yield bending will occur at some depth in the slope, especially in thin to mid-thick carbonatites, sandstones and marlites at the front of the slope, a little higher than the slope foot. When yield bending develops to the critical strength of the rock, yield bending will give rise to a bedding landslide in bedrock (Fig. 2).

Thrust yield bending A dam built on bedded strata will be damaged if not properly designed due to variations in the properties of strata and the horizontal thrust of the reservoir against the dam which can promote the gliding curve of the strata downstream from the dam (Fig. 3).

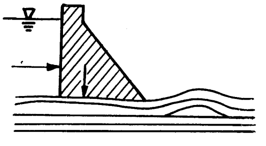

Fig. 3 σ_3-effect in the yield bending process in dip-bedded rock slopes.

σ-Effect in the yield bending process in dip-bedded rock slopes

Yield bending phenomena of dip-bedded strata in slopes were cited above to demonstrate that yield bending phenomena are an inherent attribute of geological materials. The occurrence of yield break rockslides is the formative transformation of such mechanical attributes.

A simple experiment of yield bending

(a) *The compressive deformation of objects under the effect of evenly distributed load.* Figure 4 shows the deformation of a rubber tube proportionally with length under the effect of a concentric load, which is similar to the wall failure of typical shafts in engineering. At the cross section half-way along the tube in full free space, the tube wall will bulge towards the free space at an angle of 360° with an equal value everywhere. If a concentric load is applied after a rigid plane is put into the space below the tube, a small change will occur in the deformation of the tube. The expansion of the lower tube wall is restricted by the rigid plane and a thrust is induced to move the tube upward Δh. Thanks to the free gliding of the slide objects at both ends of the tube, the tube will remain stable under the effect of an evenly distributed load. This

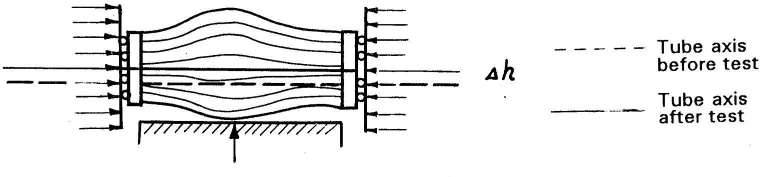

Fig. 4 Compressive deformation of a rubber tube.

simple experiment suggests that when an object is affected by compressive stress, if it is laterally restricted somewhere, the object will move in the direction away from the laterally restricting object.

(b) *An analysis of yield bending deformation of rectangular material under the effect of a concentric load.* Considering the case of elastic material in a rigid flume (Fig. 5). Suppose there is no friction between elastic the material and the flume walls. Laterally limited by three sides, the rectangular material affected by the horizontal concentric load under the condition of free space will deform by rising upwards. This mechanism can be roughly explained as follows.

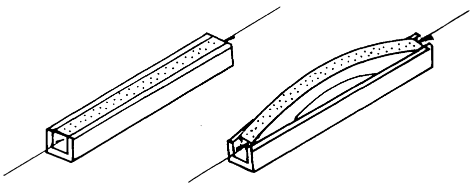

Fig. 5 A simple experiment of yield bending.

Under the effect of an ample concentric load (maximum principal stress σ_1), the stress-strain of the rectangle resembles that of the rubber tube (Fig. 6). Because the front and the back of the rectangle are confined by the rigid flume, the expansive stresses (second principal stress σ_2) of the rectangle are equal and counteract each other in opposite directions, thus not leading to a formative change in the rectangle. Only the expansive stress on the bottom (the least principal stress σ_3) promotes the rectangle to move upwards by Δh. It is noted in the concept of yield bending that only if there is a very small side stress (e.g. if heavy rainfall enters the pores between strata, the water level will rise to form "water wedges"), an unvanishing deflection will occur to make the effect line of load (σ_1) deviate from the centre of the rectangle and transform σ_1 from a concentric load to an eccentric load. Under the effect of an eccentric load, the rectangle will give rise to a moment curve M to form an upward yield bend. Therefore, the stress-strain process of rectangle yield bending caused by the effect of σ_3 is termed the σ_3-effect.

Yield-break rockslides in dip-bedded slopes The stress-strain characteristics of a rectangle show that the yield bending upheaval is generated

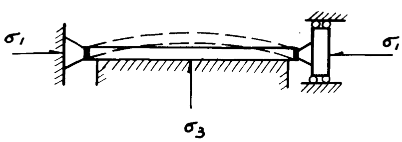

Fig. 6 Explanation of the deformation of a slender column.

by the σ_3-effect under the condition of partial lateral confinement. In nature, what resembles the yield bending of a rectangle is yield-break landslides in dip-bedded strata (Fig. 2). The rock in the lower part of some stratum under the effect of the gravity component of the upper rock, which corresponds to an external agent, may give rise to yield bending – a yield-break rockslide at a place a little higher than the slope foot.

Under the effect of the gravity component, dip-bedded strata experience the same stress-strain process at the slope foot as that of a rectangle. The difference is the friction at the side faces and at the base, which increases the critical load. However, the following factors would reduce the stability of the strata:

(a) weak strata and folds created by tectonics favour the development of yield bending in hard strata;

(b) dislocations between tectonic beds weaken the shear strength between strata faces, even a residual shear strength can be reached;

(c) seasonal freeze-thaw and weathering can foster the development of yield bending;

(d) the action of "water wedges" induced by heavy rainfall may increase a horizontal thrust to strata at the slope foot and deflection to accelerate the process of yield bending.

So far, studies on yield bending rock failures in dip-bedded slopes are not adequate. In the 1970s, Watton observed and examined such phenomena at an open cast mine in England. H. K. Kutter in the book *Rock Mechanics* (Muller, 1974) described yield bending failures of slopes.

Kutter adopted simplified load distribution and boundary conditions to evaluate the critical length of the top layer of a slope. Take the friction angle between the top layer and the underlying stratum as θ, then the yield bending load of the geometric conditions of the slope shown in Fig. 7 is:

$$P = Lt\gamma\cos\alpha(\tan\alpha - \tan\phi) \tag{1}$$

where:

L = the length of the top rock layer,
t = the thickness of the top rock layer,
γ = the unit weight of the rock,
α = slope angle,
ϕ = internal friction angle of the rock.

Kutter considers that the stress-strain of the top layer is similar to the yield bending of a column in mechanics of materials (see Fig. 1(c)). According to Euler's theorem, the yield bending load of a column is:

$$Per = \frac{\pi^2 EI}{(0.7L)^2} \tag{2}$$

where E = elastic modulus of strata; and I = moment of inertia. Insert formula (1) into formula (2) to obtain the following yield bending length:

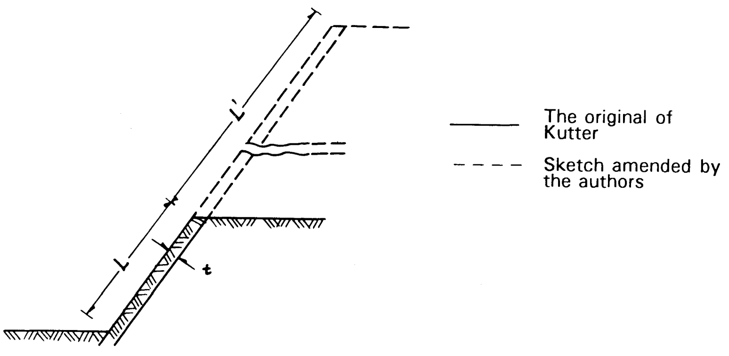

Fig. 7 Calculation of the critical length of a yield bend in an anacline-bedded slope.

$$L = \left[\frac{\pi^2 E t^2}{6\gamma \cos\alpha (\tan\alpha - \tan\phi)} \right]^{1/3} \qquad (3)$$

It is acceptable to approximate yield bending in strata with that of a column, but there is a mistake in calculation which must be noted. In formula (2) for the critical load of yield bending determined by Euler's theorem, the length of column where a yield bend occurs is known, i.e. L is a known. In other words, for standing columns with known lengths, the Euler theorem can be used to calculate the critical load for yield bending, i.e. the external agent. Formula (1), however, tries to calculate the self-weight component of strata under the geometric conditions of a slope shown in Fig. 8. There is an error in the figure design, which attempts to take the gravity component of the upper rock in the slope for the critical load of the upper rock, just as the geometric conditions shown by dotted lines in Fig. 7, not the critical length of the rock where yield bend occurs. Therefore, it is not feasible to insert formula (1) into formula (3) with no symbol difference for L; so formula (3) is untenable.

Now let us go back to see the meaning of yield bending in strata. Yield bending is a deformation of material under the effect of an external agent. Slopes where a yield bend occurs are not complete strata from top to bottom,

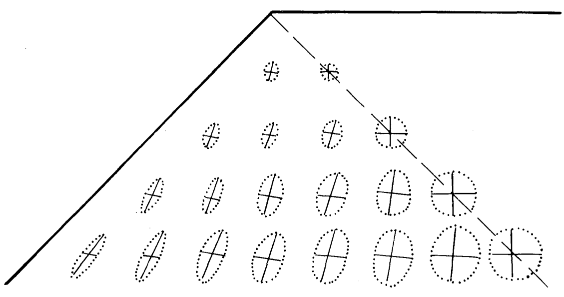

Fig. 8 The theoretical stress field of a slope (when $\lambda_o = 1$, $\alpha = 45°$)(after Emel'yanova, 1972).

merely one part of the slope foot. The self gravity component of the strata at the slope foot is not big enough to trigger a yield bend; a curve only occurs when the upper rock gains a sufficient gravity component. There is a complication of the term "yield", so the concepts of yield bending and yield break are adopted here. Yield bending is a stress-strain process; yield break is a form of failure.

EXPANSIVE LANDSLIDES IN HORIZONTALLY BEDDED STRATA

Expansive landslide phenomena

Under the pressure of overlying strata, horizontal weak strata will turn to plastic yielding and be squeezed out towards the free face to produce an expansive landslide that makes the overlying strata subside, disintegrate and slowly glide. Besides geological factors, an important cause of landsliding is the mechanical properties of soft rocks.

Mechanism for the development of expansive landslides – σ_3 The theoretical gravity stress field of a uniform slope is shown in Fig. 8. There are two characteristics for the field: (a) the stress at the top of the slope indicates that the maximum principal stress may almost equal the least stress σ_3, and there is no obvious tip of the maximum principal stress of the stress circles near the slope surface. From top to bottom, $\sigma_3 < \sigma_1$ and the maximum principal stress σ_1 is tipping to the inside of the slope with its tip angle approximate to the slope angle; (b) laterally, the stress circles near to the slope surface take the form of an ellipse, while those deep inside the slope are circular, i.e. σ_3 increases gradually from the surface downwards until $\sigma_3 = \sigma_1$. Therefore, in the theoretical gravity stress field of a slope, a gradient of the least principal stress σ_3 occurs on the horizon of the slope foot and the ultimate value of the gradient is found on the border of the slope foot.

Figure 9 is an ideal section through a clay bed sandwiched between other strata. Units A and A' are taken from the infinite depth of the free face and from the boundary of the slope foot.

Unit A can be regarded as a differential unit in the half space with a boundary on the horizon, which bears the load of the overlying strata. If in the air, the unit may extend or shrink freely in the x-y direction and will not produce lateral stress under the effect of the pressure in the z direction (x and y are in the horizontal plane, and z is in the vertical plane). In fact, located at depth, the unit is not likely to expand freely in the x-y direction due to the resistance of surrounding earth. The earth must have an effect of side stress σ_3 on the unit to keep the side strain nil. As the side stress coefficient of earth is close to 1, the stress applied to the unit will approximate the state of static

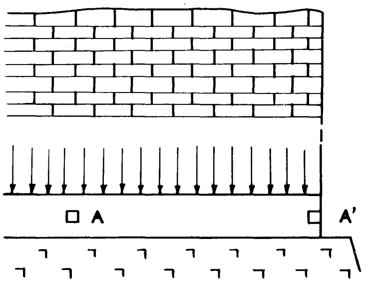

Fig. 9 Ideal section through a clay bed.

stress, i.e. $\sigma_1 = \sigma_2 = \sigma_3$.

Unit A' is located on the surface of the ideal section. It can expand freely in the normal direction of the axis x, thus, $\sigma_3 = 0$. In the opposite direction the side strain remains nil and a side stress occurs in the minus direction of x axis ($\sigma_3 \neq 0$) due to the confinement of the earth. As a result, a stress gradient (σ_3-effect) with deviation σ_3 occurs on the x axis. Clay or other soft rocks will flow like a liquid and be squeezed out slowly from the free face. This failure is characterized by neither an obvious failure load nor a unified fracture plane, only mutual displacement of grains. The maximum stress gradient is at the free face. With the distance farther and farther from the free face, the stress gradient decreases towards zero.

The formative process of yielding-flow landslides Take the ideal

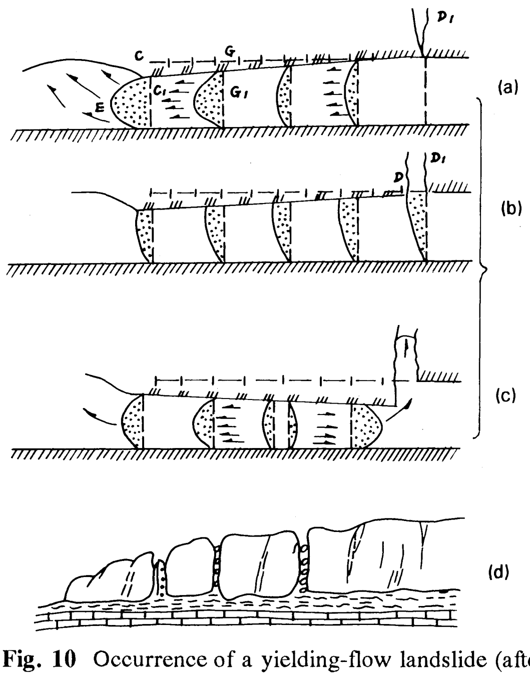

Fig. 10 Occurrence of a yielding-flow landslide (after Emel'yanova, 1972).

section in Fig. 10 as an example. At first, clay at the free face is squeezed out by the σ_3-effect due to quantity decreasing of the gradient of the least principal stress σ_3 from the free face to the depth. As a result, the clay bed is thinned to cause uneven subsidence of the overlying strata and a curved deformation of the overlying strata like a hanging arm. With an increment of the subsidence rate, when the deflection and the length of the hanging arm reach their ultimate value, the top of the strata will rupture due to the tensile stress being higher than the tensile strength of the rock. As the crack gradually develops towards the bottom, the overlying strata will be cut into separate blocks moving like a boat to become an expansive landslide. After the clay is squeezed out, the top of the clay will tip to the free face. Moreover, breaking off the original stratigraphic relations, the sliding body not only move like a boat, but also glide towards the free face under the effect of a self sliding force, thus accelerating the flow velocity of the clay at the contact plane.

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