Chapter 4

Stability of Rock Slopes

4.1 Non-Engineered Slopes

The Earth's solid surface is not everywhere flat. Hills, mountains, and valleys, for example, are local features that incorporate hilly topography. The ever-present force of gravity, acting on material resting on an inclined surface, tends to induce landslides, rock slides, avalanches, etc. These events present immediate hazards to nearby life and property. Hence, it is usually a serious concern to see to it that a local arrangement of earth materials on a slope does not pass from a static to a dynamic state. Engineering intervention may be necessary if the risk of sliding is significant. Just how to assess this risk, and then to reduce it, is the theme of this chapter.

Examine, then, a block of intact rock resting on an inclined surface or slope. *Intact* rock means that the rock has the strength to resist rupture under the applied forces, and that if these forces set the block in motion, the rock will slide, or at least begin to slide, as a single entity or block. It is assumed that there is no rock mass immediately downslope from the block to prevent sliding (the block *daylights into free space*).

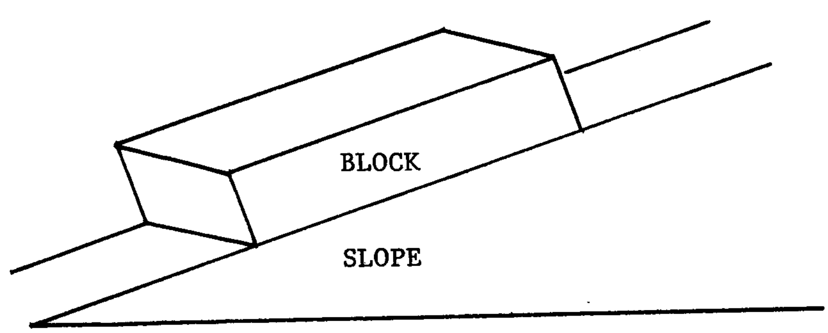

Fig.(4.1) Block on Slope

In Fig.(4.1) a block of rock is shown resting on a slope. This sketch is an idealization of an actual field situation; for example, the actual block may not be a perfectly rectangular solid in shape, and there may be other blocks of rock in close proximity upslope, or to the sides. It is also assumed that the slope itself is an intact block, and that all the rock is dry.

The block is at rest. The immediate query is: How stable is the block in this position? Can the possibility of the block sliding at some time in the future be quantitatively evaluated?

To answer these questions, it is necessary to examine the forces acting on the block. These forces are conveniently divided into two groups: *driving forces*, forces tending to move the block down the plane, and *resisting forces*, forces tending to hold the block in place.

Begin with the driving forces. One driving force that is always present, as already mentioned, is the force of gravity due to the Earth (minus the block); this force is represented by the weight W of the block. It is not feasible to measure W directly by placing the block on a scale, but the weight can be calculated if the mass density ρ and volume V of the block can be ascertained. The density could be found by chipping off a representative piece of the block of manageable size, and then finding the volume and density as indicated in Chapter 1. The weight itself is found either from $W = \rho g V$ or, using the unit weight γ instead of ρ, from $W = \gamma V$.

The weight force acts at the *center of gravity* of the block and is directed vertically down. For a uniform rectangular block, the center of gravity is at the middle of the block, i.e., at the point where the body diagonals intersect. For other shapes, the location of the center of gravity may be more difficult to find.

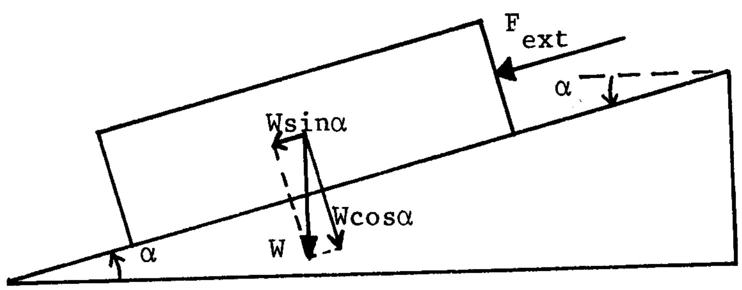

Fig.(4.2) Driving Forces

The weight force is shown on Fig.(4.2). Only the component $W \sin \alpha$, however, is directed down the slope. The angle α is the angle made by the inclined surface of the slope with the horizontal. As shown on Fig.(4.2), it may be thought of as an *elevation angle* above the horizontal, or as a *dip angle* below the horizontal.

Gravity cannot be "switched-off", so the $W \sin \alpha$ driving force is ever present. But there may, or may not, be other driving forces acting. For instance, although for clarity the block is drawn as an isolated entity on the slope, it may in fact be separated from an uphill block only by a narrow fracture, or joint. If the fracture is empty, no other driving force is produced. But if water seeps into the joint, an additional driving force can be generated in several ways. First, there is the hydrostatic force itself. Second, if the water freezes, the accompanying expansion produces strong forces that will be exerted on the rock adjacent to the joint. Third, even if the water does not freeze, it can still expand if the temperature rises (thermal expansion). If the water is confined, the forces produced will act to split the rock even more.

The sum of these driving forces other than gravity is represented by the symbol F_{ext}, for extra driving force. Also, to keep the analysis relatively simple, it is presumed that F_{ext} is directed parallel to, and down, the slope; see Fig.(4.2). Under these conditions, the total driving force DF (single symbol) is given by

$$DF = W \sin\alpha + F_{\text{ext}}. \tag{4.1}$$

Turn now to resisting forces. The first of these to be considered is the force of static friction f_s. This is the familiar force that resists the start of sliding of an object over a surface on which the object is initially at rest, but on which an external force is acting so as to induce sliding. The numerical value of f_s on such an object that nevertheless remains at rest is precisely the value that makes the net force on the object equal to zero, in accordance with Newton's second law ($\Sigma F = ma$ with $a = 0$). If the magnitude of the external force is increased, the value of f_s will also increase to keep the net force equal to zero, and thereby maintain the object at rest.

But the value of f_s cannot increase forever: there is an upper limit to the magnitude of the friction force. Experiments show that this maximum possible value of the friction force, $f_{s,\text{max}}$, in any particular situation, is given by Coulomb's law:

$$f_{s,\text{max}} = \mu_s R. \tag{4.2}$$

On the right-hand side of Eq.(4.2), μ_s is the coefficient of static friction. This is a dimensionless number, the numerical value depending on the composition and condition of the two surfaces that are in contact. The R in Eq.(4.2) is the sum of the normal forces on the object. (The word *normal* is not used as the opposite to *abnormal*, but rather means *perpendicular*.) A normal force is a force on the object that is directed perpendicular to the surface of contact.

Sometimes, in place of the coefficient of friction μ_s, an *angle of friction* ϕ is employed. The angle of friction is related to the coefficient of friction by

$$\tan\phi = \mu_s. \tag{4.3}$$

The choice of using either ϕ or μ_s in the treatment of friction is entirely personal preference. If ϕ is employed, then Eq.(4.2) becomes

$$f_{s,\text{max}} = R\tan\phi. \tag{4.4}$$

Regardless of whether ϕ or μ_s is used, if the value of f_s needed to keep the object at rest comes to exceed $f_{s,\text{max}}$, sliding will occur.

Now apply these considerations to the block of rock on the slope. Under the conditions so far specified, the normal force R must equal the component of the force of gravity that acts normal to the slope, for there is no acceleration normal to the slope, even if the block slides. From Fig.(4.2), it is evident that this component is $W \cos\alpha$. Hence,

$$f_{s,\max} = W \cos\alpha \tan\phi. \tag{4.5}$$

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EXAMPLE 1 With only friction acting as the resisting force, angle of friction ϕ, and no extra driving force present, find the angle of the steepest slope on which the block can remain at rest.

The driving force is $DF = W \sin\alpha$ and the resisting force is f_s. If the block remains at rest, then

$$\Sigma F = 0,$$

$$W \sin\alpha - f_s = 0,$$

$$W \sin\alpha = f_s.$$

Now $W \sin\alpha$ is larger in value for steeper slopes, since α is greater. Therefore, to keep the block at rest on steeper slopes, f_s must be larger also. The steepest slope on which the block can remain at rest is that for which f_s has increased to its maximum possible value $f_{s,\max}$. By Eq.(4.5), for this steepest slope, the last equation gives

$$W \sin\alpha_{\max} = W \cos\alpha_{\max} \tan\phi.$$

Divide this equation (both sides, of course) by $\cos\alpha_{\max}$. But, for any angle θ, $\sin\theta/\cos\theta = \tan\theta$. Hence, the equation reduces to

$$\tan\alpha_{\max} = \tan\phi,$$

$$\alpha_{\max} = \phi.$$

This result provides a physical interpretation to the angle of friction ϕ. With only friction acting as a resisting force, and no driving force present except gravity, ϕ equals the elevation angle of the steepest slope on which the block can remain at rest. This greatest slope angle for the block to be at rest is sometimes called the *angle of repose*, especially if the block and slope are made of the same material.

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Another resisting force that occurs naturally in rocks (and soils) is the *cohesion force* F_{coh}. The force of cohesion is a resisting force the value of which is independent of the value of the normal force R. Unlike the friction force, the force of cohesion is directly proportional to the area of contact A between the block and the slope. The force is written as

$$F_{\text{coh}} = cA, \tag{4.6}$$

where the constant of proportionality c is called the *cohesion stress.* Like ϕ (and μ_s), the numerical value of c depends on the composition and condition of the two surfaces in contact. The area A in Eq.(4.6) is shown shaded in Fig.(4.3). The direction of F_{coh} is, like f_s, parallel to the slope and upward (opposite to the direction of the driving force $W \sin\alpha$), opposing the tendency of the block to slide down under gravity.

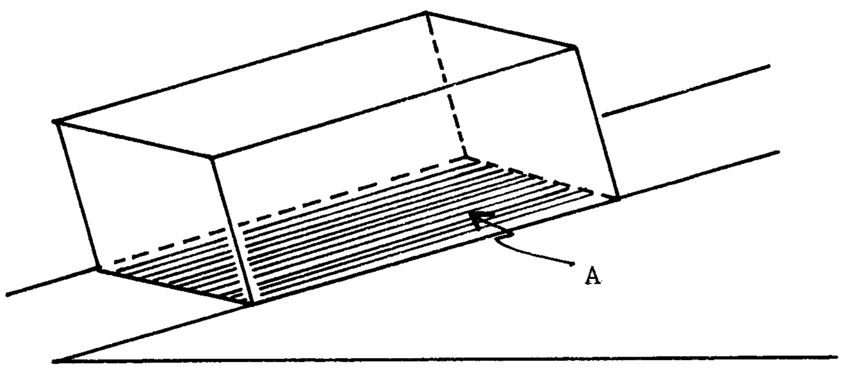

Fig.(4.3) Contact Area

The forces of friction and of cohesion are naturally occurring resisting forces. With both acting, the total resisting force RF_{acting} is

$$RF_{\text{acting}} = f_s + cA. \tag{4.7}$$

If the block remains at rest,

$$\Sigma F = 0,$$
$$DF - RF_{\text{acting}} = 0,$$
$$RF_{\text{acting}} = DF, \tag{4.8}$$

in accordance with Newton's second law $\Sigma F = ma$, with $a = 0$ for a system that remains at rest.

Now suppose that in Eq.(4.7) the acting friction force f_s is replaced with $f_{s,\max}$, the maximum possible value of f_s. Then Eq.(4.7) yields the largest possible value of the total resisting force; this maximum value is given the symbol RF; that is,

$$RF = f_{s,\max} + cA, \tag{4.9}$$

$$RF = W \cos\alpha \tan\phi + cA, \tag{4.10}$$

the last step by Eq.(4.5).

The ratio of the maximum possible value of the total resisting force to the driving force is called the *factor of safety against sliding*, symbol FS; that is,

$$FS = \frac{RF}{DF}. \tag{4.11}$$

Substituting Eqs.(4.1) and (4.10) into Eq.(4.11) yields

$$FS = \frac{W \cos\alpha \tan\phi + cA}{W \sin\alpha + F_{\text{ext}}}. \tag{4.12}$$

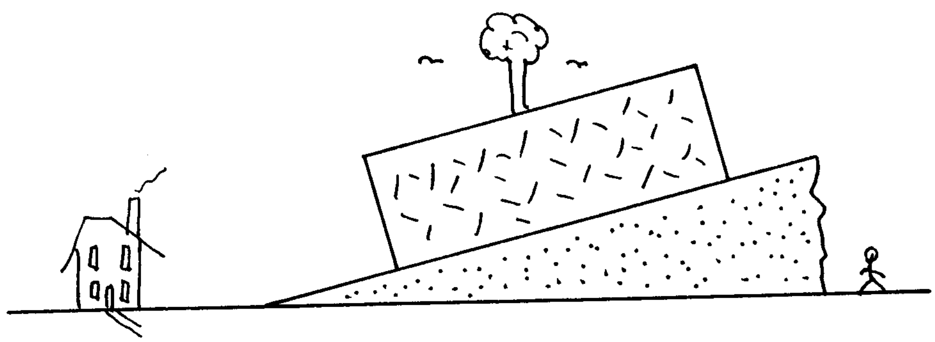

Fig.(4.4) House at Risk

The numerical value of the factor of safety indicates how safe the block is against the tendency to slide down the slope. For example, suppose that the purchase of the house shown in Fig.(4.4) is being contemplated; i.e., a house located at the bottom of a hill, say, on which a slab of rock is resting. The builder, or real estate agent, imply that there is no need to worry about the slab suddenly sliding down the hill into the house, because the factor of safety, calculated by Eq.(4.12), has the value 1.12. This means that the maximum available resisting force RF has the value $RF = 1.12(DF)$. For the slab to remain at rest, it is only necessary that $RF = 1.00(DF)$, or $FS = 1$. It seems that there is $0.12(RF)$ of "extra" resisting force, and so no concern need be felt about the presence of the slab lurking uphill.

However, bear in mind that the values of some of the terms in Eq.(4.12) can vary in the course of time, sometimes in very little time. For instance, if the ground becomes saturated with water, the values of $\tan\phi$ and c can decrease considerably, lowering the value of RF. If an uphill tension crack forms and fills with water which later freezes, an extra driving force is produced, increasing the value of DF. Both of these events force the factor of safety to smaller values. As soon as FS diminishes to $FS = 1$, the slab will slide on the slightest disturbance. The fact that this has not yet happened may not be a reason for complacency.

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EXAMPLE 2 A rectangular block of rock, density 2.90 g/cm^3 and edge lengths 17.0 m, 2.30 m, 8.47 m, rests on a 16.0° incline, as shown in Fig.(4.5). An extra driving force of 734 kN, acting parallel to and down the incline, will just start the block sliding. The angle of friction between block and incline is 7.00°. Find the cohesion stress on the block.

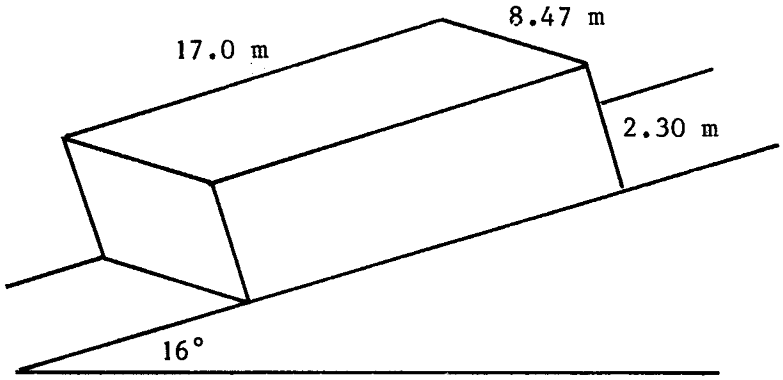

Fig.(4.5) Example 2

The weight of the block is calculated from

$$W = \rho V g$$

Hence,

$$W = (2900 \text{ kg/m}^3)[(17 \text{ m})(8.47 \text{ m})(2.3 \text{ m})](9.8 \text{ m/s}^2),$$
$$W = 9.412 \text{ X } 10^6 \text{ N}.$$

From Fig.(4.5), the area of contact A between block and slope is seen to be

$$A = (17 \text{ m})(8.47 \text{ m}),$$
$$A = 144.0 \text{ m}^2.$$

With the extra driving force, the block just starts sliding; this implies that $FS = 1$. Use Eq.(4.12), with all quantities in SI base units, to get

$$FS = \frac{W \cos\alpha \tan\phi + cA}{W \sin\alpha + F_{\text{ext}}},$$

$$1 = \frac{(9.412 \text{ X } 10^6 \text{ N}) \cos 16° \tan 7° + c(144 \text{ m}^2)}{(9.412 \text{ X } 10^6 \text{ N}) \sin 16° + 734 \text{ X } 10^3 \text{ N}},$$

$$c = 15.4 \text{ kPa}.$$

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4.2 Slope Stress

The condition for stability on a non-engineered slope with no extra driving force, as expressed in Eq.(4.12) with $F_{\text{ext}} = 0$, often is written in terms of stresses rather than forces. To do this, set $F_{\text{ext}} = 0$ and divide numerator and denominator by the contact area A, to obtain

$$FS = \frac{(W\cos\alpha/A)\tan\phi + c}{(W\sin\alpha/A)}.$$

Since all of the forces in Eq.(4.12), the resisting forces of friction and cohesion and the driving force due to gravity, act parallel to the incline, and hence to the contact area A, the associated stresses are shear stresses, so that the factor of safety can be expressed as

$$FS = \frac{\tau_{\text{R}}}{\tau_{\text{D}}},$$

where τ_{R} is the total resistive shear stress and τ_{D} is the driving shear stress. There is a compressive stress σ acting across the contact area on the block: it is due to the reaction of the slope surface to the component of the weight perpendicular to the surface, i.e., it is due to the normal force. Since this normal force is $W\cos\alpha$, the compressive stress, in magnitude, is

$$\sigma = W\cos\alpha/A.$$

It follows that the values of the shear stresses τ_{R} and τ_{D} are related to that of the compressive stress:

$$\tau_{\text{R}} = \sigma\tan\phi + c,$$

$$\tau_{\text{D}} = \sigma\tan\alpha.$$

(The last equation follows by noting that $\tan\alpha = \sin\alpha/\cos\alpha$.) Hence, in terms of stress,

$$FS = \frac{\sigma\tan\phi + c}{\sigma\tan\alpha}. \tag{4.13}$$

If $c = 0$ (no cohesion, or cohesion ignored), the factor of safety and the angles of the slope and of friction are related by

$$FS < 1 \text{ if } \phi < \alpha,$$
$$FS = 1 \text{ if } \phi = \alpha,$$
$$FS > 1 \text{ if } \phi > \alpha.$$

The situation with $c \neq 0$ is sometimes presented graphically. In Fig.(4.6), the shear stresses τ_{R} and τ_{D} are plotted on the ordinate (the "y axis") and the compressive stress σ on the abscissa (the "x axis"). The driving shear stress plots as a straight line through the origin with slope α, and the resisting shear stress plots as a straight line with σ-intercept c and slope ϕ.

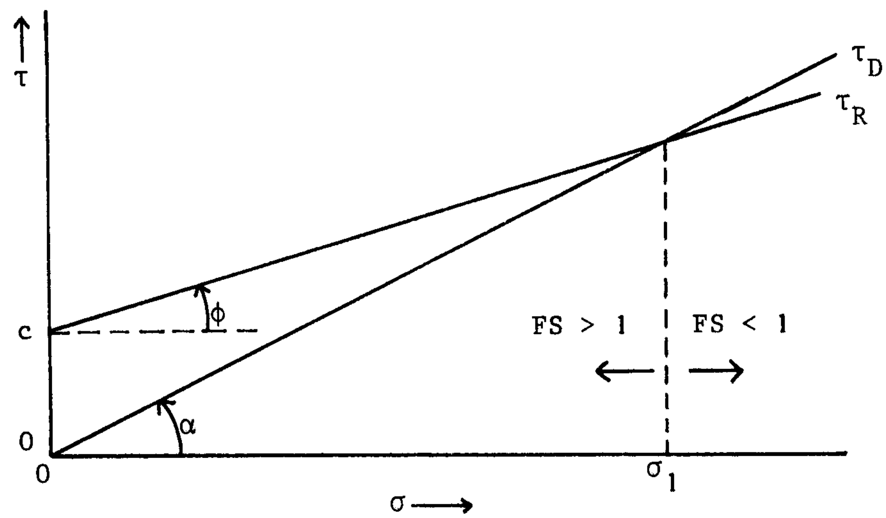

Fig.(4.6) Stresses on a Non-Engineered Slope

Figure (4.6) is drawn with $\phi < \alpha$. (The situation with $\phi > \alpha$ always gives $FS > 1$.) The two lines representing the shear stresses intersect at a value of the compressive stress labelled σ_1. For configurations with $\sigma < \sigma_1, FS > 1$ and for $\sigma > \sigma_1, FS < 1$.

In evaluating the utility of Fig.(4.6), it should be borne in mind that σ hides a dependence on the angle of dip α ($\sigma = W\cos\alpha/A$), so that Eq.(4.13), on which Fig.(4.6) is based, does not explicitly display all the dependence of FS on α. For this reason, it seems more clear-cut to evaluate the factor of safety in terms of forces, as is done in Eq.(4.12).

4.3 Engineered Slopes

Suppose that the factor of safety, calculated from Eq.(4.12), is not sufficiently large to provide confidence that the block will not slip under conditions that are expected to vary. Then it may be necessary to stabilize the block by some engineering expedient, and thereby avoid having to rely completely on the naturally occurring resisting forces. Two related stabilizing techniques are analyzed in this section.

The first of these techniques is the installation of rock bolts. Rock bolts are solid rods, usually of steel, driven through the block into the slope. They are generally installed at 90° to the slope. This means that if the block tries to slide, it will exert a force on the bolt that is parallel to a cross section of the bolt. By Newton's third law, the bolt exerts an equal and opposite force on the block. This force will also be parallel to a cross section of the bolt and therefore is a shear force. The force acts to resist the sliding of the block.

The largest possible value F_B of this force exerted by the bolt on the block is given by

$$F_B = \tau_B A_B, \tag{4.14}$$

where τ_B is the shear strength of the material of which the bolt is made, and A_B is the cross-sectional area of the bolt. As described in Chapter 2, the shear strength represents the greatest shear stress that can be applied, in this case to the bolt, without causing the bolt to lose all meaningfull resistance to the applied shear force. If n identical bolts are installed, the net effect is to add nF_B to the resisting force RF in Eq.(4.10).

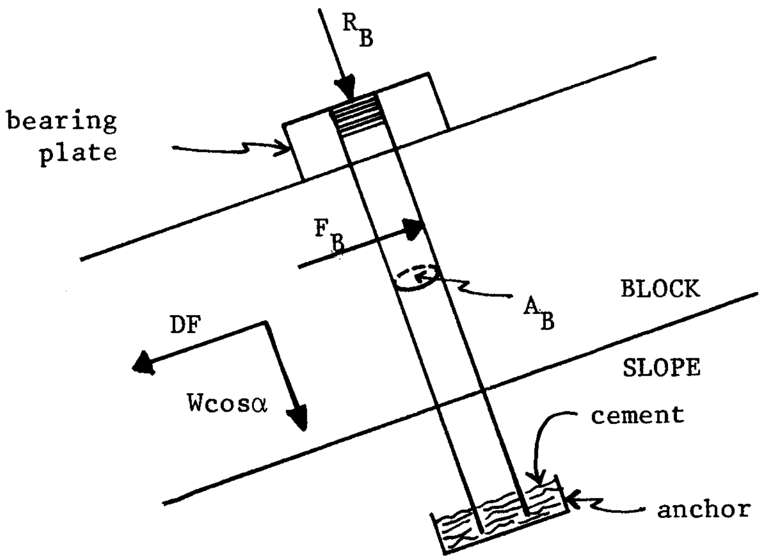

Fig.(4.7) Installed Rock Bolt

If the base of the bolt is cemented into the slope, then the bolt can be tightened. This action squeezes the block and slope together. Since each bolt is installed perpendicular to the slope, the force exerted due to the tightening is also perpendicular, or normal to, the slope. Call this force R_B, the normal force each tightened bolt exerts on the block. This force can be expressed as

$$R_B = \sigma_B A_B, \tag{4.15}$$

where σ_B is the stress on the bolt due to the tightening and, as before, A_B is the cross-sectional area of the bolt. On the bolt, the stress is one of axial tension, since the block and slope want to "spring apart", and the tightened bolt resists this. Hence, the bolt cannot be tightened beyond the tensile strength of the bolt material.

The force R_B itself is not a resisting force on the block, since it is exerted normal to the slope. The effect of R_B is to increase the normal force and therefore to increase the maximum friction force available. By Eq.(4.2), $f_{s,max} = \mu_s R$. The part of R due to gravity,

$W \cos\alpha$ is always present. If there are n bolts, all tightened to the same tension, then the total normal force becomes

$$R = W\cos\alpha + nR_{\mathrm{B}}. \tag{4.16}$$

Hence,

$$f_{\mathrm{s,max}} = \mu_{\mathrm{s}}(W\cos\alpha + nR_{\mathrm{B}}),$$

or

$$f_{\mathrm{s,max}} = (W\cos\alpha + nR_{\mathrm{B}})\tan\phi. \tag{4.17}$$

Therefore, by Eqs.(4.14), (4.15), and (4.17), the maximum resisting force available with n rock bolts installed perpendicular to the slope is

$$RF = (W\cos\alpha + n\sigma_{\mathrm{B}}A_{\mathrm{B}})\tan\phi + cA + n\tau_{\mathrm{B}}A_{\mathrm{B}}. \tag{4.18}$$

It is assumed that the bolts are identical and that all have been tightened to the same tension σ_{B}. The driving force on the block is unaffected by the rock bolts. Combining the last equation with Eqs(4.1) and (4.11) gives for the factor of safety

$$FS = \frac{(W\cos\alpha + n\sigma_{\mathrm{B}}A_{\mathrm{B}})\tan\phi + cA + n\tau_{\mathrm{B}}A_{\mathrm{B}}}{W\sin\alpha + F_{\mathrm{ext}}}. \tag{4.19}$$

Often in engineering situations, it is important to know the number of bolts needed to achieve a desired factor of safety. With this in mind, Eq.(4.19) can be solved for n with the result

$$n = \frac{FS(W\sin\alpha + F_{\mathrm{ext}}) - W\cos\alpha\tan\phi - cA}{A_{\mathrm{B}}(\sigma_{\mathrm{B}}\tan\phi + \tau_{\mathrm{B}})}. \tag{4.20}$$

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EXAMPLE 3

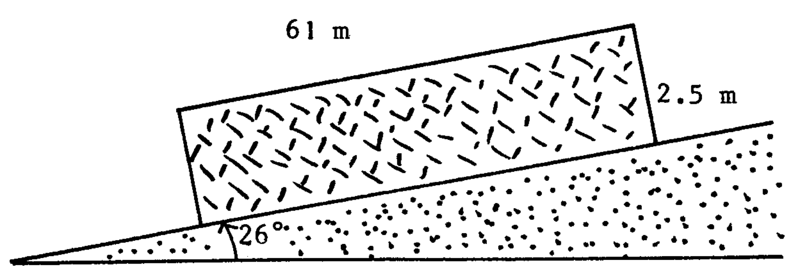

Fig.(4.8) Example 3

The slab shown in Fig.(4.8) has a width of 13 m; its density is 3.2 g/cm^3. The angle of friction between the slab and the slope is 20° and cohesion equals 75 kN/m^2. Rock bolts are installed but not tightened. Each bolt has an area of 6.2 cm^2 and shear strength 740 MPa. A factor of safety of 3.0 is desired. How many rock bolts are needed?

Calculate the weight of the slab from $W = \rho V g$; the result is W = 62.2 MN. The angle of friction is $\phi = 20°$ and the angle of the slope, from Fig.(4.8) is $\alpha = 26°$. With cohesion present, $c = 75 \text{ X } 10^3$ N/m^2, the contact area between slab and slope must be calculated. This area is A = (61 m)(13 m), A = 793 m^2. Since the bolts are not tightened, $\sigma_B = 0$. The bolt cross-sectional area is $A_B = 6.2 \text{ X } 10^{-4}$ m^2 and their shear strength is $\tau_B = 740 \text{ X } 10^6$ Pa. (The SI prefixes cannot be overlooked.) Write Eq.(4.20) with $\sigma_B = 0$, and also with F_{ext} = 0, since no extra driving force is mentioned. Using SI base units, then, and with $FS = 3$, the result is

$$n = \frac{W[(FS)\sin\alpha - \cos\alpha\tan\phi] - cA}{A_B \tau_B},$$

$$n = \frac{(62.2 \text{ X } 10^6 \text{ N})(3\sin 26° - \cos 26° \tan 20°) - (75 \text{ X } 10^3 \text{ Pa})(793 \text{ m}^2)}{(6.2 \text{ X } 10^{-4} \text{ m}^2)(740 \text{ X } 10^6 \text{ N})},$$

$$n = 4.3.$$

Of course, there cannot be 4.3 identical bolts. Suppose that "safety first" is the work philosophy; then install $n = 5$ bolts.

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Another method to prevent sliding is to stitch the block to the slope. The technique is similar to the use of rock bolts. A hole is drilled through the block perpendicular to, and into, the slope. Some cement is poured into the bottom of the hole. Then, instead of a bolt, a cable is inserted. One end of the cable is secured by the cement, when hardened. At the outer surface of the block, a cap and nut secure the other end of the cable. The nut is then tightened.

When the cable is tightened, the block and slope are pulled together. Hence, the effect is the same as tightening a rock bolt. However, a cable, being flexible, is presumed to offer no shearing resistance to the block. If the cable bends after installation, then the block must have moved and this indicates sliding.

The formula for the factor of safety in stitching can be derived from the corresponding formula for rock bolts, Eq.(4.19) by: (*i*) replacing σ_B, bolt tension, with σ_C, cable tension; (*ii*) replacing A_B, bolt cross-sectional area, with A_C, cable cross-sectional area; (*iii*) deleting the term $n\tau_B A_B$. Hence, with n identical stitches, each tightened to tension σ_C, the factor of safety against sliding is given by

$$FS = \frac{(W\cos\alpha + n\sigma_C A_C)\tan\phi + cA}{W\sin\alpha + F_{ext}}. \tag{4.21}$$

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EXAMPLE 4

A rectangular block of rock is stitched to a 27.0°-slope. The block has unit weight 30.4 kN/m^3 and edge lengths 10.8 m, 12.6 m, 2.10 m. The angle of friction between block and slope is 18.0°. Ignore cohesion. The stitching cable has cross-sectional area 7.50 cm^2 and is tightened to tension 620 MPa. (*a*) How many stitches are needed to provide a factor of safety against sliding equal to 2.00? (*b*) With the stitches installed, find the smallest extra driving force that will cause the block to slip.

(*a*) The weight of the block is $W = \gamma V$, $W = 8.687$ MN. The angle of friction is $\phi = 18°$ and the angle of the slope is $\alpha = 27°$. Since cohesion is to be ignored, set $c = 0$. The tension in the cable is $\sigma_C = 620$ MPa and the cable area is $A_C = 7.5 \text{ X } 10^{-4}$ m^2. No extra driving force is mentioned in this part, so put $F_{ext} = 0$. Also, $FS = 2$. Use Eq.(4.21) to find

$$FS = \frac{[W \cos\alpha + n\sigma_C A_C] \tan\phi}{W \sin\alpha}.$$

Substitute the data (in SI base units, of course):

$$2 = \frac{[(8.687 \text{ MN}) \cos 27° + n(620 \text{ MPa})(7.5 \text{ X } 10^{-4} \text{ m}^2)] \tan 18°}{(8.687 \text{ MN}) \sin 27°}.$$

Solve for n. Note that since Pa = N/m^2, then MPa = MN/m^2. The result is $n = 35.56$, so that, practically speaking, $n = 36$.
(*b*) With the stitches installed, put $n = 36$. To find the smallest extra driving force needed to cause slipping, set $FS = 1$. In this part, $FS \neq 0$, but $c = 0$ still. Eq.(4.21) now yields

$$FS = \frac{[W \cos\alpha + n\sigma_C A_C] \tan\phi}{W \sin\alpha + F_{ext}},$$

$$1 = \frac{[(8.687 \text{ MN}) \cos 27° + (36)(620 \text{ MPa})(7.5 \text{ X } 10^{-4} \text{ m}^2)] \tan 18°}{(8.687 \text{ MN}) \sin 27° + F_{ext}},$$

$$F_{ext} = 4.01 \text{ MN}.$$

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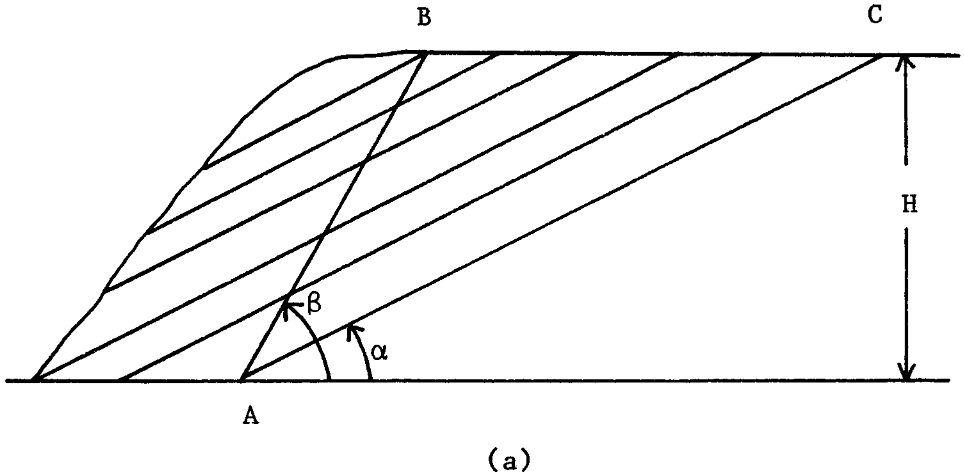
4.4 Roadcuts

In the discussion so far, the block has been drawn as a rectangular solid in shape. However, nature seldom forms blocks of rock with such a simple shape. Also, engineering projects often create blocks of a more irregular shape.

For example, suppose that a road under construction must pass for part of its length through hilly or mountainous terrain. Figure (4.9a) shows a cross section of part of a mountain before excavation of the road. The hillside is composed of sedimentary rock. Sedimentary rock often forms in parallel layers (*beds*). The planes of demarcation between contiguous beds are notoriously weak in resisting driving forces that induce sliding. The planes could also represent a system of joints in other kinds of rock. In any event, in Fig.(4.9a), the layers of rock are inclined at angle α with the horizontal and dip directly toward the projected roadway. Any one of these planes separating layers of rock is potentially a plane along which a block (the rock above the plane) can slide.



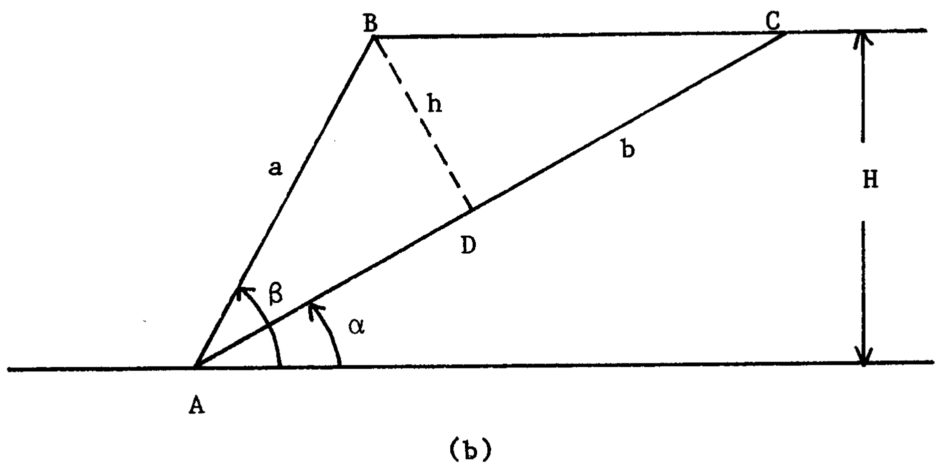


Fig.(4.9) Roadcut

In Fig.(4.9b) the hill is shown with the section that must make way for the road removed. The cut AB is made at an angle β ($\beta > \alpha$) with the horizontal. Only one of the weak bedding planes along which sliding is possible is shown. Specifically, this is the plane with its lower edge through A at the road. It is assumed, however, that the road exerts no supporting force on the block at its *toe* at A. The top of the hill is horizontal.

Of course, Fig.(4.9) is a cross section of a three-dimensional construction: the road extends for a length L perpendicular to the page. The bedding planes also are perpendicular to the page.

The geometry of the roadcut affects the analysis of slope stability only through the calculation of the weight of the block. The weight is given either by $W = \rho V g$ or from

$W = \gamma V$. Previously, the block volume V is calculated as the product of the three edge lengths of the block. However, the block in Fig.(4.9) is not rectangular. Rather, it is a cylinder of length L and triangular cross section ABC.

The volume of a cylinder is the product of the length and the cross-sectional area. Therefore, if A_x is the area of the triangle ABC, then

$$V = A_x L, \tag{4.22}$$

where the area A_x is to be expressed in terms of the height H of the hill, the angle α of the plane and the angle β of the cut.

Write a for the distance AB and b for the distance AC. The area of triangle ABC is

$$A_x = \frac{1}{2} bh, \tag{4.23}$$

where $h =$ BD is the "height" of the triangle perpendicular to "base" AC. Now

$$\sin\alpha = \frac{H}{b},$$

$$b = \frac{H}{\sin\alpha}. \tag{4.24}$$

Similarly,

$$a = \frac{H}{\sin\beta}. \tag{4.25}$$

From triangle ABC and Eq.(4.25),

$$\sin(\beta - \alpha) = \frac{h}{a},$$

$$h = (\frac{H}{\sin\beta}) \sin(\beta - \alpha). \tag{4.26}$$

Substituting Eqs.(4.24) and (4.26) into Eq.(4.23) gives for the area

$$A_x = \frac{1}{2} [\frac{H}{\sin\alpha}] [\frac{H}{\sin\beta} \sin(\beta - \alpha)],$$

$$A_x = \frac{1}{2} H^2 \left(\frac{\sin\beta\cos\alpha - \cos\beta\sin\alpha}{\sin\alpha\sin\beta} \right),$$

$$A_x = \frac{1}{2} H^2 (\cot\alpha - \cot\beta).$$

With the volume of the block given by Eq.(4.22), $V = A_x L$, the weight of the block is

$$W = \rho (A_x L) g,$$

$$W = \frac{1}{2}\rho L H^2 g(\cot\alpha - \cot\beta). \tag{4.27}$$

If cohesion must be accounted for, then an expression is needed for the contact area. By Eq.(4.24), this is

$$A = bL,$$

$$A = HL\csc\alpha. \tag{4.28}$$

The length L may not be the complete length of the cut. The types of rock, the angle of the bedding planes, and their orientation, may vary along the length of the cut. In that case, the length L is the length of an intact block along which these parameters do not change significantly.

It may appear that the block ABC cannot slide, as it seems to be held in place against the roadway at A. But it must be remembered that Fig.(4.9) is an idealization, or approximation, to the actual situation. The block is not perfectly triangular in outline, with absolutely straight edges; A, B, and C are not really mathematical points. The rock mass probably contains many other fractures that will yield if sliding begins. In short, it cannot be considered that the block is geometrically "locked in" at A.

Also, sliding could begin along any of the other bedding planes shown on Fig.(4.9a), for which the associated block "daylights into free space"; there is nothing, even in the idealized construction discussed, to prevent a slide if $FS < 1$. Equations (4.27) and (4.28) can be used for such a block, once the new vertical thickness H of the block is evaluated.

To find a convenient formula for the factor of safety for a non-engineered roadcut, with no extra driving force, in terms of the angles rather than the weight of the block, substitute Eq.(4.27) and (4.28) into Eq.(4.12) to obtain

$$FS = \frac{\tan\phi}{\tan\alpha} + \left(\frac{2c}{\rho g H}\right)\frac{1}{\sin^2\alpha[\cot\alpha - \cot\beta]}. \tag{4.29}$$

Now $\tan\phi/\tan\alpha$ is the value of the factor of safety if $c = 0$; i.e., either if there is no cohesion or cohesion is to be ignored. See Eq.(4.12). Call this value of the factor of safety FS_0:

$$FS_0 = \frac{\tan\phi}{\tan\alpha}. \tag{4.30}$$

Also, define a quantity B by

$$B = \frac{c}{\frac{1}{2}\rho g H}. \tag{4.31}$$

The quantity B is the ratio of the cohesion stress to the vertical stress at one-half the greatest depth in the block; B is dimensionless. With these substitutions, Eq.(4.29) becomes

$$FS = FS_0 + \frac{B}{\sin^2\alpha[\cot\alpha - \cot\beta]}. \tag{4.32}$$

Sometimes it is usefull to calculate, before making a cut, just what angle of cut is needed to achieve a desired factor of safety. For this purpose, Eq.(4.32) can be rearranged to read

$$\cot\beta = \cot\alpha - \frac{B}{(\Delta FS)\sin^2\alpha}, \tag{4.33}$$

where

$$\Delta FS = FS - FS_0, \tag{4.34}$$

FS being the factor of safety desired with cohesion taken into account. If the slope is stabilized with rock bolts or stitches, then Eqs.(4.27) and (4.28) must be substituted into the appropriate equation for the factor of safety of the engineered slope.

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EXAMPLE 5

For a roadcut like that shown in Fig.(4.9), the vertical thickness of the hill is 16.5 m and the dip angle of the bedding plane is 35.0°. The angle of friction is 31.0° and the cohesion stress equals 38.4 kPa. The unit weight of the rock is 23.7 kPa/m. Find the factor of safety for a vertical cut.

The data are: $H = 16.5$ m, $\alpha = 35.0°$, $\phi = 31.0°$, $c = 38.4$ kPa, $\gamma = 23.7$ kPa/m. For a vertical cut, $\beta = 90°$, $\cot\beta = 0$. First, calculate the quantity B; since $\gamma = \rho g$, Eq.(4.31) yields

$$B = \frac{2c}{\gamma H},$$

$$B = \frac{2(38.4\ \text{kPa})}{(23.7\ \text{kPa/m})(16.5\ \text{m})},$$

$$B = 0.1964.$$

If cohesion was zero, the factor of safety, by Eq.(4.30), would be

$$FS_0 = \frac{\tan 31°}{\tan 35°},$$

$$FS_0 = 0.8581.$$

Equation (4.32) now yields

$$FS = 0.8581 + \frac{0.1964}{\sin^2 35°[\cot 35° - \cot 90°]},$$

$$FS = 1.28.$$

****

This discussion on roadcuts assumes that the angle β of the cut is greater than the dip angle α of the planes of potential slip. What about $\beta < \alpha$? A sketch like Fig.(4.9) with $\beta < \alpha$ shows that the block so formed cannot slide, as it is constrained by the horizontal ground surface. This begs the question: Why not make all cuts with $\beta < \alpha$? The figure shows that this would require the removal of much larger amounts of material than in the case of $\beta > \alpha$, so that it may be simply impractical in terms of impact on the road environment.

4.5 Topples

The blocks whose stability with respect to sliding have been examined in the preceding sections possess one characteristic in common: they are much "longer" than they are "higher". This makes them relatively immune to "tipping over" or *toppling*. Contrast the two blocks shown in Fig.(4.10). Block A will not tip, but block B might, even if sliding does not take place.

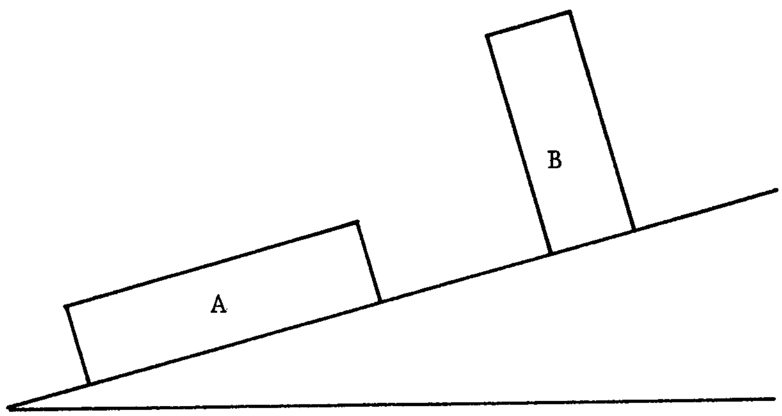

Fig.(4.10) To Tip or Not

It is important to determine the conditions that lead to toppling; clearly it is hazardous to be beneath a block of rock that is susceptible to such a maneuver, as it is to be down-slope from a block of rock with an inclination to slide.

In the preceding sections, the conditions for sliding are analyzed by examining the forces acting on the block, because sliding is a translational motion to which Newton's laws of motion apply.

Toppling is a rotational motion, and rotation is usually analyzed by applying Newton's laws as rewritten in the form convenient for rotational situations: that is, by considering the torques acting on the object. A brief tutorial on torque follows.

See Fig.(4.11). A force F acting on an object at a point P exerts a torque τ about origin O, which lies at a perpendicular distance r from the line of action of F, with τ given by

$$\tau = rF. \tag{4.35}$$

The symbol τ is already used as the symbol for shear stress; it is also used here as the symbol for torque because it is the symbol very commonly used in technical literature.

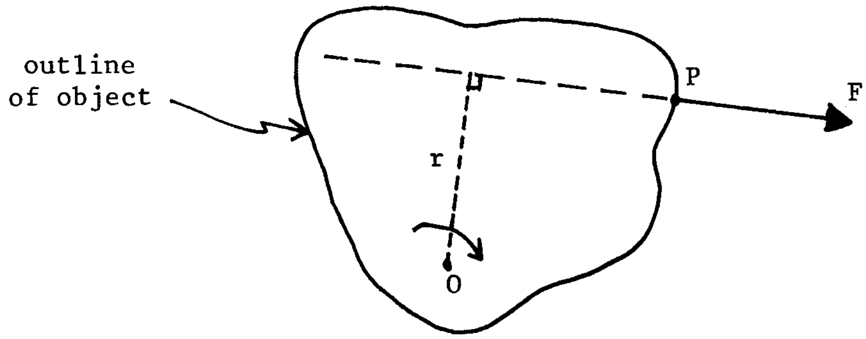

Fig.(4.11) Definition of Torque.

The distance, or line, from O to the line of action of F, the line segment whose length is r, is called the *lever arm* or *moment arm* of the force F about origin O. Torque, itself, is sometimes referred to as *moment.*

The SI base units of torque are, as seen from Eq.(4.35), units of force times units of distance; to wit, N·m. This combination is called a *Joule* (J) in the SI system. But the unit Joule is generally not used with torque; rather, the unit for torque is generally written out as N·m.

There is a *sense* (direction) associated with torque. In Fig.(4.11), the force F, acting alone at point P on the object, pivoted at O, tends to induce a rotation of the object in the clockwise sense, as indicated by the arrow at O. Clockwise torques are taken as negative; counterclockwise torques are positive.

Newton's second law written for rotation reads

$$\Sigma\tau = I\alpha, \tag{4.36}$$

where α now is the angular acceleration of the object, I is its rotational inertia about an axis through O, and $\Sigma\tau$ is the sum of all the torques acting on the object. In examining the conditions for toppling, only the sense of the angular acceleration need be determined, not its numerical value. Therefore, the numerical value of the rotational inertia will not be needed.

To see how Eq.(4.36) is applied, consider the specific case of a uniform, rectangular block of rock on a slope of inclination angle α. (Since a numerical value of angular acceleration will not be calculated, from this point on α will only be used for slope angle. Use of the same symbol for different quantities is not uncommon in engineering writing.) It is assumed here, as in all cases in this chapter, that the block is not susceptible to sliding before toppling.

The block has base length b, height h, and width w (dimension perpendicular to paper); see Fig.(4.12). To see if the block will topple (*i*) suppose that it does topple, (*ii*) draw the block slightly displaced toward toppling, (*iii*) examine the forces and their associated torques, (*iv*) determine the sense of the net torque and therefore of the angular acceleration induced, (*v*) see if the angular acceleration takes the block back to its original position.

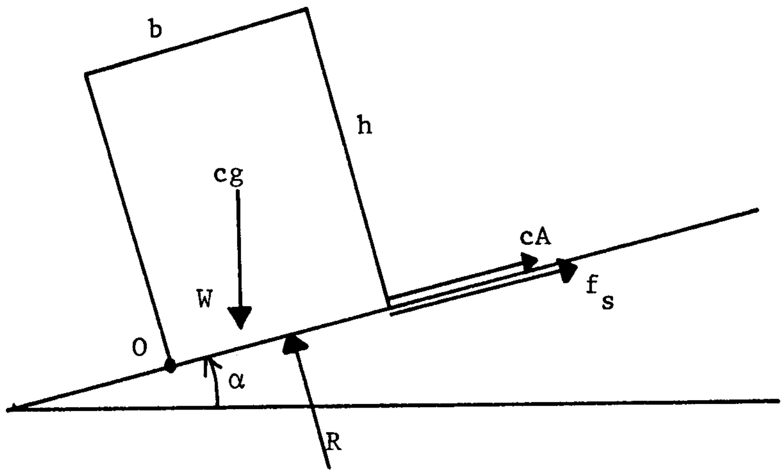

Fig.(4.12) Block before Tipping.

The forces on the block are its weight W, acting vertically down from the center of gravity cg of the block, the normal force R exerted by the slope, and the resisting forces of friction f_s and of cohesion cA. These are shown on Fig.(4.12).

In Fig.(4.13), the block is shown slightly tipped. Since it is presumed that the block does not slide, the axis of rotation about which the block tips passes along the bottom front edge O of the block. Since now there is only a very narrow region of contact between block and slope, namely along the edge through O, the normal force R and the friction force f_s must act there. The cohesion force is proportional to the area of contact; since this area virtually goes to zero in tipping, the cohesion force vanishes and therefore is not shown.

The lines of action of both R and f_s pass through O; hence, each contributes zero torque about O, for their lever arms are zero. The only force that does produce a torque is the weight W, drawn vertically down from the center of gravity. The crucial question, then, is just where, relative to O, the line of action of W passes. Two possible locations for the center of gravity are shown on Fig.(4.13). For position 1, the weight W passes O on the "inside" of the base of the block; this induces a clockwise torque which tends to return the block to its original position. On the other hand, for a center of gravity in position 2, the line of action of the weight W falls "outside" the base of the block; the associated torque about O tends to rotate the block farther away from its original position; i.e., it topples over.

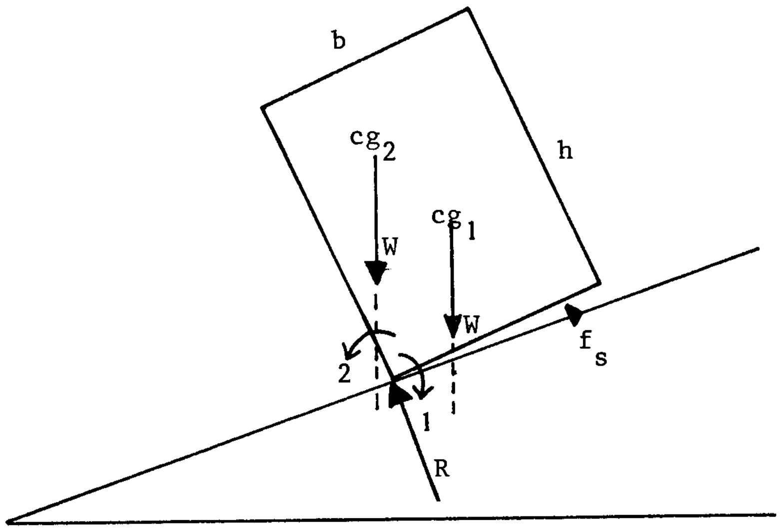

Fig.(4.13) Tipping Block

The two factors that govern toppling, then, are the location of the center of gravity of the block, and the value of the inclination angle of the slope. The steeper the slope the more likely it is that the line of action of W will fall outside the block, indicating toppling. If the line of action of the weight passes through O itself, then the angle of the slope is the largest angle for which the block does not topple, or the smallest angle at which it does (there is no practical difference between these two interpretations).

Figure (4.14) shows a rectangular block at this largest possible slope angle for which toppling does not occur. The center of gravity of a uniform rectangular solid is at the "center"; that is, at the intersection of the body diagonals. For a rectangular block, a line normal to the surface (dashed line) is parallel to the sides of the block. This means that the angle between W and the normal also is α, the slope's dip angle. Therefore, the greatest angle α consistent with stability against toppling is given from

$$\tan\alpha = \frac{b/2}{h/2},$$

$$\tan\alpha = \frac{b}{h}. \tag{4.37}$$

This equation applies for rectangular blocks. A different relation may hold for rocks of a different shape.

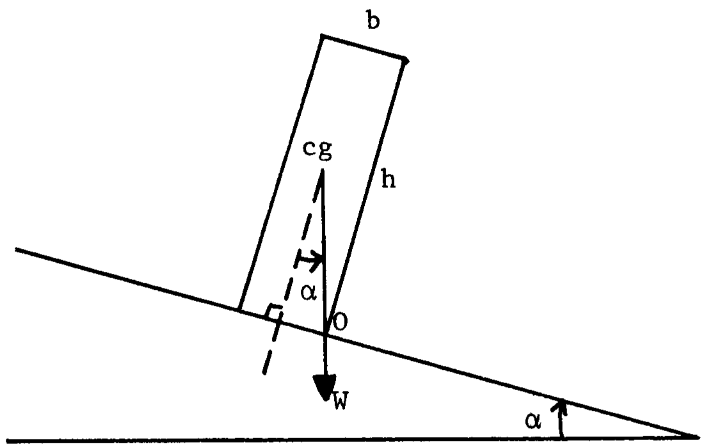

Fig.(4.14) Block in Critical Condition

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EXAMPLE 6

Due to chemical weathering, a block of granitic rock has eroded to a uniform hemisphere of radius 2.63 m. Find the elevation angle of the steepest slope on which it will not tip. (Assume that the rock does not slide.) For a hemisphere of radius R, the center of gravity is at a distance $\frac{3}{8}R$ above the center of the base.

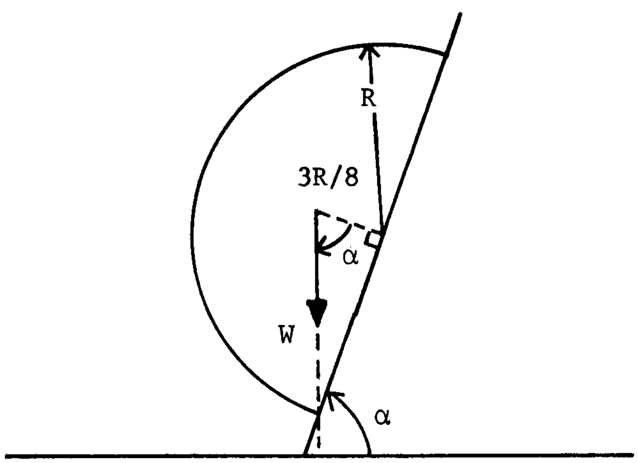

Fig.(4.15) Example 6

Figure (4.15) shows the rock on the point of toppling, since the line of action of the weight W passes through the lowest point on the base perimeter. The slope angle is given by

$$\tan\alpha = \frac{R}{\frac{3}{8}R},$$

$$\alpha = 69.4^\circ.$$

Evidently, a very steep slope is needed to induce toppling. Unless the resisting forces of friction and/or cohesion are exceptionally large, the "block" will slide on shallower slopes.

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4.6 Problems

1. The rectangular slab of rock of density 3.40 g/cm^3 shown in Fig.(4.16) has edge lengths a = 28.0 m, b = 19.0 m, c = 3.60 m, and is resting on a 17.0°-incline. Ignore friction. The slab will slide if it is disturbed even very slightly. Find the cohesion stress between slab and incline.

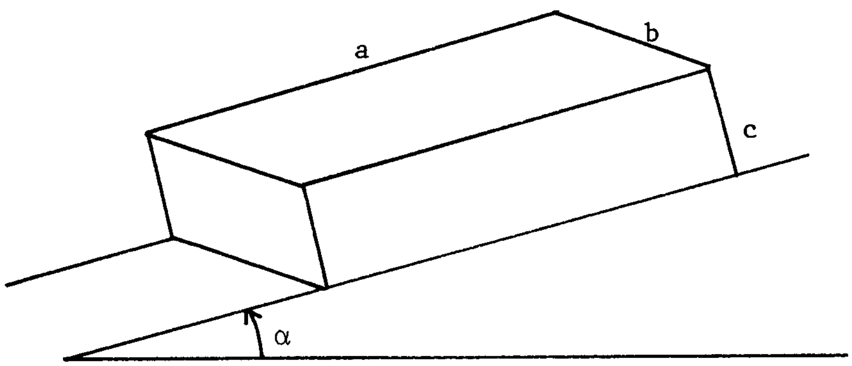

Fig.(4.16) Problems 1 and 2

2. The slab shown in Fig.(4.16) has density 3.15 g/cm^3 and edge lengths a = 17.6 m, b = 9.30 m, c = 1.80 m. The cohesion stress between the slab and the 21.0°-slope is 8.56 kN/m^2. Tests show that the slab will slide if disturbed in the slightest manner. Find the angle of friction between slab and slope.

3. A rectangular block with dimensions 7.92 m, 4.81 m, 1.27 m has a unit weight of 26.4 kN/m^3. It rests on an incline with elevation angle 22.5° with its shortest dimension perpendicular to the incline. Cohesion between block and incline is 23.0 kN/m^2. Ignore friction. Find the factor of safety against sliding.

4. A 17.0 m, 5.80 m, 2.40 m block with density 2600 kg/m^3 rests on an 18.0°-slope with its shortest dimension normal to the slope. The angle of friction between block and slope is 12.0° and cohesion equals 17.0 kPa. (a) Find the factor of safety against sliding. (b) Find the smallest extra driving force that will trigger sliding.

5. The weight of the slab shown in Fig.(4.17) is 22.3 MN. The angle of friction between slab and slope is 8.50° and the factor of safety against sliding is 1.60. Find the force of cohesion

between slab and slope.

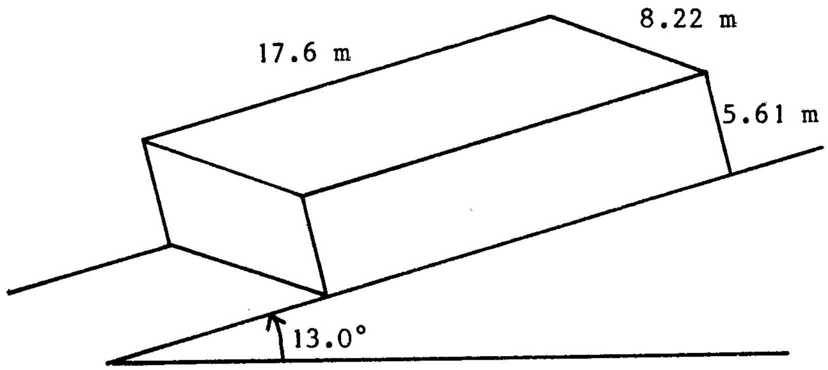

Fig.(4.17) Problem 5

6. A slab of rock has edge lengths 8.30 m, 12.0 m, 1.92 m and a density of 2.96 g/cm^3. It sits on a slope with its shortest dimension perpendicular to the slope. Between slab and slope the coefficient of friction equals 0.411 and the cohesion stress is 47.5 kPa. Tests show that an extra driving force of 5.18 MN will just start the slab sliding. Find the dip angle of the slope. (*Hint*: Write the equation for the factor of safety as a quadratic equation in $\cos\alpha$.)

7. A rock bolt has a cross-sectional area of 6.60 cm^2 and a shear strength of 450 MPa. What shearing force will just rupture the bolt?

8. A block of rock, density 3270 kg/m^3, has edge lengths 14.6 m, 6.31 m, 7.20 m. It is to be bolted to a vertical rock face with 25 identical, loosely-installed rock bolts. It is desired that, if cohesion is ignored, the factor of safety will be 2.00. The bolts have a shear strength of 633 MPa. Find the diameter of the bolts.

9. A slab of rock of mass 2.30 X 10^6 kg is to be bolted to a 31.0°-incline. Friction and cohesion are to be ignored. Each rock bolt has area 4.80 cm^2 and shear strength 510 MPa. Find the minimum number of loosely-installed rock bolts needed.

10. A rectangular block of rock with dimensions 1.22 m, 3.71 m, 1.83 m and of density 2.86 g/cm^3 is to be secured to a vertical rock face with a single rock bolt, as shown in Fig.(4.18). The bolt has a shear strength of 340 MPa. The angle of friction is 25.0°; cohesion is to be

ignored. The bolt is not tightened. Calculate the minimum diameter bolt needed.

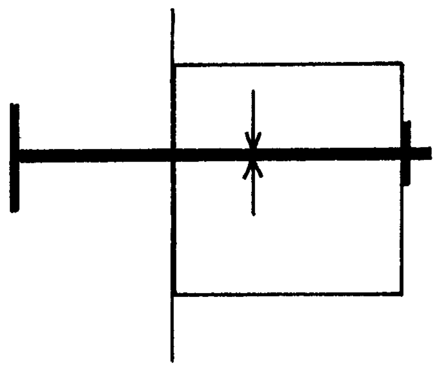

Fig.(4.18) Problem 10

11. A slab resting on a 13.0°-incline has a weight of 48.8 MN. Workers have installed 17 identical rock bolts. Each bolt has a shear strength of 870 MPa and area 14.0 cm^2. Ignore friction and cohesion. The workers did not tighten the bolts. (*a*) Find the factor of safety against sliding. (*b*) Find the minimum extra driving force that will cause the block to slip.

12. The slab shown in Fig.(4.19), mass 2.84 X 10^5 kg, will drop if the vertical joint ruptures. The contact area is 38.0 m^2. Between slab and cliff face the coefficient of friction is 0.300 and cohesion 73.3 kPa. To keep the slab from dropping, stitches are installed. Each cable has area 8.42 cm^2 and is tightened to tension 410 MPa. How many stitches are needed to get a factor of safety of 1.50?

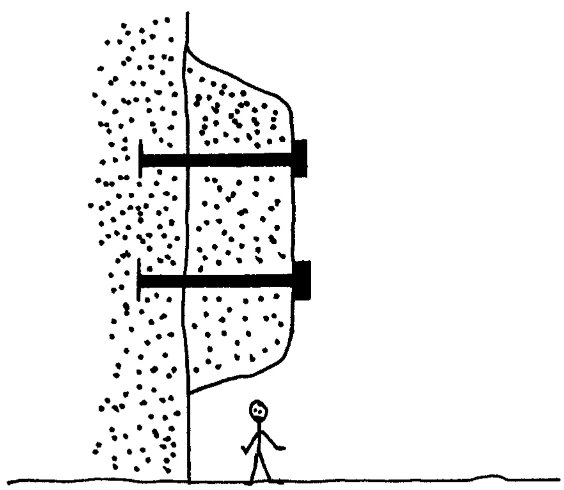

Fig.(4.19) Problem 12

13. A slab with edge lengths 12.0 m, 59.5 m, 2.82 m rests on an incline with its shortest dimension normal to the incline. The elevation angle of the slope is 28.5° and the density of the slab is 3.16 g/cm^3. The angle of friction between slab and incline is 18.0° and cohesion equals 84.2 kN/m^2. Rock bolts are installed but not tightened. Each bolt has an area of 7.30 cm^2 and shear strength 550 MPa. A factor of safety of 2.75 is desired. How many rock bolts are needed?

14. A slab of rock sits on a rock surface that dips at 16.0°. The unit weight of the slab is 28.7 kN/m^3, and its edge lengths are 17.4 m, 8.27 m, 5.58 m. It rests on one of its faces with the largest surface area. The angle of friction is 11.2° and cohesion is 20.7 kPa. (*a*) How many loosely-installed rock bolts are needed to get a factor of safety of at least 1.63? The bolts have shear strength 474 MPa and area 7.30 cm^2. (*b*) With the bolts installed, find the extra driving force that will bring the slab to the verge of slipping.

15. A block of rock weighing 320 MN is to be bolted to a 19.0°-slope. The angle of friction is 14.0°; cohesion has been destroyed by nearby rock blasting. Rock bolts of area 9.34 cm^2 and shear strength 472 MPa are installed. (*a*) How many bolts, not tightened, are needed for a factor of safety of 1.20? (*b*) To what tension must the bolts in (*a*) be tightened to increase the factor of safety by 0.200?

16. A rectangular slab of rock is to be secured to a 32.0°-incline by stitches. The slab of rock has density 2700 kg/m^3 and edge lengths 1.80 m, 7.60 m, 8.20 m. The coefficient of friction between slab and incline is 0.364. Ignore cohesion. The stitching cable has area 9.40 cm^2 and is tightened to tension 320 MPa. (*a*) Find the minimum number of stitches needed. (*b*) Suppose that nine stitches actually are installed. What is the factor of safety that results?

17. A block of rock with dimensions 28.0 m, 13.0 m, 5.30 m rests on a 24.0°-slope with its shortest dimension normal to the slope. The density of the block is 2.90 g/cm^3. Between slab and slope the cohesion stress equals 25.0 kPa and the coefficient of friction is 0.250. A factor of safety of 1.45 is needed. (*a*) If this is to be obtained with loosely-installed rock bolts, how many are required? Each bolt has area 9.20 cm^2 and shear strength 760 MPa. (*b*) The supplier is out of bolts, so the job must be done with stitches. The cable has area 5.30 cm^2 and each stitch is tightened to the tensile strength of 380 MPa. How many stitches are needed?

18. Figure (4.20) shows the cross section of a road cut into the side of a mountain. The line AA is a weak bedding plane along which sliding is possible. The block B, 18.6 m wide, directly above a stretch of the road is separated from uphill rock by a tension crack T normal to AA. The dip angle of the bedding plane is 19.2° and the coefficient of friction between the block B and the bedding plane is 0.390. The density of the block is 2.88 g/cm^3. Ignore

cohesion. (*a*) Show that the block does not slide. (*b*) Water seeps into the tension crack and freezes, exerting a driving force on the block. What value of this force will trigger a slide?

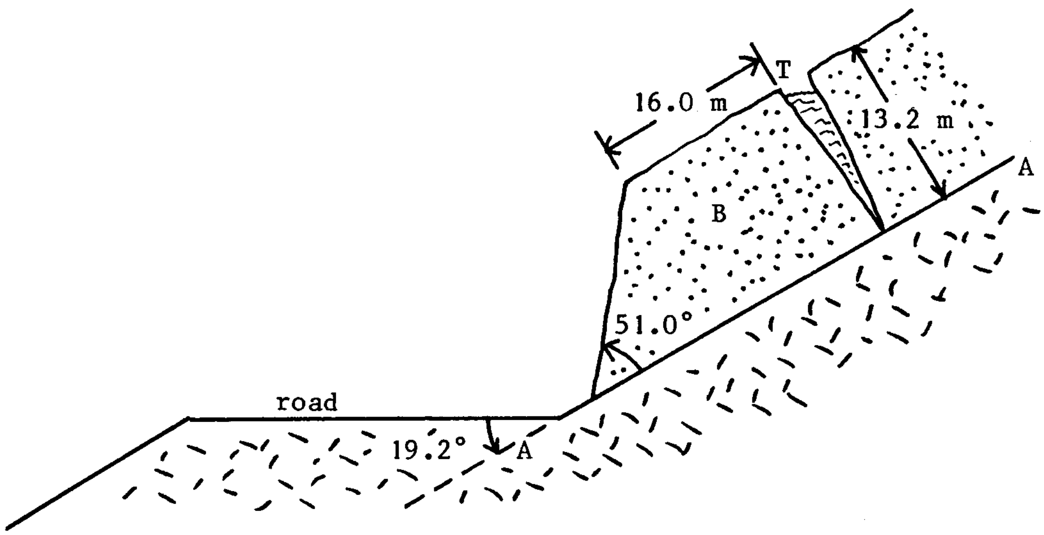

Fig.(4.20) Problem 18

19. A slab of weight 28.0 MN sits on a 23.0°-incline. The angle of friction between slab and incline is 15.0°; cohesion equals zero. (*a*) How many tightened rock bolts are needed to get a factor of safety of at least 1.50? The bolt specifications are: shear strength 230 MPa; area 5.80 cm^2; tightened to tension 86.4 MPa. (*b*) Due to an oversight, only 20 of the needed bolts actually are tightened; what is the real factor of safety?

20. Show that the extra driving force needed to trigger sliding of a block at rest is given by

$$F_{\text{ext}} = W \sin\alpha (FS_{\text{actual}} - 1),$$

where FS_{actual} is calculated with an integral number of bolts or stitches.

21. A block weighing 28.4 MN sits on a 19.0°-slope. The angle of friction is 13.0°. Cohesion equals 430 kPa. Tests show that the factor of safety against sliding is 1.70. Find the contact area betwen block and slope.

22. A block rests on a slope of dip angle α. The angle of friction is ϕ. No engineering steps have been taken to secure the block. Show that, if $\alpha > \phi$, the smallest value of the cohesion stress that keeps the block from sliding is given by

$$c = \sigma(\tan\alpha - \tan\phi),$$

where σ is the stress on the block due to the normal force.

23. Water just fills an isolated pore in a rock. Both the water and the rock are initially at temperature 20°C, but the temperature soon rises to 30°C. Find the stress exerted by the water on the rock due to the thermal expansion. The coefficient of volume expansion of water is 2.55 X 10^{-4} $(C°)^{-1}$, and of the rock is 4.80 X 10^{-5} $(C°)^{-1}$.

24. Suppose that in the roadcut of Fig.(4.9), the depth H is 14.6 m, the bedding angle 26.0° and the cut angle 48.5°. The density of the rock is 2550 kg/m^3. Due to heavy rain the block slides on to the road surface over a 94.0 m length. How many metric tons of rock must be removed to clear the roadway?

25. In Example 5, what angle of cut would yield a factor of safety of (*a*) 2.00, and (*b*) 3.00?

26. Sketch a graph of the factor of safety FS versus roadcut angle β for the range $90° \geq \beta > \alpha$. Pick values of ϕ and α, with $\phi < \alpha$, so that cohesion is necessary for stability. To get a value of B, use $c \approx 300$ kPa, $\gamma \approx 25$ kPa/m and $h \approx 10$ m. A graphing calculator may be handy, but not necessary.

27. A section of thruway is constructed through sandstone beds that dip at 41.5° directly toward the thruway. A section of the roadcut, 19.2 m high, is made at an angle of 70.0° to the horizontal. The angle of friction between the beds of the sandstone is 28.0°, and the density of the rock is 2.24 g/cm^3. Tests show that the factor of safety of the slope thus created is 1.35. Find the cohesion stress in the sandstone.

28. In the thruway roadcut of Problem 27, the factor of safety against sliding is 1.35. It is thought wise to secure the slope with a sufficient number of rock bolts so as to increase the factor of safety to 2.00. The bolts are standard steel rock bolts with diameter 2.54 cm and shear strength 348 MPa. Due to a manufacturing defect, the bolts cannot be tightened. How many bolts are needed for a roadcut 100 m long in the same kind of rock as described in Problem 27?

29. A 56.0°-roadcut is made in sedimentary rock. The bedding planes are parallel and evenly spaced from, and including, the edge E of the block. See Fig.(4.21). The bedding planes dip at 27.0°. Bedding plane I passes through the toe of the cut, just where you are standing. The angle of friction between bedding planes is 20.0°. Tests show that the factor of safety against the entire block sliding as a unit along plane I is 1.60. (*a*) Find the factor of safety against sliding of the entire block above plane II along plane II. (*b*) Similarly, find the factor

of safety against sliding of the block above plane III along plane III.

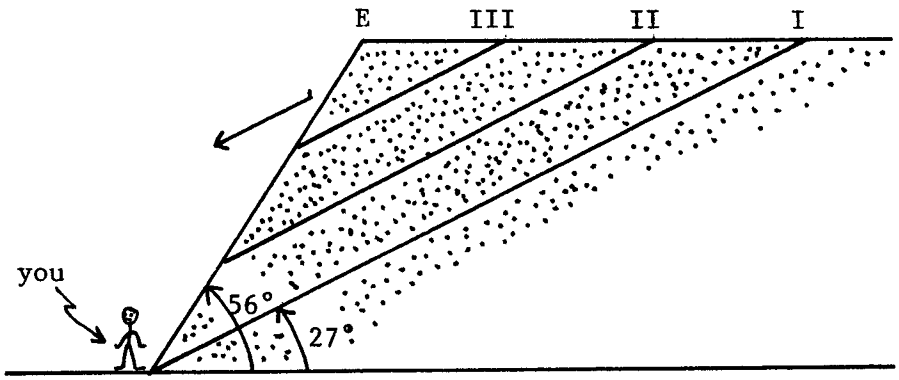

Fig.(4.21) Problem 29

30. A 57.0°-roadcut 11.2 m deep and 75.0 m long is made in granitic rock of density 2.77 g/cm^3. A set of parallel joints in the rock dip at 43.5° directly toward the cut. Tests show that cohesion equals 23.6 kPa and the angle of friction is 19.0°. (*a*) Find the factor of safety. (*b*) How many stitches, each of diameter 2.34 cm and under tension 512 MPa, must be installed to raise the factor of safety to 1.50?

31. Which, if any, of the rectangular blocks in Fig.(4.22) will topple? Assume no sliding.

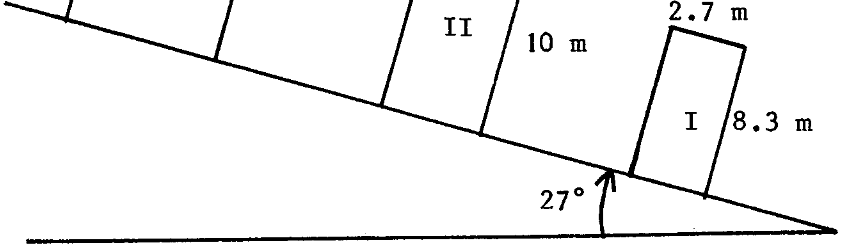

Fig.(4.22) Problem 31

32. A block has the shape of a right-triangular prism, as shown on Fig.(4.23). The block has height 13.0 m and is 11.0 m wide. It rests on a 35.0°-slope. Find the largest possible value of the angle θ of the block so that it will not topple. Assume no sliding.

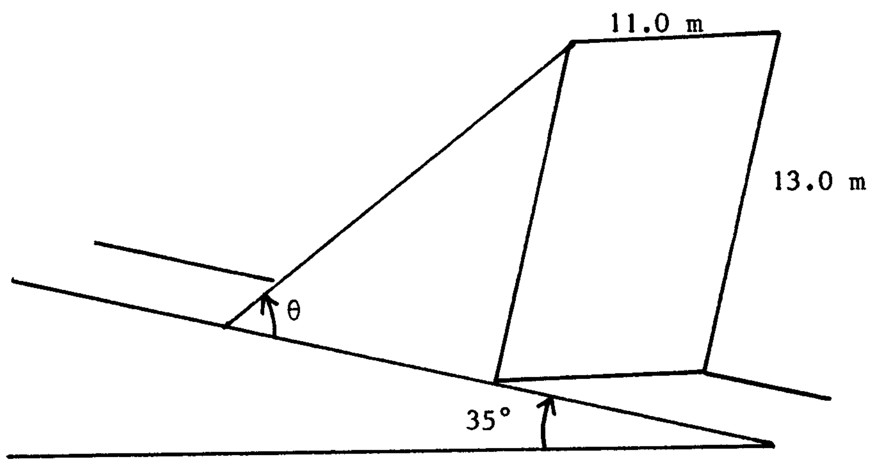

Fig.(4.23) Problem 32