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The mechanics of surficial failure in soil slopes

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ABSTRACT

It is not safe to employ the classical infinite slope failure analysis procedure in which the Coulomb failure criterion is used, because a very large portion of the factor of safety is assigned to the effective cohesion which is not present in the soil. Part of the problem arises from the normal stresses used in the drained direct shear tests, which are high relative to the normal stresses prevailing in surficial failures. The real effective strength envelope is curved, and it is proposed to model it by a power function whose parameter values may be determined from the usual shear tests performed at the normal stress magnitudes usually employed. Based on the factor of safety calculations from the curved failure envelope and observations from field rainfall infiltration experiments, the mechanics of surficial failure of slopes is explained.

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1. Introduction

The surficial stability of slopes is seriously affected by rainfall, because the shear strength that is present in unsaturated soils due to matric suction is lost as a result of rainwater infiltration into the soil. While surficial failures of soil slopes may happen anywhere, they tend to attract more attention in semi-arid areas of the world in which the upper layer of the soil dries out for some years followed by a year with heavy rainfalls which saturate the upper layers and cause a large number of surficial failures. In Southern California the annual precipitation typically varies from 25 to 50 cm (10 to 20 in.) of water with an average of about 38 cm (15 in.) and most of the rainfalls occur in the winter months. In some years the rainfall increases to unusual magnitudes. Based on data from the National Weather Service, the Los Angeles Times reports annual above-normal winter rains (measured from July 1 to June 30) as follows:

1940–41:	81.2 cm (32.76 in.)
1968–69:	69.8 cm (27.47 in.)
1977–78:	84.9 cm (33.44 in.)
1982–83:	79.4 cm (31.25 in.)
1992–93:	69.5 cm (27.36 in.)
1997–98:	78.7 cm (31.01 in.)

It is during such years of unusual, heavy precipitation that surficial failures occur in large numbers. For example, the third heaviest storm recorded since 1877 occurred in 1977–78 (Los Angeles Times: July 5, 1986), and it produced more than a thousand slope failures in Los Angeles County, a large proportion of which were surficial failures.

In an excellent study of the conditions leading to surficial failure, Pradel and Raad (1993) found that the rainfall has to be sufficiently intense to exceed the infiltration rate of the soil and it has to be sufficiently heavy to saturate the slope. Pradel and Raad (1993) indicated that the permeability of the soil plays a role in the susceptibility to surficial failure. They argued that soils with permeabilities above a certain limiting value would not become saturated, and slopes made of sandy and gravelly soils would therefore not exhibit surficial instability. Rather, it was the slopes made of clayey and silty soils that would be prone to become unstable, as is in agreement with actual observations made by Hollingsworth and Kovacs (1981).

Surficial failure is most often addressed by an infinite slope stability analysis, as reviewed below. However, the effective cohesion plays an inordinate large role in calculation of the factor of safety by the classical infinite slope analysis. It will be shown that effective cohesion does not exist in non-cemented soils, but rather the failure envelope for soils is curved, and this may be correctly accounted for in the infinite slope stability analysis employed for surficial stability. Finally, experiments on water infiltration into a soil slope performed by Ng and Zhan (2007) are used to indicate the mechanics leading to surficial instability of soil slopes.

2. Classical infinite failure analysis

It is well-known that effective stress analyses in soils can be performed in two different ways using:

(1) Total unit weights and water pressures
or
(2) Buoyant unit weights and seepage forces

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Both procedures employ effective strength parameters, c′ and φ′, and both may be used to find the factor of safety for a saturated, homogeneous, infinite slope (Skempton and DeLory 1957), as shown in Fig. 1(a). The two procedures produce the same answer, but the first procedure is generally more straight-forward (Lambe and Whitman, 1969; Abramson et al., 2002; Duncan and Wright, 2005).

The water enters the slope and is directed parallel to the surface by an impervious layer at some depth. The water table is at the sloping ground surface, the flow lines are parallel to the slope, and the equipotential lines are perpendicular to the slope. The water pressure is therefore zero at the ground surface and it increases with depth as indicated in Fig. 1(a). At the vertical depth h the water pressure is:

$$u = \gamma_w \cdot h \cdot \cos^2\alpha \tag{1}$$

The total weight of the block with depth $h \cdot \cos\alpha$ and length b is:

$$W = \gamma_{sat} \cdot b \cdot h \cdot \cos\alpha \tag{2}$$

in which γ_{sat} is the saturated unit weight of the soil. The side forces parallel to the slope at the two ends of the block are opposite and equal in magnitude in an infinite slope, and they cancel out of the equilibrium considerations.

Thus, only the vertical force W and the water pressures u directed perpendicular to the base are considered in the force equilibrium of the block. The vertical force W is resolved into components parallel and perpendicular to the slope as shown in Fig. 1(b), and these components are then employed in determination of the shear stress and the effective normal stress at the base of the block:

$$\tau = \frac{W \cdot \sin\alpha}{b} = \frac{\gamma_{sat} \cdot b \cdot h \cdot \cos\alpha \cdot \sin\alpha}{b} = \gamma_{sat} \cdot h \cdot \cos\alpha \cdot \sin\alpha \tag{3}$$

$$\sigma' = \frac{W \cdot \cos\alpha}{b} - u = \frac{\gamma_{sat} \cdot b \cdot h \cdot \cos^2\alpha}{b} - \gamma_w \cdot h \cdot \cos^2\alpha = (\gamma_{sat} - \gamma_w) \cdot h \cdot \cos^2\alpha \tag{4}$$

The shear strength available at the base of the block according to the Coulomb failure criterion is therefore:

$$s = c' + \sigma' \cdot \tan\phi' = c' + (\gamma_{sat} - \gamma_w) \cdot h \cdot \cos^2\alpha \cdot \tan\phi' \tag{5}$$

The factor of safety is then calculated as:

$$F = \frac{s}{\tau} = \frac{c' + (\gamma_{sat} - \gamma_w) \cdot h \cdot \cos^2\alpha \cdot \tan\phi'}{\gamma_{sat} \cdot h \cdot \cos\alpha \cdot \sin\alpha} \tag{6}$$

In this expression $(\gamma_{sat} - \gamma_w)$ is equal to the buoyant unit weight γ_b. For a cohesionless soil, $c' = 0$ and the factor of safety becomes independent of depth h:

$$F = \frac{\gamma_b}{\gamma_{sat}} \cdot \frac{\tan\phi'}{\tan\alpha} \tag{7}$$

Since the buoyant unit weight, γ_b, is approximately one half of the saturated unit weight, γ_{sat}, the factor of safety is approximately:

$$F \cong \frac{1}{2} \cdot \frac{\tan\phi'}{\tan\alpha} \tag{8}$$

In comparison, the factor of safety for a completely dry, cohesionless slope is:

$$F = \frac{\tan\phi'}{\tan\alpha} \tag{9}$$

Failure in a dry sand slope will occur for $F = 1$ at which $\alpha = \varphi' =$ angle of repose. Actual observations indicate that failure occurs by raveling of a thin layer of dry sand right at the sloping ground surface. If the slope is saturated and water seeps parallel to the sloping surface, Eq. (8) indicates that the factor of safety is only half of that for a dry slope in cohesionless soil.

Note that for a soil with effective cohesion, Eq. (6) indicates that the factor of safety decreases with increasing depth, while the factor of safety is independent of depth for a slope without cohesion. Thus, no particular unsafe depth or location at which shear failure will occur is indicated by Eq. (8).

3. The nature of effective cohesion in soils

3.1. Components of shear strength

The shear strength of soils consists of contributions from the granular portion and from the clay size portion of the soil. The

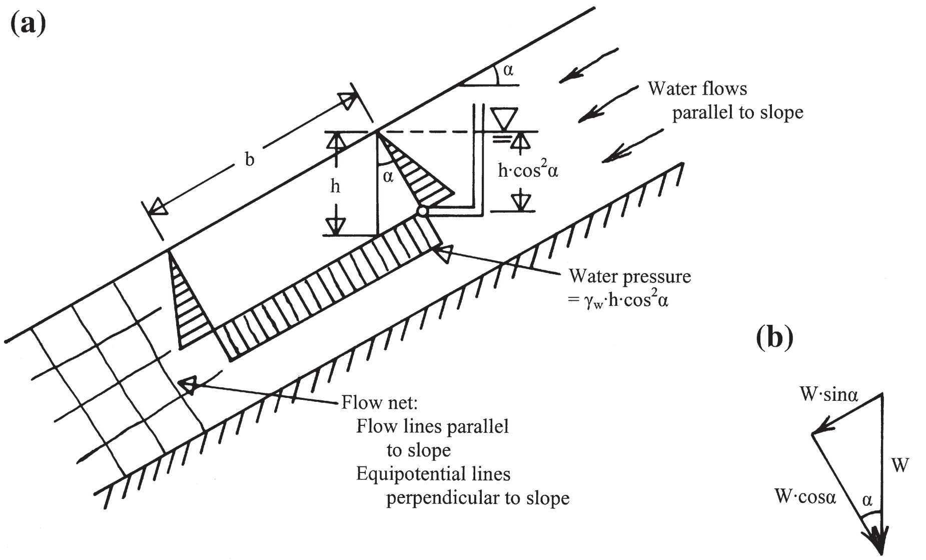

Fig. 1. Surficial stability analysis by total unit weights and water pressures: (a) forces acting on soil block, and (b) resolution of forces parallel and perpendicular to soil slope with inclination α.

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