Supplementary Item DR1

Estimate of maximum levee height with deep-seated failure

In a channel-levee system (Figure 1), slope stability is decreased through both levee deposition, which increases levee height (hl), and channel erosion, which decreases the thickness of sediment beneath the channel (hc). We simulate the stability of this channel-levee system as a system of earth retaining structures at Coulomb failure (e.g. Lambe and Whitman (1969)).

Slope stability is controlled by the weight of the embankment (Wedge II and Wedge III) (Figure 1), the resisting force provided by the passive weight of Wedge I (channel), and the friction along the basal failure surfaces. Wedge III works with gravity, while Wedge I works against gravity. We assume that the effective stress is zero along the basal failure surface (Wedge II is freely sliding), that there is hydrostatic pressure above this surface, and that material properties are homogenous with a friction angle, ϕ, = 30°; and unit weight, γ, = 20 kN/m^3. We assume that the levee wedge (Wedge III) is in a state of active (extensional) failure, and the channel wedge (Wedge I) is in passive (compressional) failure. This leads to a normal fault of 60° on the levee side and a thrust fault at 30° at the toe of the channel (for a friction angle ϕ=30°, failure planes occur at $45 \pm \frac{\phi}{2}$).

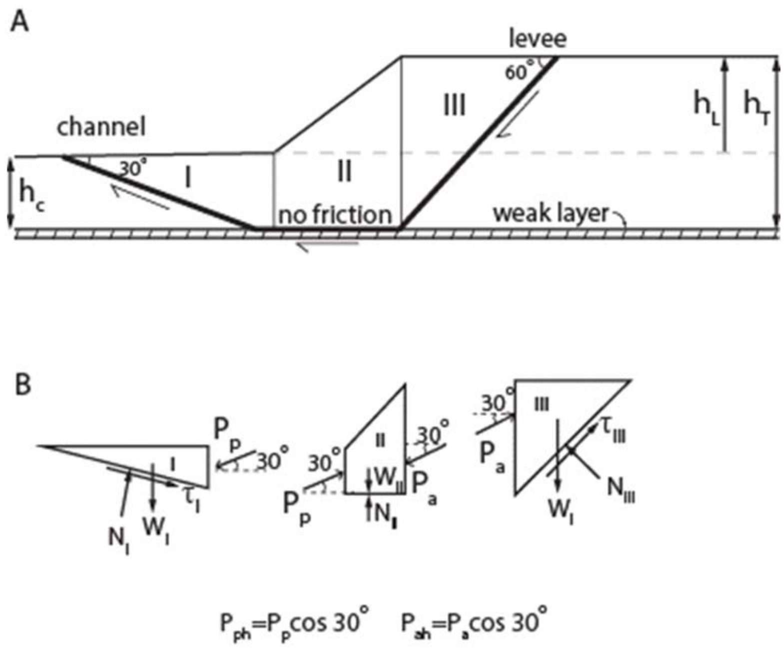

Figure DR1. A) Simplified channel-levee system. Failure surface (bold line with arrows showing sense of direction) for an embankment of total height h_T adjacent to a channel with a height h_c. B) Forces acting on Wedges I, II, and III.

The active pressure (P_a) and passive pressure (P_p) act at an angle of $\phi = 30°$, due to friction between the wedges (theory of retaining walls with wall friction, Lambe & Whitman (1969)) (Fig. 2).As wedge II is sliding in a frictionless manner, horizontal equilibrium gives:

$$P_{a,h} = P_{p,h} \tag{1}$$

where,

$$P_a = \frac{1}{2}\gamma h_T^2 K_a \tag{2}$$

and

$$P_p = \frac{1}{2}\gamma h_c^2 K_p \tag{3}$$

The coefficients of active stress, K_a and passive stress, K_p are obtained by graphs correlating the friction angle of the material, ϕ with the wall friction ϕ_w. In this case, $K_a \approx 0.295$ and $K_p \approx 7$ (Lambe and Whitman, 1969). Substituting (2) and (3) in (1):

$$P_a \cos(30°) = P_p \cos(30°), \tag{4}$$

$$\frac{1}{2}\gamma h_T^2 K_a = \frac{1}{2}\gamma h_c^2 K_p, \tag{5}$$

$$h_T^2 * 0.295 = h_c^2 * 7, \tag{6}$$

$$h_T = 4.9 h_c\ . \tag{7}$$

At failure, the total height (h_T) above the weak layer on the active (levee) side is 4.9 times the height (h_c) above the weak layer on the passive (channel) side. At Ursa, h_c is 75m. Thus, by Eq. 7, the total height (h_T) is 367.5m, which means the maximum levee height is 217 m with the given sand unit (Blue Unit) thickness of 150 m (h_L = 367.5m – 150m). We estimate from seismic data that the the levee thickness at Ursa was 200m, which is consistent with this analysis. If no channel erosion had occurred, h_c would have been 150 m and the maximum levee height before failure would increase to 585m (4.9x150m-150m). No levees of this scale were observed. In summary, a meter of incision in the channel creates the same amount of instability as 4.9 meters of deposition and levee failure will be very sensitive to erosion (destabilization) and deposition (stabilization) in the channel.

References

Lambe, T. W., and Whitman, R. V., 1969, Soil Mechanics, New York, John Wiley & Sons, Series in Soil Engineering, 553 p.:

Supplementary Item DR2

Soil Model

We use a two-dimensional finite element soil modeling package PLAXIS (Brinkgreve, 2002). For plane strain, the mean total stress is (p) is

$$p = \frac{\sigma_1 + \sigma_3}{2}, \qquad (1)$$

and the maximum shear stress (q) is

$$q = \frac{\sigma_1 - \sigma_3}{2}, \qquad (2)$$

where σ_1 and σ_3 are the principal stresses. The mean effective stress (p') controls soil behavior and is equal to the total stress less the pore pressure (u)

$$p' = p - u . \qquad (3)$$

The excess pore pressure (u_e) is the pore pressure less hydrostatic pressure (u_h)

$$u_e = u - u_h. \qquad (4)$$

For a change in total mean stress (Δp), the change in pore pressure (Δu) is

$$\Delta u = B \Delta p , \qquad (5)$$

where B is Skempton's pore pressure parameter. The value of B is 1 for saturated soils, but is set to 0.99 for numerical stability in PLAXIS (Brinkgreve, 2002). The diffusion of excess pore pressure with time (t) is solved with the consolidation equation (Biot, 1941)

$$\frac{\delta u_e}{\delta t} = c_v \left(\frac{\delta^2 u_e}{\delta x^2} + \frac{\delta^2 u_e}{\delta y^2} \right). \qquad (6)$$

For each lithology we define a single value of hydraulic conductivity (K) and compressibility (m_v), which are related to the coefficient of consolidation (c_v):

$$c_v = \frac{K}{m_v * \gamma_w}, \qquad (7)$$

where γ_w is the unit weight of water. The hydraulic conductivity is related to absolute permeability (k) by

$$k = \frac{K\mu}{\gamma_w}, \qquad (8)$$

where μ is the dynamic viscosity of water. We do not model the change in permeability or compressibility with effective stress.

To link effective stress to soil strain we used the well-known Mohr-Coulomb model (MC). MC is a poro-elastoplastic constitutive model in which a yield function separates elastic (recoverable) strain and plastic (irreversible) strain. Elastic strain obeys Hooke's Law of linear elasticity, with the input parameters Young's modulus (E) and Poisson's ratio (υ). The yield function is the extension of Mohr-Coulomb theory to general states of stress with the effective stress input parameters of angle of internal friction (ϕ) and cohesion (c). Non-associated flow is assumed and defined with the dilatancy angle (ψ). The angle of internal friction also defines the value of the lateral stress ratio (K_0) according to Jaky's formula ($K_0 = 1\text{-}\sin\phi$).

REFERENCES

Biot, M. A., 1941, General Theory of Three-Dimensional Consolidation: Journal of Applied Physics, v. 12, no. 2, p. 155-164.

Brinkgreve, R. B. J., 2002, PLAXIS 2D, Finite Element Code for Soil and Rock Analyses, Version 8: Netherlands, A.A. Balkema Publishers.