curvature in the slip surface. Assuming that the plane slip surface approximation is valid and is properly oriented relative to the principal stresses, the shear stress on it is:

$$\tau = SMF\ (c) + \sigma'_n\ SMF\ (\tan \phi) \qquad [3\text{-}9]$$

Thus, the shear stress on a presumed slip surface is taken to be a function of the shear strength parameters, the effective normal stress, and the strength mobilization factor.

c. Developed Shear Strength Parameters. Multiplying the shear strength parameters (c and $\tan \phi$) by the appropriate SMF reduces them to the "developed" values (c_d and $\tan \phi_d$) assumed to be operative in equilibrium conditions. The developed shear strength parameters, the actual shear strength parameters, and the SMF are related as follows:

$$SMF = \frac{\tan \phi_d}{\tan \phi} = \frac{c_d}{c} \qquad [3\text{-}10]$$

To estimate at-rest pressures for design using Coulomb's active earth pressure equation or the general wedge equation, the SMF should be taken as 2/3 (0.667). K_o values so obtained are compared with Jaky's equation in Figure 3-6. The Coulomb equation with an SMF of 2/3 is compared to the Danish Code and Jaky equations in Appendix E. It should be noted that as the ratio, $\tan \beta / \tan \phi$, exceeds 0.56, the lateral earth force computed by the Coulomb or general wedge equations using an SMF = 2/3 will be increasingly larger than that given by computing the earth force using a K_o given by the Danish Code equation, for those conditions where the Danish Code equation applies. Therefore, computing at-rest earth loadings using the Coulomb or general wedge equations for a sloping backfill when $\tan \beta / \tan \phi$ exceeds 0.56 will be conservative (see Appendix E).

3-12. Earth Force Calculation, Coulomb's Equations.

a. General.

(1) Coulomb's equations solve for active and passive earth forces by analyzing the equilibrium of a wedge-shaped soil mass. The mass is assumed to be a rigid body sliding along a plane slip surface. Design (at-rest) earth pressures and forces may be estimated using developed shear strength parameters (Equation 3-10) corresponding to an SMF of 2/3 in the Coulomb active earth force equation. The Coulomb equations have the advantage of providing a direct solution where the following conditions hold:

(a) There is only one soil material (material properties are constant). There can be more than one soil layer if all the soil layers are horizontal.

(b) The backfill surface is planar (it may be inclined).

(c) The backfill is completely above or completely below the water table, unless the top surface is horizontal, in which case the water table may be anywhere within the backfill.

(d) Any surcharge is uniform and covers the entire surface of the driving wedge.

(e) The backfill is cohesionless, unless the top surface is horizontal, in which case the backfill may be either cohesionless or cohesive.

(2) Although Coulomb's equation solves only for forces, it is commonly expressed as the product of a constant horizontal pressure coefficient K and the area under a vertical effective stress diagram. Assuming the concept of a constant K is valid, horizontal earth pressures can be calculated as the product of K times the effective vertical stress. The variation of the Coulomb solution from a more rigorous log-spiral solution is generally less than 10 percent, as shown in Figure 3-9.

b. <u>Driving-Side Earth Force</u>.

(1) The total active force P_A on a unit length of wall backfilled with a cohesionless material (c = 0) is given by:

$$P_A = \frac{1}{2} \gamma' \frac{1}{\sin \theta \cos \delta} K_A h^2 \qquad [3\text{-}11]$$

and acts at an angle δ from a line normal to the wall. In the above equation (refer to Figure 3-10):

γ' = effective unit weight (moist or unsaturated unit weight if above the water table, submerged or buoyant unit weight if below the water table)

θ = angle of the wall face from horizontal (90 degrees for walls with a vertical back face or structural wedge)

δ = angle of wall friction

K_A = active earth pressure coefficient

h = height of fill against gravity wall or height of fill at a vertical plane on which the force is being computed where

$$K_A = \frac{\sin^2(\theta + \phi)\cos\delta}{\sin\theta\sin(\theta - \delta)\left[1 + \sqrt{\frac{\sin(\phi + \delta)\sin(\phi - \beta)}{\sin(\theta - \delta)\sin(\theta + \beta)}}\right]^2} \quad [3\text{-}12]$$

Examples 1 and 2 in Appendix M and the examples in Appendix N demonstrate the use of Equation 3-12.

(2) When wall friction is neglected ($\delta = 0$), Equation 3-12 reduces to:

$$K_A = \frac{\sin^2(\theta + \phi)}{\sin^2\theta\left[1 + \sqrt{\frac{\sin\phi\sin(\phi - \beta)}{\sin\theta\sin(\theta + \beta)}}\right]^2} \quad [3\text{-}13]$$

(3) For the case of is no wall friction ($\delta = 0$) and a vertical wall ($\theta = 90$ degrees),

$$K_A = \frac{\cos^2\phi}{\left[1 + \sqrt{\frac{\sin\phi\sin(\phi - \beta)}{\cos\beta}}\right]^2} \quad [3\text{-}14]$$

(4) For the special case of no wall friction, horizontal backfill surface, and a vertical wall, Coulomb's equation for K_A reduces to:

$$K_A = \frac{1 - \sin\phi}{1 + \sin\phi} = \tan^2\left(45° - \frac{\phi}{2}\right) \quad [3\text{-}15]$$

which is identical to Rankine's equation for this special case.

(5) As stated in paragraph 3-11c and demonstrated in Figure 3-6 and Appendix E, a developed ϕ angle computed by Equation 3-10 using an SMF of 2/3 can be used in Coulomb's equation to compute an earth pressure coefficient close to that given by the Jaky or Danish Code equations.

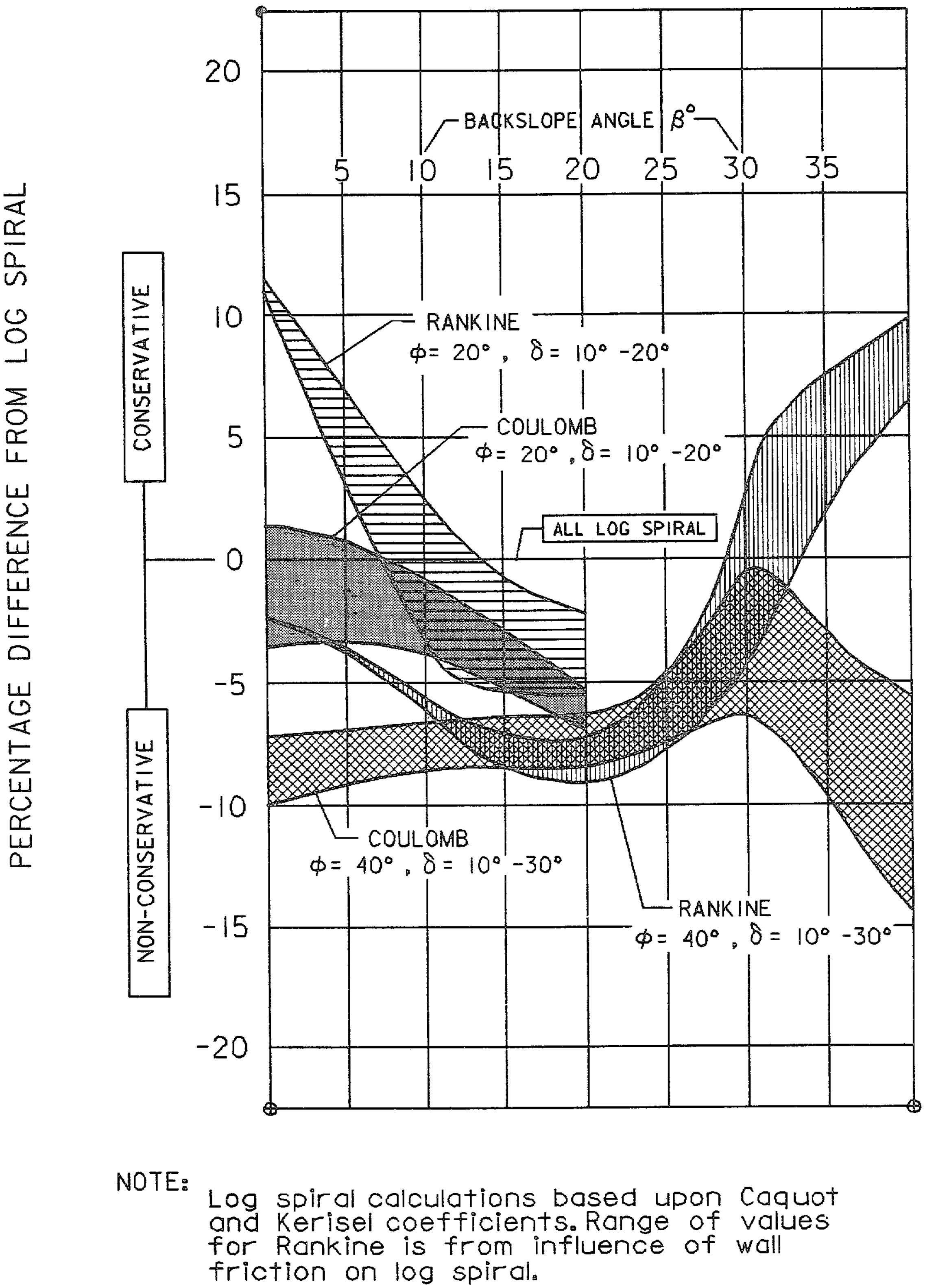

Figure 3-9. Comparison of active earth pressures (after Driscoll 1979)

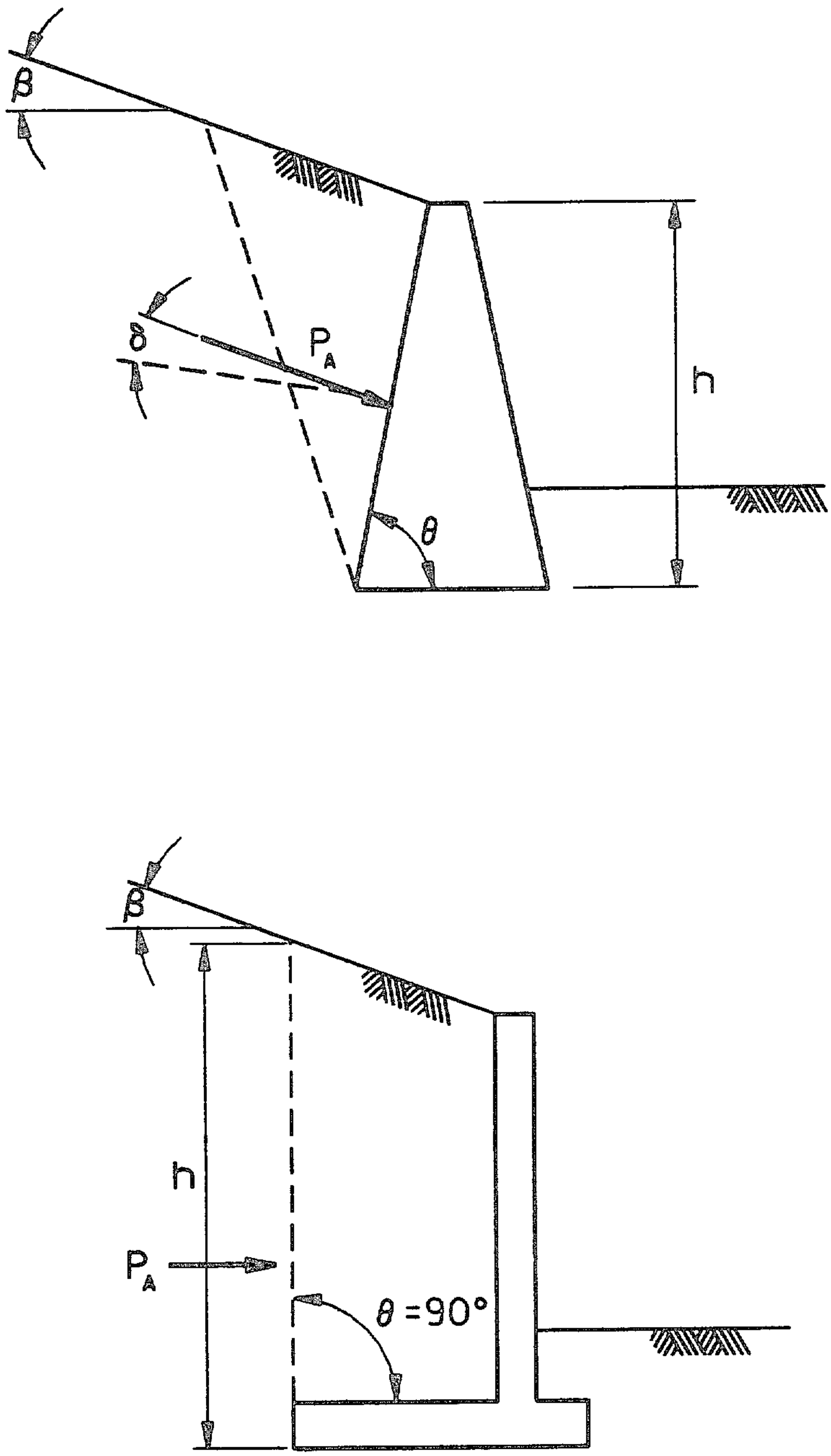

Figure 3-10. Variables used in Coulomb equation

(6) For the horizontal component of the earth force acting on a vertical plane, with no wall friction, the term ($1/\sin\theta\cos\delta$) in Coulomb's equation is equal to unity. Thus, Equation 3-11 reduces to

$$P_{AH} = \left(\frac{1}{2}\right) K_A \gamma' h^2 \qquad [3\text{-}16]$$

(7) If total stress or undrained strength parameters are used and there is a cohesion term c it has the effect of reducing the active earth force P_{AH} :

$$P_{AH} = \left(\frac{1}{2}\right) K_A \gamma' h^2 - 2c\sqrt{K_A}\, h + \frac{2c^2}{\gamma'} \qquad [3\text{-}17]$$

For a backfill with a horizontal surface, K_C given in Appendix H, paragraph H-2c, equals $\sqrt{K_A}$. The second term is the reduction in the active force due to the effect of cohesion on the slip plane and the third term accounts for the shortened length of slip plane due to the effect of a tension crack. If the third term is neglected, and K is assumed constant with depth, the active pressure can be obtained as the derivative of P_{AH} with respect to the depth from the top of the wall z :

$$p_{AH} = K_A \gamma' z - 2c\sqrt{K_A} \qquad [3\text{-}18]$$

Refer to examples 5 and 8 of Appendix M for examples involving cohesion.

(8) Estimation of at-rest pressures using the SMF concept with Coulomb's equation may give unreliable results for medium to highly plastic cohesive materials. If these materials cannot be avoided in the area of the driving side wedge, the at-rest pressure should be taken as the overburden pressure times as empirical K value, such as from Massarsch's (1979) or Brooker and Ireland's (1965) correlation of K with the plasticity index. Because of the number of uncertainties about the behavior of cohesive materials, a degree of conservatism should be exercised in the selection of the K values. Also, the effects of short and long term conditions (paragraph 3-5c) and compaction (paragraph 3-17) should be included in estimating the at-rest pressure.