Evaluation of Earth Pressures Acting on Slide Suppressor Walls

S. G. WRIGHT, W. M. ISENHOWER, AND M. K. KAYYAL

In Texas, successful repair of shallow slides in earth slopes has been made by embedding retaining walls within the failed slope. Design of these walls requires that the forces exerted on the wall by earth pressures be estimated. Frequently, estimates of the forces must be made with little knowledge of the shear strength properties of the soils involved. This paper presents procedures for calculating forces on the walls using shear strength parameters that are calculated from back-analysis using information pertaining to the original slope when it failed. Simplified procedures are presented that should yield forces nearly as accurate as the forces calculated by much more rigorous procedures.

The Texas State Department of Highways and Public Transportation (SDHPT) has successfully used special retaining "slide suppressor" walls to repair shallow slides in earth slopes. A typical slide suppressor wall is illustrated in Figure 1. The slide suppressor wall consists of a precast panel supported by drilled piers. The wall is placed against the drilled piers, and the piers may contain a semicircular half-section at the point where they support the wall. The slide suppressor wall appears to have been first developed and used by the Texas SDHPT in San Antonio for repair of slides in cut slopes.

The design of the slide suppressor wall requires estimating earth pressure forces that the wall must resist. Conventional earth pressure theories may be used to calculate the earth pressures. Such theories require some knowledge of the shear strength properties of the backfill materials. The backfill material is usually the original slope material, but often there is little information about shear strength properties for design of the wall. In some cases the shear strengths measured in the laboratory may not agree with what is apparently developed in the field. Such inconsistencies between field and laboratory strength values have been found to occur for highly plastic soils used in embankments in Texas [Green and Wright (*1*)].

The long-term shear strength properties, measured using either consolidated-drained or consolidated-undrained test procedures, have been found to be significantly higher than the shear strengths developed in the field. In such cases, use of laboratory shear strength values is unsatisfactory for predicting long-term performance. One way to determine shear strength properties of the slope materials is to calculate the properties from back-analysis using information pertaining to the original slope when it failed.

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Approaches for back-analysis to determine shear strength from slides and to calculate the earth pressure required for design of slide suppressor walls are presented in this paper. Design procedures for the slide suppressor walls themselves are presented by the authors in a companion paper published in this Record.

BACKGROUND

Abrams and Wright (*2*) studied slide suppressor walls and developed a series of charts for computing the forces on walls like the one illustrated in Figure 1. These charts are based on the assumption that a slide has occurred in the slope and this information is used to determine shear strengths by back-analysis. The shear strength parameters determined by back-

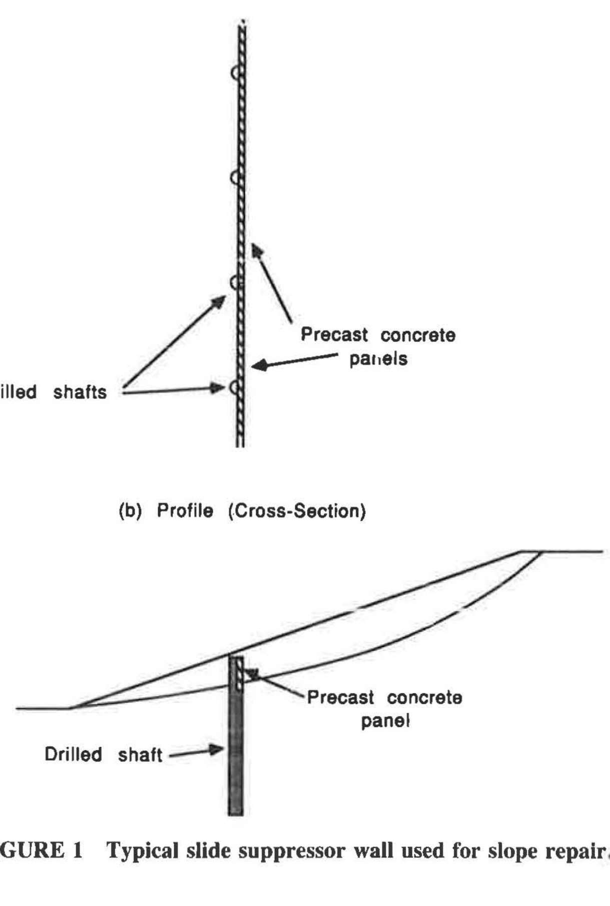

FIGURE 1 Typical slide suppressor wall used for slope repair.

analysis are then used to compute earth pressures for slide suppressor walls.

Shear strengths can be calculated by back-analysis using either a total stress or an effective stress approach. For total stresses the shear strength is expressed as

$$s = c + \sigma \tan\phi \tag{1}$$

where c and ϕ are the cohesion and friction angle, respectively, and σ is the total normal stress on the failure surface.

The shear strength parameters, c and ϕ, can be calculated by back-analysis by knowing (a) the slide geometry and the unit weight of the soil and (b) that the factor of safety is unity (1.0) in a slope that has failed.

Although an infinite number of combinations of c and ϕ theoretically will produce a factor of safety of unity for a slope of a given height and inclination, only one set of values for c and ϕ will also produce a critical shear surface that has the same depth as the observed slide. In general, as the cohesion value increases relative to the friction angle, the depth of slide will increase. Thus, knowing the slope height (H), slope inclination (β), unit weight of soil (γ), and the depth of slide (d), a unique set of values for c and ϕ can be obtained. Any representative definition may be used for the "depth of slide," provided that it is used consistently.

Abrams and Wright (*2*) employed circular shear surfaces, and the depth of slide was defined as the maximum perpendicular distance between the face of the slope and the shear surface, (Figure 2). This measure of the depth of slide is used throughout the following analyses.

When shear strength parameters are calculated by back-analysis using effective stresses, the shear strength is expressed as

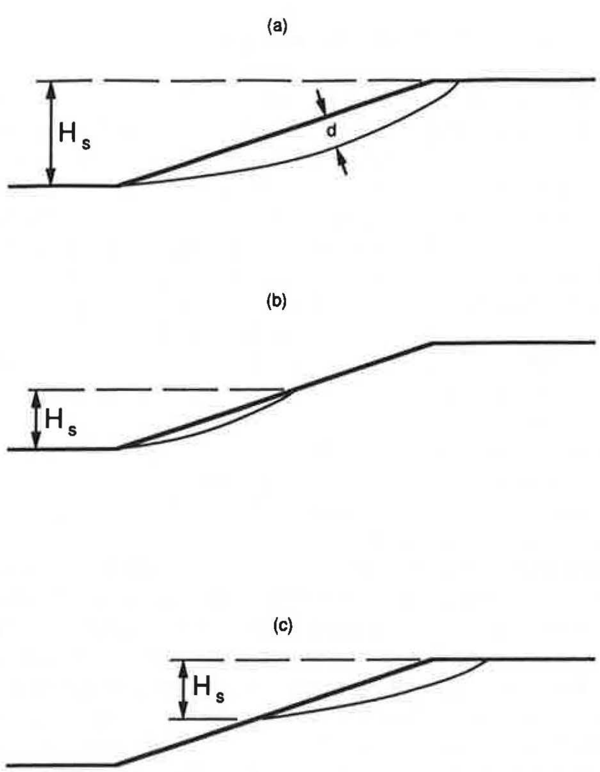

FIGURE 2 Illustration of "depth" and "height" of slide.

$$s = \bar{c} + (\sigma - u) \tan\bar{\phi} \tag{2}$$

where $\bar{c}$ and $\bar{\phi}$ are the cohesion and friction angle, respectively, expressed in terms of effective stresses, and σ and u are the total normal stress and the pore water pressure, respectively, on the failure surface.

To back-calculate effective stress shear strength parameters, the pore water pressure must either be known from measurements or estimated from other information and analyses.

Once shear strength parameters (c and ϕ or $\bar{c}$ and $\bar{\phi}$ are calculated, they can be used to compute the force (P) that would act on a wall extending from the surface of the slope to the shear plane as shown in Figure 3. Different values are calculated for the earth pressures depending on whether the shear strength parameters are expressed using total stresses or effective stresses, and, in the case of effective stresses, on what assumptions are made regarding the pore water pressures.

Abrams and Wright (*2*) studied the differences between earth pressures calculated based on total stresses and effective stresses. For effective stress calculations they assumed several different sets of pore water pressure conditions. In several cases they assumed that the pore water pressures were equal to some constant fraction of the overburden pressure, characterized by values of Bishop and Morgenstern's (*3*) pore pressure coefficient r_u. [The pore pressure coefficient r_u is defined as the ratio of the pore water pressure to the total overburden pressure (i.e., $r_u = u/\gamma z$).] Values for r_u of 0.4 and 0.6 were considered, which represent relatively high values of pore water pressure. Abrams and Wright also considered pore water pressures, which were represented by a relatively high piezometric line in the slope, with at least 80 percent of the soil in the slope located beneath the piezometric line. They found that the differences between the total earth pressures on a wall calculated by effective and total stress procedures were less than 20 percent. The largest differences between earth pressures calculated using total and effective stresses occurred when relatively high values (0.6) were used for r_u. More typical values of pore water pressure produced differences significantly less than 20 percent.

The reason for the relatively small differences in the earth pressures calculated by total and effective stress analyses may be understood by reviewing the effective stress analyses. In the case of effective stress analyses, the highest pore water pressures that are assumed for back-analysis produce the largest values (highest $\bar{c}$ and $\bar{\phi}$) calculated for the shear strength parameters. When these shear strength parameters are used with the corresponding pore water pressures on which they are based, very little difference is found between the total forces on a wall calculated with high pore water pressures and with low pore water pressures. Similarly, little difference is calculated between forces using total stress and any of the effective stress conditions. This observation may only be valid for slopes with a factor of safety of unity, but is applicable to all of those cases of present interest where walls are to be used as remedial measures.

Abrams and Wright (*2*) developed a series of charts for calculating earth pressure forces on slide suppressor walls based on shear strengths calculated by back-analysis of actual slides. They expressed the forces in the form:

$$P = N_P \gamma H_s^2 \tag{3}$$

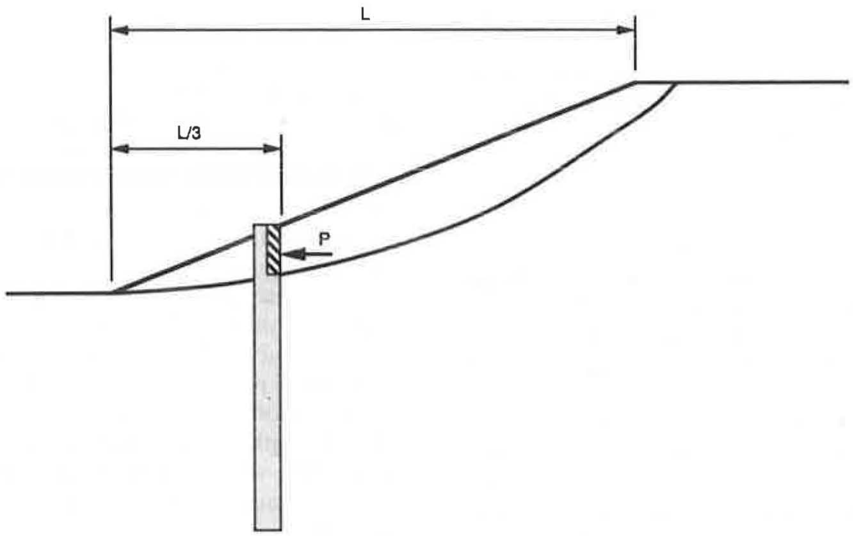

FIGURE 3 Slide suppressor wall and earth pressure force.

where P is the lateral force on the wall, N_P is a dimensionless earth pressure coefficient that depends on the relative depth of the slide (d/H_s), and H_s is the height of the slide. In the case of full-slope failures (Figure 2a) the height of the slide and the height of the slope are the same; however, in the case of partial-slope failures (Figures 2b and 2c), the height of the slide may be less than the slope height. The earth pressure coefficient, N_P, also depends on whether the shear strengths are expressed using effective or total stresses, and in the case of effective stresses, on what assumptions are made concerning the pore water pressures. As discussed earlier, these effects are minor for the present problem. Abrams and Wright plotted charts showing values of N_P versus the relative slide depth (d/H_s) for various slopes, and for both total and effective stresses. A typical chart is shown in Figure 4. This chart was developed using total stresses for a 3:1 slope with the wall located at the lower third point of the slope (Figure 3).

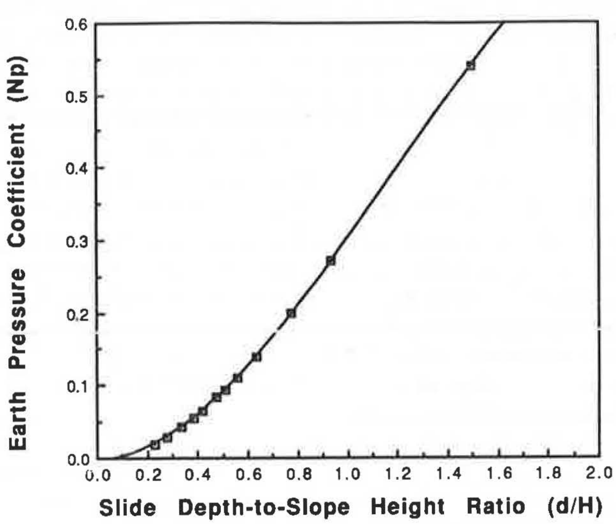

FIGURE 4 Earth pressure coefficients for slide suppressor walls (2).

Procedures based on shear strengths determined by back-analysis to calculate earth pressures should provide as good an estimate of the forces on slide suppressor walls as can possibly be made with existing analysis procedures. However, the procedures can be relatively time-consuming to use. The charts developed by Abrams and Wright considerably simplify computations, but the charts encompass only a relatively narrow range of slope, wall, and slide geometries. For most cases the charts cannot be used. In such cases shear strengths must first be calculated by back-analysis and then earth pressures must be calculated.

EFFECT OF SHAPE OF SHEAR SURFACE

Earth pressures are usually calculated using theories based on an assumed shape for the shear surface and satisfying one or more of the equations of static equilibrium. For conventional retaining walls, the shear surface is usually assumed to be planar. However, for slopes that have failed by sliding, the shear surface is seldom planar. Theoretically, the shear surface is more likely to be circular, or, in cases of nonhomogeneous materials, may be some shape other than circular or a simple plane. Abrams and Wright (*2*) employed circular shear surfaces to calculate the earth pressures on slide suppressor walls using a procedure based on an extension of Spencer's procedure of slices (*4*). The procedure satisfies all requirements of static equilibrium. The procedure should be more correct than the classical earth pressure theories (which are restricted to a planar shear surface and do not explicitly satisfy moment equilibrium).

Approaches based on Spencer's procedure of slices are fundamentally more correct than simpler procedures to calculate earth pressures on walls embedded in slopes. However, the procedures are relatively cumbersome to use and require a computer program to implement. A computer program was developed and used by Abrams and Wright to perform the earth pressure calculations; however, this program has not been maintained. To the author's knowledge, no computer program is currently generally available for computing earth pressures employing Spencer's procedure of slices. For most practical cases it is desirable to use simpler procedures to calculate the earth pressures, especially when conditions are outside the range of the charts developed by Abrams and Wright.

To examine the feasibility of using simpler approaches to calculate earth pressures on slide suppressor walls, forces were calculated using two procedures: (a) Spencer's procedure with circular shear surfaces, and (b) the classical "trial wedge" earth pressure theory employing planar shear surfaces. Calculations were performed for seven slides for which data are summarized in Table 1. Five of the seven slides (1, 2, 3, 4, and 7) selected for study occurred in cut slopes; the remaining two slides (5 and 6) occurred in fill slopes. Measured and/or estimated dimensions of the slides are shown in Table 1. In all cases the total unit weight of soil was assumed to be 125 pcf.

In Texas, experience with shallow slides in embankments, as well as with many cut slopes, suggests that the pore water pressures in the slopes are negligible (Stauffer and Wright (*5*)). Many of the soils involved are highly desiccated and failures have occurred during wet periods due to surface water infiltration and soil expansion. However, there appears to be little evidence of significant positive pore water pressures. Accordingly, calculations were performed for the seven slides summarized in Table 1, assuming that the pore water pressures were zero. In this case, there was no difference between effective stresses and total stresses.

Calculations were performed for the forces on slide suppressor walls located at a point one-third of the distance from the toe of the slope to the crest, as shown in Figure 3. The walls were assumed to extend vertically from the surface of the slope to the slide surface. Earth pressures based on Spencer's procedure were calculated using the charts developed by Abrams and Wright. For the trial wedge procedure the shear strength parameters were calculated using the known slide geometry and Spencer's procedure of slope stability analysis. This is the same procedure used by Abrams and Wright to calculate shear strengths and, accordingly, the shear strength parameters are identical. The calculated shear strength parameters (c and ϕ) are included in Table 1.

The earth pressure forces calculated using Spencer's procedure and the trial wedge procedure are summarized in Table 2. In all but one case, the earth pressures based on Spencer's procedure were slightly larger, probably due to the fact that the forces are based on a more critical shear surface (circular versus planar). In the one case where Spencer's procedure yielded a lower force, the difference is believed to be due to the difficulty in reading values precisely from Abrams and Wright's charts. In all cases, the differences between the two sets of earth pressures shown in Table 2 are considered insignificant. Accordingly, it appears that planar shear surfaces can be used for computations of earth pressures on slide suppressor walls.

INFLUENCE OF COHESION VALUE

The cohesion values, which were calculated and summarized in Table 1 for the seven slides, are all relatively small. This is typical of shallow slides like those shown in Table 1 where the slide depth-to-height ratio (d/H_s) is approximately one-third or smaller. This suggests that shear strengths could be calculated by assuming zero cohesion and by calculating the friction angle corresponding to a factor of safety of unity. In such cases, the friction angle is simply equal to the slope angle (i.e., $\phi = \beta$).

Although not shown directly in Table 2, the previous calculations also revealed that the assumed distance that the backfill extended behind the wall had a relatively minor effect on the earth pressure force and, thus, the distance may be unimportant. To illustrate the effect of the extent of the backfill, calculations were performed using the two sets of slope and soil properties shown in Table 3. The distance between the wall and the horizontal ground surface (w) was varied from a value equal to the height of the wall to values much

TABLE 1 INFORMATION FOR SLIDES USED IN STUDIES

Slide No.	Location	Slope Ratio	Height of Slide (ft)	Depth of Slide (ft)	Cohesion (psf)	Friction Angle (degs)
1	US 75 at Lamberth Road Northeast Quadrant	2:1	22	4.5	17	19
2	US 82 and FM 131 Southeast Quadrant	3:1	14	5	18	51
3	US 82 and FM 131 Southwest Quadrant	3:1	13	3	5	17
4	US 75 North and FM 691 West Side	3:1	6	2	6	15
5	South US 82 @ M & P Railroad	3:1	24	4.8	6	17
6	US 271 @ Stillhouse Road	2.5:1	13	2	2.3	21
7	US 271 @ B & N Railroad	3:1	14	2.5	2.5	17

TABLE 2 COMPARISON OF EARTH PRESSURE FORCES CALCULATED USING TRIAL WEDGE AND SPENCER'S PROCEDURES

Slide No.	Force - Trial Wedge (lbs)	Forces - Spencer's Procedure (lbs)	Difference[1] (percent)
1 (r_u = -0.2)	785	941	- 17
1 (r_u = 0)	824	941	- 12
2	1074	1159	- 7
3	409	456	- 10
4	155	184	- 16
5	1023	1123	- 9
6	197	211	- 7
7	295	254	16

[1]Percent Difference $= \frac{P_{Trial\ Wedge} - P_{Spencer's}}{P_{Spencer's}} \times 100\%$

TABLE 3 PARAMETERS USED IN STUDIES TO ILLUSTRATE EFFECT OF THE EXTENT OF THE BACKFILL SLOPE

Parameter	Case I	Case II
Wall height, h	10 ft.	5 ft.
Slope angle, β	20°	18.4° (cot β = 3.0)
Unit weight of soil, γ	125 pcf	125 pcf
Cohesion, c	0	10 psf
Friction angle, f	20°	15°

greater than the height of the wall (Figure 5). The earth pressure forces for the two sets of parameters are plotted versus the extent of the backfill in Figure 6. For illustrative purposes the distance, w, has been normalized by dividing it by the height of the wall, h. For both cases the extent of the backfill slope has only a moderate influence on the forces and is insignificant when the backfill extends behind the wall a distance equal to more than five times the wall height.

The above observations indicate that the earth pressure forces could be calculated based on the assumption of a just-stable, cohesionless backfill, extending an infinite distance behind the wall, and using a planar shear surface. Earth pressure forces calculated by this simplified procedure are compared in Table 4 with those calculated employing Spencer's procedure and the shear strength parameters (c and ϕ) summarized in Table 1. Earth pressures by the simplified procedure were calculated for a planar shear surface using both Coulomb and Rankine classical earth pressure theories. For the Coulomb theory the earth pressure force is assumed to act horizontally on the wall; for the Rankine theory the earth pressure force is assumed to act parallel to the slope. (Assumption of an earth pressure force acting parallel to the ground surface in the Coulomb theory will produce results identical to those by the Rankine theory). These two assumptions for the inclination of the resultant earth pressure force should bracket the probable inclinations of the earth pressure force. The backfill slope was assumed to be infinite (i.e., the backfill extended an infinite distance behind the wall with no horizontal ground surface). The results of the calculations summarized in Table 4 show that the differences between the earth pressures computed by the rigorous and simplified approaches are usually no larger than 12 percent and could be considered negligible for practical purposes. Abrams and Wright's charts were used to perform the calculations by the rigorous procedure. For the one case where larger differences are shown

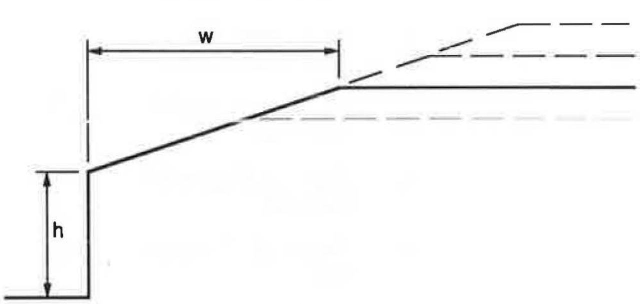

FIGURE 5 Illustration of extent of backfill varied for parametric study.

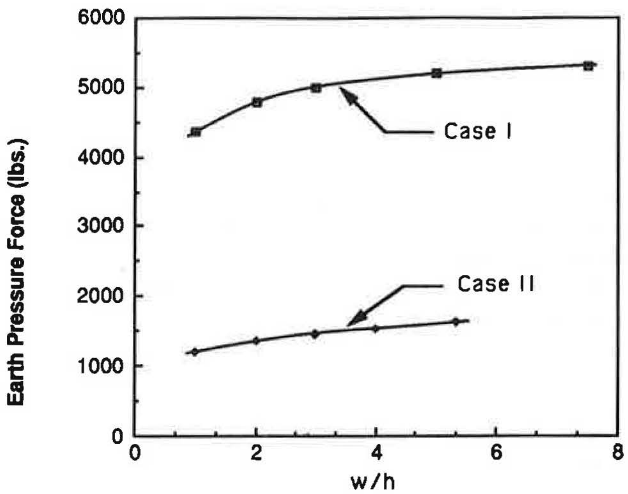

FIGURE 6 Variation in earth pressure force with extent of backfill.

(Slide 7), the differences are believed to be due to difficulties encountered with accurately picking values of the coefficient N_P from Abrams and Wright's charts. Selection of precise values from the charts was difficult for very small slide depth-to-height ratios.

FURTHER SIMPLIFICATION OF PROCEDURES

Examination of the earth pressures shown in Table 4 suggested that even further simplification of the procedures is possible. Active earth pressure coefficients, K_A, were calculated for a cohesionless material with a backfill sloping at the same angle as the angle of internal friction for the soil. The earth pressure coefficients calculated in this manner correspond to earth pressures calculated using the simplified procedures described in the previous section. The coefficients were calculated using the expression

$$P = \frac{1}{2} K_A \gamma h^2 \qquad (4)$$

where P is the earth pressure force calculated by the simplified procedures. The earth pressure coefficients were calculated for both Rankine and Coulomb earth pressure theories. In the case of the Coulomb theory, the earth pressures were assumed to act in the horizontal direction. The earth pressure coefficients are plotted in Figure 7.

The earth pressure coefficients in Figure 7 show that for slopes 2:1 or flatter (slope angle less than 26.5 degrees) the earth pressure coefficient is at least 0.8 and in many cases 0.9 or larger. Thus, the earth pressures are within 20 percent of what they would be if the wall were assumed to be backfilled with a fluid having the same unit weight as the soil. The differences between the pressures calculated by earth pressure theories and those for an equivalent fluid would be expected to be even smaller if curved, rather than planar, shear surfaces had been assumed. Consequently the differences are minor and for design of slide suppressor walls in slopes which have failed or are barely stable, the backfill can be assumed to act as a fluid.

TABLE 4 COMPARISON OF EARTH PRESSURE FORCES CALCULATED USING RIGOROUS PROCEDURE AND TRIAL WEDGE PROCEDURE ASSUMING JUST-STABLE COHESIONLESS BACKFILL SLOPE

	Rigorous	Coulomb Theory		Rankine Theory	
Slide No.	Procedure	Force	Difference[1]	Force	Difference[2]
	(lbs)	(lbs)	(%)	(lbs)	(%)
1	941	841	-11	940	≈ 0
2	1159	1089	- 6	1148	- 1
3	456	410	-10	432	- 5
4	184	163	-12	171	- 7
5	1123	1040	- 7	1096	- 2
6	211	195	- 8	209	- 1
7	254	298	17	314	23

[1] Percent Difference $= \dfrac{P_{Coulomb} - P_{Rigorous}}{P_{Rigorous}} \times 100\%$

[2] Percent Difference $= \dfrac{P_{Rankine} - P_{Rigorous}}{P_{Rigorous}} \times 100\%$

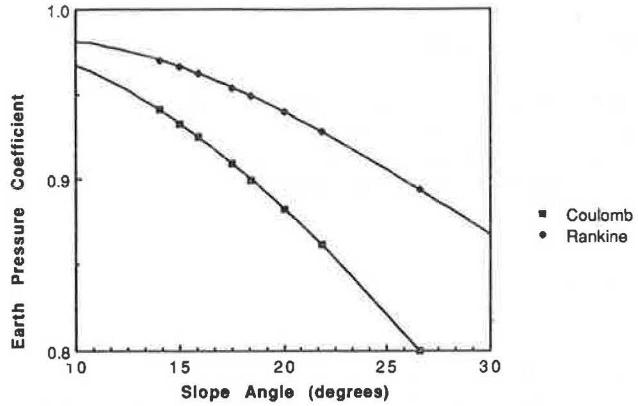

FIGURE 7 Earth pressure coefficients for just-stable cohesionless backfill.

SUMMARY AND RECOMMENDATIONS

Design of slide suppressor walls to be installed in slopes that have experienced shallow slides can be based on shear strength parameters calculated by back-analysis of the slide. Results of this study show that for slide depth-to-height ratios (d/H_s) of one-third or less the shear strengths can be calculated assuming that the backfill is cohesionless. In the case of a just-stable slope and cohesionless backfill the angle of internal friction, ϕ, is equal to the slope angle, β.

The studies also show that for just-stable backfills in cohesionless materials, the earth pressure coefficient for most of the slopes of interest (2:1 or flatter) will be within 20 percent, and often 10 percent, of unity, indicating nearly hydrostatic stresses. Accordingly, for design of walls in marginally stable slopes, where the slide depth and wall height do not exceed one-third of the height of the slide, an earth pressure coefficient of unity can be assumed. Thus, the earth pressures for walls embedded in the slope can be computed from

$$P = \frac{1}{2}\gamma h^2 \tag{5}$$

where h represents the wall height, assuming that the wall extends from the ground surface downward. If the top of the wall is below the ground surface, h should represent the depth from the ground surface to the bottom of the wall. The expression given by Equation 5 should be valid for walls embedded up to one-third the height of the slide ($h \leq H_s/3$). This range in depths (0 to $H_s/3$) covers a large number of the slides in highway cuts and embankments in Texas.

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