

# An investigation to arching effect on reinforced slopes with vertical reinforcement

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**ABSTRACT:** Nearly a decade has passed since the technique of reinforcing slopes with vertical geosynthetics was introduced. Through laboratory investigations, arching has been observed and reported, and through a number studies, carried out on this subject, it was declared that taking the arching phenomenon into account increases the safety factor against sliding to some extent. The achievement of this paper is to study and analyze the arching phenomenon in reinforced slopes with vertical geosynthetics, in both vertical and horizontal directions, considering the current theories about arching. The safety factor is computed by using the limit equilibrium method and taking the following factors into account: the uniform surcharge effects on ground surface, pore water pressure and the horizontal pseudo-static force equivalent to earthquake. The optimum configuration of this kind of reinforced soil structures can be achieved by simultaneous control of the size of the failed wedge and the amount of the safety factor.

## 1 INTRODUCTION

The issue of reinforced soil has been considered for centuries because of its simple principles. Beside this advantage, its cost-effectiveness and easy performance has introduced reinforced soil as a useful technique in civil engineering applications. Reinforcing soils with vertical geosynthetics is one of the methods, which has been brought up during the last decade. Figure 1 shows a general view of a vertically reinforced soil structure. The idea of using this method was first introduced through two papers by Barker & Wood (1989), who showed the effect of vertical elements of geosynthetics or grid elements, cross placed inside the trenches, on the safety factor with a simple analytical method. Since then some other empirical and laboratory investigations have been carried out at Manchester University (Jackson, 1998). Davari (2000) studied, to some extent, the arching effect on reinforcing elements by developing an analytical solution based on the limit equilibrium method.

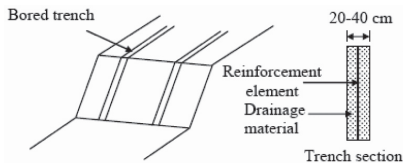


Figure 1. Reinforced slope with vertical geosynthetics.

## 2 ARCHING PHENOMENON AND PREVIOUS STUDIES

Once the support of a soil body fails, by any cause, the part of the soil mass that is nearby the support moves outward against the adjacent soil mass. The mobilization of the shearing strength in the contact zone fails and the stationary portion causes the body to resist against the deformation of the sliding area, so that the pressure on the failed support decreases and increases on the adjacent stationary portion. This type of transferring the stress from a failing mass to the adjacent stable and stationary masses is called "effect of arching". Arching theories are usually divided into two groups; the shearing planes theory, Terzaghi (1943) and elastic method, Finn (1963). Using Terzaghi's shearing planes theory, Wang & Yen (1974) studied this phenomenon on infinite slopes, and included an investigation on transferring the stress through two high-diameter concrete piles, stabilizing the slopes against probable slides. Handy (1985) showed that the shape of the arched soil is like a catenary that is determined on the basis of the principal stresses trajectories (Fig. 4b). According to his studies, he suggested the lateral earth pressure coefficient:

$$K = 1.06 (\cos^2 \theta + K_a \sin^2 \theta) \quad (1)$$

in which  $K_a$  is the active earth pressure coefficient and  $\theta = 45^\circ + \phi/2$ .

Laboratory studies of reinforced slopes with vertical geosynthetics reported that arching occurs in the spans between reinforcing elements (Jackson, 1998; Rose, 1990). Using the method of Wang & Yen (1974) and adapting it with the geometry of reinforced slopes with vertical geosynthetics, Davari (2000) studied arching in reinforced slope spans and indicated its effect on the safety factor against sliding. In this two-dimensional analysis the failure surface was considered as a one-plane wedge and the soil was assumed to be in dry condition and completely granular.

Tasi & Chang (1996) studied the stability of a slurry wall in a three dimensional analysis, using arching and limit equilibrium concepts. At first they studied stress and strain fields. Using Handy's results, they determined the exact shape of the 3-D failure surface on the trench walls, and then used limit equilibrium concept to calculate the safety factor for the sliding wedge.

In the present paper Tasi & Chang's concepts have been used and adapted with the geometry and assumptions of the vertically reinforced slope, in order to study the arching phenomenon in this structure.

### 3 3-D SHELL-SHAPED SLIDING SURFACE

It would be considerable to determine a failure surface as a three-dimensional shell, because in all existing methods of analyzing slopes, the shape of the sliding surface has been hypothetical.

In this proposed method, the external forces equilibrium on the sliding surface is estimated and to find the shape of the failure surface, the following two assumptions should be considered: (1) The horizontal displacement of the soil mass is confined by a horizontal compressive arch similar to an inclined half-silo, supported by reinforcement elements on its sides. (2) The displacement of the inclined half-silo, in the dip direction of the soil mass, is as extensive half-arch (a catenary hung on the silo wall, for instance), Figure 4b. These assumptions are based on the virtual stress and strain conditions of this case. Therefore the inclined half-silo separates the stationary portion of the mass that has a potential to slide, in the direction parallel to the dip, and forms a rough wall between the two parts, which acts similar to the silo wall. On one hand the displacement in the dip direction is confined to the slope toe (i.e. the points located on the slope toe) have no displacement in the slope's dip direction.

### 4 FORMULATION

As Figure 2 shows, in the Mohr's circle, an arching boundary is obtained on a horizontally spread plane (the X-Y plane). In Figure 3b, circles 1 and 2 express

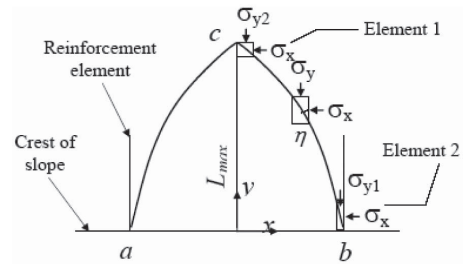


Figure 2. Horizontal arch formed on the ground.

the failure stress condition in the center of the elements 1 and 2 that are presented in Figure 2.

Two additional circles can be drawn between these two existing circles, which represent the primary stress condition, when no strain has occurred. Since no strain will occur in the X direction,  $\sigma_x$  on the X-Y plane is assumed to be constant. In accordance to Figure 3b, the incline angle of the failure shearing stress plane ( $\eta$ ) is determined. Therefore:

$$\sigma_x = K_x(\gamma z + q)2C\sqrt{K_x} \quad (2)$$

$$\sigma_y = K_y(\gamma z + q)2C\sqrt{K_y} \quad (3)$$

$$r = \left( \frac{\sigma_x + \sigma_y}{2} \right) \sin \phi + C \cos \phi \quad (4)$$

$$\cos \theta = \frac{\sigma_x - \sigma_y}{2r} \quad (5)$$

$$\eta = \frac{1}{2} (90^\circ + \phi - \theta) \quad (6)$$

where  $K_x, K_y$  are coefficients of lateral earth pressures in the X and Y directions.  $C$  and  $\phi$  are the soil strength parameters,  $\gamma$  is the soil density and  $q$  is the uniform surcharge intensity on the crest of the slope. If no strain is assumed in the X direction, the coefficient of lateral earth pressure will be considered as the coefficient of earth pressure at rest ( $K_0$ ). When  $\sigma_x$  is constant,  $\sigma_y$  changes due to the change of  $K_y$ , as a result the angle  $\eta$  will change, which determines the three-pointed arch in Figure 2. This is the result of arching in the horizontal direction. If it is assumed that the arch on the X-Y plane, is supported by the reinforcement elements at the points a and b (Figure 2) the curvature of the arch increases from the ends to the center (point c). According to the principles of the lateral earth pressure, it is obvious that the coefficient of the lateral earth pressure ( $K_y$ ) decreases from the ends to the center of the arch. Now it is assumed that the coefficient decreases linearly from  $K_0$  (the coefficient of the lateral earth pressure at rest) at the points a and b, to  $K_a$  (the coefficient of active lateral earth pressure) at the point c. This arch in the Z direction (the direction of the slope hill)

makes a rough wall similar to the inclined half-silo (Figure 4a). The curvature of each catenary equals to:

$$\frac{dZ}{dy} = \sin h \left( \frac{y}{C_{yz}} \right) \quad (7)$$

where:

$$C_{yz} = - \frac{Y_w \sin \beta}{\sin h^{-1} [\tan (45^\circ - \phi/2)]} \quad (8)$$

in which  $y_w$  is the  $Y$  component of the rough wall and  $\beta$  is the angle between the slope and horizon.

According to the theory of limit analysis, the soil will slide on a slip plane (or a shear surface) and as it is assumed, the adjacent mass to the wedge will stay stable. To obtain the sliding surface, where the Mohr's failure criterion can be applied. Noting the point in the soil elements, the angle between the sliding surface and the minor principle stress direction ( $\sigma_3$ ) equals to  $45^\circ + \phi/2$ , the path of the sliding surface, on any planes that are parallel to the  $y$ - $Z$  plane, will be determined as shown in Figure 4b. On the  $X$ - $Z$  plane, arching happens due to the displacement in the dip direction and the reinforcement elements existing as lateral supports.

Using equations (7) and (8), the arch coordinates on the  $X$ - $Z$  plane will be obtained:

$$Z = \frac{H}{\sin \beta} - C_{xz} \left[ \cosh \left( \frac{X}{C_{xz}} \right) - 1 \right] \quad (9)$$

$$C_{xz} = B/2 \{ \sinh^{-1} [\tan (45^\circ - \phi/2)] \} \quad (10)$$

Repeating the above-described process, on any plane parallel to the  $Y$ - $Z$  plane, the three-dimensional location of the slope failure shell can be determined. The result of the process is shown in Figure 4a.

## 5 COMPUTING THE SAFETY FACTOR

Considering the sliding surface as what is illustrated in Figure 4a, the gravity force effect, uniform surcharge, pore water pressure, and the pseudo-statistical force equivalent to earthquake, the force equilibrium in both vertical and horizontal directions can be satisfied. In order to make the mathematical operations and the computer programming easier, the wedge is divided into several soil columns (Figure 4a) and the forces are calculated on the lower base. The total forces are obtained by adding up partial forces. To determine the soil column weight, the equation of the vertical stress in arching condition is applied. In this equation (11) the effect of the uniformly distributed surcharge is considered:

$$\sigma'_v = \frac{B\gamma' - 2Cf_b}{2Kf_b \tan \phi} + \left( q - \frac{B\gamma' - 2Cf_b}{2Kf_b \tan \phi} \right) \exp \left( -2Kf_b \frac{z}{B} \tan \phi \right) \quad (11)$$

in above equation,  $B$  is the distance between reinforcement elements on the slope,  $q$  the uniform surcharge on the slope,  $\gamma$  effective unit weight of the soil, and  $K$  is the coefficient of lateral earth pressure, considered between at rest and active states.  $f_b$  is the uniformity coefficient and in fact the resemblance of the interaction between the geosynthetics and the soil, which varies between 0 and 1.

To determine the effective unit weight of the soil, pore water pressure ratio is needed, which is expressed as the ratio of the under water soil mass volume to twice of the total volume of the sliding mass [Davari, 2000].

The computer program, ArchSlope, based on the described formulation method, has been developed to obtain the shape of the failure wedge and to compute the safety factor against sliding.

## 6 DISCUSSION ON VALIDITY OF THE PROPOSED METHOD

To investigate the validity of the proposed method, results of the above analysis, on laboratory model samples, given by Jackson's centrifuge tests, and results of some of his tests are presented in Table 1. The numbers, expressing the dimensions of the model samples, in Table 1, are actually the dimensions of the virtual sample, corresponding to each model sample. The comparison of the safety factors reasonably corresponds to real condition Results of the proposed method are compared with Davari's (2000) solution in Figure 5, expressing that taking the arching phenomenon into account increases the safety factor, but since in his analysis of arching, Davari (2000) has considered the failure wedge bigger

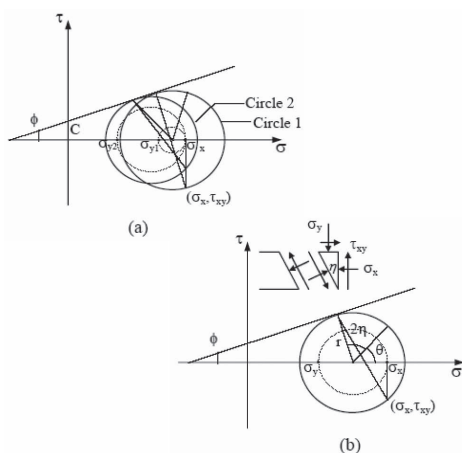


Figure 3. Stress state for elements 1 and 2 on the horizontal arch: (a) Mohr's circles for elements 1 and 2 (b) Direction of failure surface in horizon.

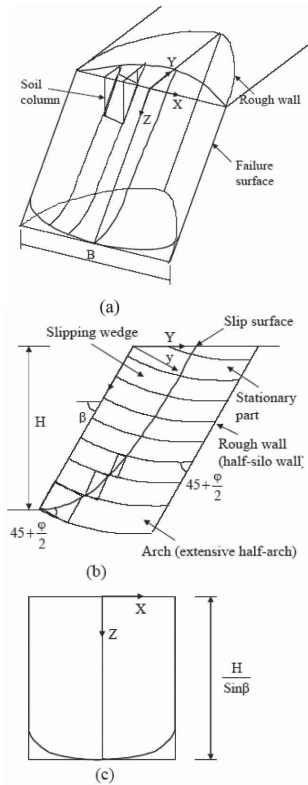


Figure 4. Determination of failure shell-shaped surface: (a) Rough wall boundary (b) extensive arches and slip surface on y-Z plane (c) Slip edges on hillside of slope.

than reality the answers for the safety factor have been overestimated.

Table 1. Comparison between results of proposed method and centrifuge tests (Jackson, 1998).

| $\beta$<br>° | H<br>m | $\gamma$<br>kN/m <sup>2</sup> | $\phi$<br>° | C<br>kPa | B<br>m | $f_b$<br>- | FS<br>(1) | FS<br>(2) |
|--------------|--------|-------------------------------|-------------|----------|--------|------------|-----------|-----------|
| 60           | 12.9   | 19.8                          | 0           | 41       | 11.2   | 0.8        | 1.41      | 1.44      |
| 60           | 9.4    | 19.8                          | 0           | 33       | 5.0    | 0.8        | 1.56      | 1.70      |
| 60           | 6.3    | 18.8                          | 0           | 14       | 2.4    | 0.8        | 1.41      | 1.45      |

(1) Centrifuge (2) Current study

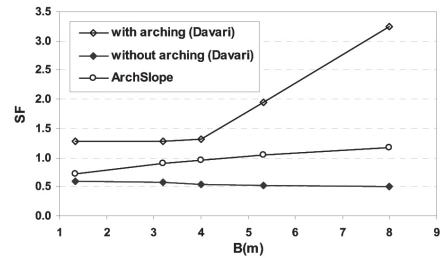


Figure 5. Comparison between results of presented solution and Davari's solutions (2000).

## 7 SUMMARY AND CONCLUSION

- In the present study, an analyzing method is proposed to estimate the safety factor against sliding in the reinforced slopes with vertical geosynthetics, using the limit equilibrium concept and existing theories about arching in both vertical and horizontal directions.
- The comparison between the proposed three-dimensional analyzing method and the laboratory results has confirmed the validity and power of the suggested solution.

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