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Analysis of slopes reinforced with bamboo dowels

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ABSTRACT: Many slopes in the vicinity of the city of Rio de Janeiro and other localities in Brazil develop large land slides during the rainy seasons, many of them with catastrophic results in terms of human and property losses. A possible mechanism of failure is the loss of suction in the unsaturated residual soils which form the surficial layer of such slopes. To avert these failures the use of bamboo dowels have been proposed and indeed the paper presented is a first step in the envisaged investigation.
It is shown that the equation governing the mode of deformation of a dowel is in the form;

$$\frac{d}{dz}\left[\beta(z)\frac{d^4u}{dz^4} + u\right] + \lambda(z)\frac{d^3u}{dz^3} = \lambda(z)\sin\alpha$$

where $\beta(z)$ and $\lambda(z)$ are functions of the rigidity of the dowels, the shear modulus of the wet and dry soil, the spacing between dowels and their diameter. The parameter $\gamma(z)$ is a function of the unit weight of the dry and wet soil and the respective shear moduli. The angle α represents the inclination of the slope.
The governing equation is solved numerically using a microcomputer. The numerical scheme used in the analysis is described in detail and the results are presented in the form of graphs showing the distribution of the bending moments and the shearing forces in the dowels.

1 ANALYSIS

As mentioned in the abstract the failure of the slopes is contributed to a loss of suction in the active zone of the ground. Let the depth of this zone be denoted by z_a and for convenience measure the z axis from the surface of the slope as shown in Fig. (1). During the dry seasons the surficial layer for which $z < z_a$ is hard with a unit weight of γ_d and shear modulus of G_d both of which are likely to be constants but in general are functions of depth z. After prolonged rainfall the unit weight of the soil changes to $\gamma_r = \gamma_r(z)$ and its shear modulus to $G_r(z)$. It is fairly obvious that $\gamma_r > \gamma_d$ and that $G_r < G_d$ caused by saturation of the soil and a loss of rigidity due to the reduction in the suction in the soil. These changes bring about a downhill movement of the surficial layer which, if not checked, may lead to catastrophic results. A possible preventive method is, of course, the use of dowels installed to depth well below the active zone.

Let L represent the lengh of a dowel with a flexural rigidity equal to EI and an effective diameter d. Then the equilibrium of the dowel requires that

$$EI\frac{d^4u_b}{dz^4} = p(z).d \qquad (1)$$

where p(z) is the interaction pressure given by;

$$p(z) = (u_s - u_b)k(z) \qquad (2)$$

k(z) being the modulus of lateral reaction. Combining equation (1) and (2) results in;

$$\frac{EI}{kd}\cdot\frac{d^4u_b}{dz^4} = u_s - u_b \qquad (3)$$

where u_s is the lateral displacement of the soil and u_b that of the bamboo dowel.

Next consider the equilibrium of a block of soil of depth z supported by a typical dowel and let the area of this block be denoted by a. Note that if the dowels are arranged in a square pattern then $a = b^2$ where b is the distance between the dowels. If the dowels are arranged in a triangular pattern then $a = b\,.3^{1/2}/2$. Assuming the average shear at depth z to be τ_r then it is clear that;

$$\gamma_r a z \sin\alpha - d \,. \int_0^z p\,dz = \tau_r a$$

or

$$\tau_r = \gamma_r z \sin\alpha - \frac{d}{a}\int_0^z k(u_s - u_b) \qquad (4)$$

During dry periods the average shear stress is given by;

$$\tau_d = \gamma_d z \sin\alpha \qquad (5)$$

where the average shear stress under dry conditions is given by τ_d. Therefore the shearing strain caused by the reduction of soil suction is given by;

$$\frac{du_s}{dz} = \frac{\gamma_r z \sin\alpha}{G_r(z)} - \frac{d}{G_r(z)a}\int_0^z k \,. (u_s - u_b)\,dz - \frac{\gamma_d z \sin\alpha}{G_d(z)} \qquad (6)$$

which upon substitution for $k(u_s - u_b) = (EI/d)(d^4u_b/dz^4)$ reduces to

$$\frac{du_s}{dz} = \left[\frac{\gamma_r}{G_r(z)} - \frac{\gamma_d}{G_d(z)}\right] z \sin\alpha - \frac{EI}{G_r(z)a}\int_0^z \frac{d^4u_b}{dz^4}\,dz \qquad (7)$$

Integration of the second term on the right hand side of Eq.(7) yields;

$$\int_0^z \frac{d^4u_b}{dz^4}\,dz = \frac{d^3u_b}{dz^3} - \frac{d^3u_b(0)}{dz^3} = \frac{d^3u_b}{dz^3} \qquad (8)$$

since $d\,u_b(0)/dz^3 = 0$ there being no shearing force at dowel at z=0; the surface of the slope. Thus Eq.(7) may be rewritten as

$$\frac{du_s}{dz} = \gamma z \sin\alpha - \frac{EI}{aG_r(z)}\frac{d^3u_b}{dz^3} \qquad (9)$$

where $\gamma = \gamma_r/G_r(z) - \gamma_d/G_d(z) = \gamma(z)$

Let the factor EI/kd be denoted by $\beta(z)$ then from Eq.(2) it may be concluded that;

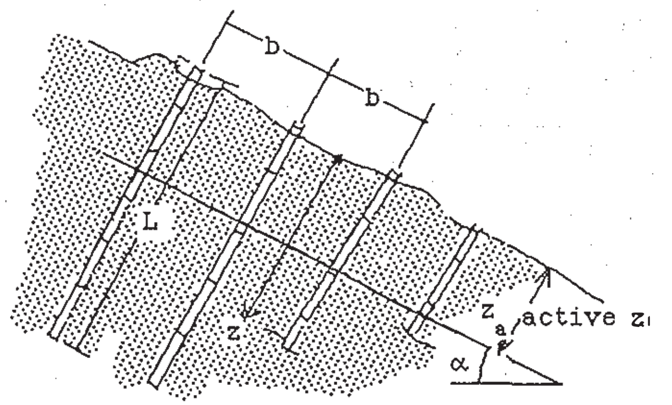

Fig.(1) - Reinforced Slope.

$$\frac{du_s}{dz} = \frac{d}{dz}\left[\beta\frac{d^4u_b}{dz^4} + u_b\right] \qquad (10)$$

Combining Eqs.(9) and (10) results in the governing equation of the problem viz:

$$\frac{d}{dz}\left[\beta(z)\frac{d^4u}{dz^4} + u\right] + \lambda(z)\frac{d^3u}{dz^3} =$$

$$= \gamma(z) z \sin\alpha \qquad (11)$$

where, for convenience the subscript b has been dropped and the factor EI/aG_r has been represented by the variable $\lambda(z)$. For numerical evaluations it is easier to use a new spacial variable ζ where $\zeta = L - z$, L being the length of the dowel as shown in Fig.(1). With this new variable Eq. (11) reads;

$$\frac{d}{d\zeta}\left[\beta(\zeta)\frac{d^4u}{d\zeta^4} + u\right] + \lambda(\zeta)\frac{d^3u}{d\zeta^3} =$$

$$-\gamma(\zeta)(L-\zeta)\sin\alpha \qquad (12)$$

The order of Eq.(12) may be reduced by one if both sides are integrated with respect to ζ and results in;

$$\beta(\zeta)\frac{d^4u}{d\zeta^4} + \lambda(\zeta)\frac{d^2u}{d\zeta^2} + u =$$

$$= C + R(\zeta) + S(\zeta) \qquad (13)$$

In Eq.(13) the constant C is given by the expression;

$$C = \beta(0)d^4u(0)/d\zeta^4 + u(0)$$

and the variables $R(\zeta)$ and $S(\zeta)$ by the definite integrals

$$R(\zeta) = \int_0^\zeta \frac{d^2u}{d\xi^2}\frac{d\lambda(\xi)}{d\xi}\,d\xi$$

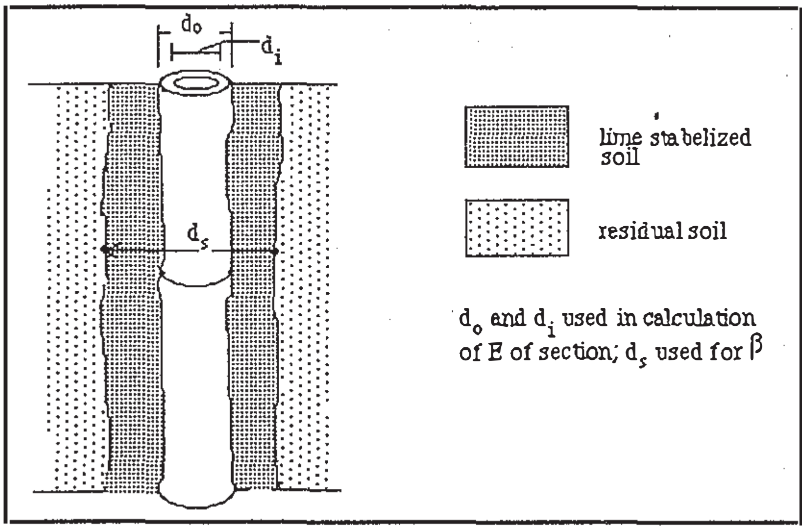

Fig. (2) - Enchased Bamboo Dowel.

and,

$$S(\zeta) = \int_0^{\zeta} \gamma(\xi)(\xi - L)\sin\alpha \, d\xi$$

Eq. (13) must be solved subject to the boundary conditions that the bending moments (BM) and the shearing forces (SF) at the extremeties of the dowel must be zero i.e.

$$BM_{\zeta=0} = 0 \qquad (14,a)$$

$$SF_{\zeta=0} = 0 \qquad (14,b)$$

$$BM_{\zeta=L} = 0 \qquad (14,c)$$

$$SF_{\zeta=L} = 0 \qquad (14,d)$$

In the numerical procedure used by the authors the governing differential equation is solved in terms of U=u-c. Since the value of c is constant the form of the governing equation does not change, neither would the boundary conditions which, when expressed in terms of U, would read as follows:

$$\partial^3 U/\partial\zeta^3 = \partial^2 U/\partial\zeta^2 = 0; \text{ at } \zeta = 0 \qquad (15,a)$$

$$\partial^3 U/\partial\zeta^3 = \partial^2 U/\partial\zeta^2 = 0; \text{ at } \zeta = L \qquad (15,b)$$

After completion of the numerical (finite difference scheme) procedure the value of constant c is evaluated noting that the total forces acting on the dowel must balance out. The nodal values of u are then calculated using the equation $u = U + c$.

Before closing this section it is worth pointing out that the matrix of the coefficients of unknown parameter u is not banded. The definite integral $R(\zeta)$ contains the unknown value of U. and hence its contribution to the matrix must be taken into account in the numerical procedure. Thus if a finite difference scheme is used and the section is divided to ns sections each of length T(=L/ns) a typical subroutine for calculation of the coefficients matrix would read:

```
FOR i = 1 TO ns
FOR j = 1 TO i
if j=i then a(i,j)=(del(j-1)-2*del(j))/T:
 :GOTO 1
a(i,j)=(del(j-1)-2*del(j)+del(j+1))/T
IF j=i THEN a(i,j+1)=del(j+1)/T
NEXT j
a(i,i-2)=a(i,i-2)+beta(i)/T^4
a(i,i-1)=a(i,i-1)-4*beta(i)/T^4+lamda(i)
 /T^2
a(i,i)=a(i,i)+6*beta(i)/T^4-2*lamda(i)
 /T^2+1
a(i,i+1)=a(i,i+1)-4*beta(i)/T^4+lamda(i)
 /T^4
a(i,i+2)=beta(i)/T^4
NEXT i
```

From the above subroutine in which del(i) is the value of $d\lambda/d\zeta$ evaluated at node (i) it may be seen that the matrix of the coefficients of the unknown U(i) is non--symmetric.

2 NUMERICAL EVALUATIONS

Before proceeding with the presentation of the numerical evaluations it should be pointed out that it is necessary to encase the individual dowels in a protective sleeve, see Fig. (2). The material used for protection

max deflexion = 1.93812 Cm., ns= 41
max S.F.=-82.37607 Kg., dowel space= 2
max BM= 7150.338 Kg. Cm
max normal stress= 123.3614 Kg/Cm^2

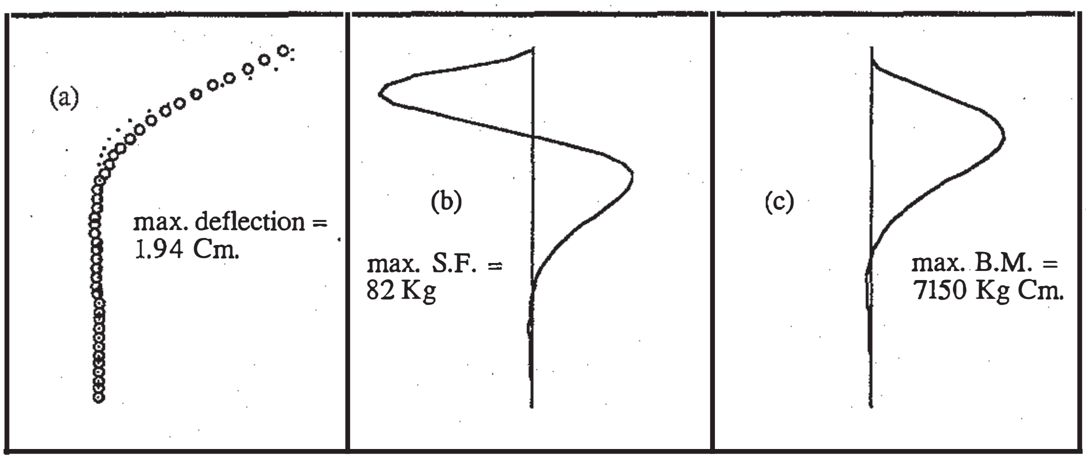

Fig. (3) - Performance of a set of bamboo dowels spaced at 2 meters intervals. (a) Deformed shape of a typical dowel, (b) Shearing force and (c) Bending moment diagrams for the dowel. Angle of slope 30 degrees.

max deflexion = 1.786847 Cm., ns= 41
max S.F.=-63.72635 Kg., dowel space= 1
max BM= 5649.52 Kg. Cm
max normal stress= 97.46849 Kg/Cm^2

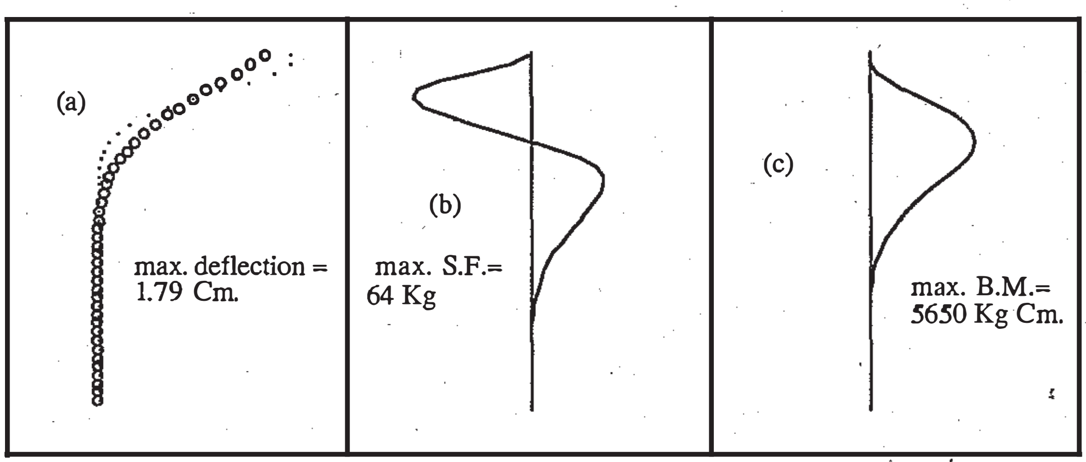

Fig.(4) - Performance of a set of bamboo dowels spaced at 1 meter intervals. (a) Deformed shape of a typical dowel, (b) Shearing force and (c) Bending moment diagrams for the dowel. Angle of slope 30 degrees.

max deflexion = 1.461587 Cm., ns= 41
max S.F.= -32.7416 Kg., dowel space= .5
max BM= 3028.413 Kg. Cm
max normal stress= 52.24777 Kg/Cm^2

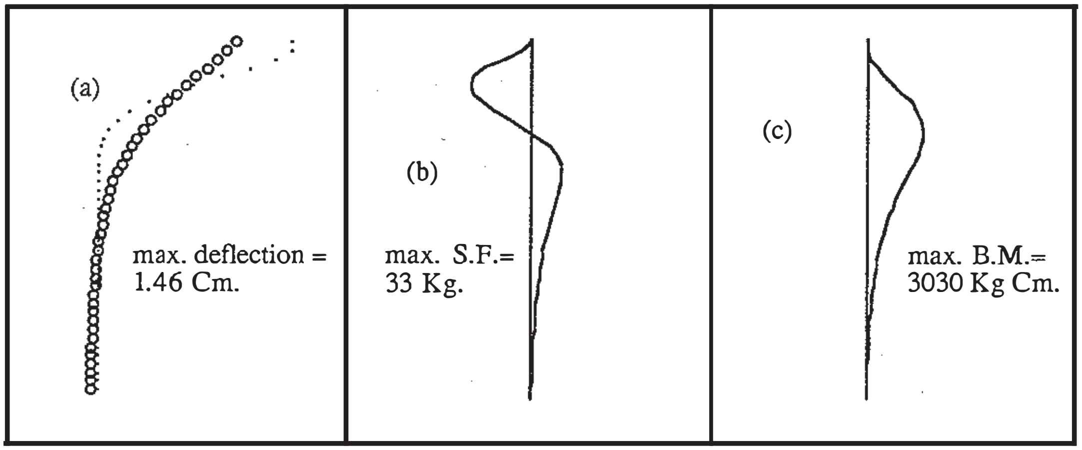

Fig. (5) - Performance of a set of bamboo dowels spaced at .5 meters intervals. (a) Deformed shape of a typical dowel, (b) Shearing force and (c) Bending moment diagrams for the dowel. Angle of slope 30 degrees.

of the dowels could be lime stabilized or portland cement stabilized soil. The former is preferable, however, in view of this low cost. The purpose of the sleeve is two fold. First it fills the space between the dowel and the soil surrounding it and thus prevents the dowel from acting as an unsupported beam, the resistance of which to bending would, of course, be very small. Second it increases the strength of the bamboo dowel in compression by prevention of local buckling. It has two undesirable side effects however. First, and this is particularly important for the lime sleeve, a deterioration of the bamboo may take place due to what is generally referred to as exothermic reaction. Second the presence of sleeve will add to the loads that each individual dowel must carry without effectively adding to its strength. Stated otherwise, since the strength of lime in tension especially is very low it is good practice to neglect the contribution of the sleeve to the second moment of area of the dowel but use its diameter (i.e. the outer diameter of the sleeve) to evaluate the value of β = EI/kd, see Fig. (2). Finally it should be noted that the magnitude of k, the modulus of lateral reaction is dependent, amongst other factors, on the spacing of the dowels. If the dowels are placed too closely to each other then a reduction of k value would result in that must be taken into account in the evaluations. In this paper this reduction is accounted for by the relationship.

$$k(z)_{group} = k(z)*(b-d_s)/b \qquad (16)$$

where k(z) is the modulus of lateral reaction corrected for depth and size (total diameter of the dowel d_s, see Fig. (2)) and b is the spacing of the dowels as defined previously. For a set of dowels spaced at 1 meter intervals the k(z) value of the group is %80 that of a single dowel with an effective diameter of 20Cm.. For the spacings of 2 and 5 meters the corresponding values would be %90 and %60 respectively. Other more elaborate relations may be used in place of Eq. (16) the results, however, are unlikely to be of consequential effects.

The results of some typical evaluations are shown in Figs. (3) to (5) inclusive. The slope to be protected is assumed to be quite steep having an angle of 30 degrees. The bamboo dowels are assumed to have an external diameter of 10 centimeters with a wall thickness of 1 centimeter with a 5Cm. cover of lime stabilized soil. The value of Young's modulus is taken equal to that of concrete $1.6x10^6$ Tons/m^2 (Ghavami and Zielinski, 1988) and the modulus of lateral reaction (for a single dowel) is assumed to vary linearly from 1000T/m^3 at the surface increasing by 100T/m^3 for every meter of depth. The depth of the active zone is taken as 2 meters and other mechanical parameters (such as dry and wet unit weights of the soil and the corresponding shear moduli) are assumed such that they would produce a total downhill creep of about 2 centimeter per year.

When the dowels are spaced at 2 meter intervals the maximum bending moment experienced by the dowel is 7150 Kg Cm. causing a normal stress of 124 Kg/Cm^2 in the fibers of the dowel. The corresponding values for 1 meter spacing and 0.5 meters spacing 5650 Kg Cm. and 3030 Kg Cm. respectively producing, in turn, maximum fiber stresses of 97 Kg/Cm^2 and 52 Kg/Cm^2. All these stress levels are well within the limits of the allowable tensile strength (about 800 Kg/Cm^2) and compressive strength (about 300 Kg/Cm^2) for the bamboo dowel (Ghavami and Zielinski, 1988 and Ghavami and Hombeeck, 1981).

The deformation values are, however, quite large. As may be noted from Fig. (5) even for closely spaced dowels (.5 meters in this case) the presence of dowels has reduced the amount of downhill creep by only about 5 milimeters. This is, of course, because of the relatively low values of E of bamboo and the low value of the second moment of area of the section used in the reinforcement. The downhill creep is, nevertheless, confined to the first rainy season after the instalment of the dowels. The drying process which takes place in the summer would relax the forces taken by the dowels and infact they would tend to move the surficial layer uphill. Subsequent wetting would only restore the stresses in the bamboo to their original values i.e. the values registered at the end of the first rainy season.

3 CONCLUDING REMARKS

From the above evaluations it is concluded that the use of bamboos is indeed a feasible method of preventing downhill movement of slopes and their eventual failure.

The analysis, however, assumes that the slope is undergoing a form of mountain creep caused by a reduction of suction pressure in the soil skeleton during the wet seasons. A second mechanism postulating the existence of a moisture sensitive layer parallel to the slope surface is treated in a companion paper.

4 ACKNOWLEDEMENT

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