Earth Reinforcement, Ochiai, Yasufuku & Omine (eds) © 1996 Balkema, Rotterdam. ISBN 90 5410 833 9

The research about designing method of vertical reinforced slopes

Yang Xueqiang
Hubei Polytechnic University, Wuhan, People's Republic of China
Liu Zude
Wuhan University of Hydraulic and Electric Engineering, People's Republic of China

ABSTRACT:Deformation effect and strength effect of flexible reinforcements and soil-nails are considered, combined with proposed safety factor,the paper gives out a designing methods of vertical reinforced slopes under theory of soil plasticity and limit analysis. The designing method in the paper can also be used in slant reinforced slopes.

1 UPPER BOUND HEIGHT H_u OF VERTICAL COHESIVE SLOPE

Chen[1] had given out the upper bound height H_u of vertical cohesive slope by formula(1) under translational failure mechanism.

$$H_u=\frac{4c}{\rho}tg(\pi/4+\psi/2) \quad (1)$$

Where c and ψ =given cohesion and friction angle, respeetively;ρ =the soil's unit weight.

To account for reinforcement's contribution,it is assumed that:(1).reinforcements are placed at same space along the slope height; (2) reinforcements have enough anchorage length and can not be pulled out from anchorage soil mass when translational failure happens; (3) flexible reinforcements have zero bend stiffness and can carry only tension force; and (4) soil- nail has certain value of bend stiffness,it can carry tension force and shear force and moment at the same time.

2 VERTICAL SLOPE REINFORCED BY FLEXIBLE REINFORCEMENTS

2.1 Deformation effect of flexible reinforcements

In fact, slip surface will be a shear zone and has certain thickness, because the flexible reinforcements can only carry tension force, in order to prevent translational failure most effectively, reinforcements at the slip surface will slowly change its orientation so that at the last the orientation of tension force will be opposite to slip velocity V of soil mass, as shown in Fig.1.

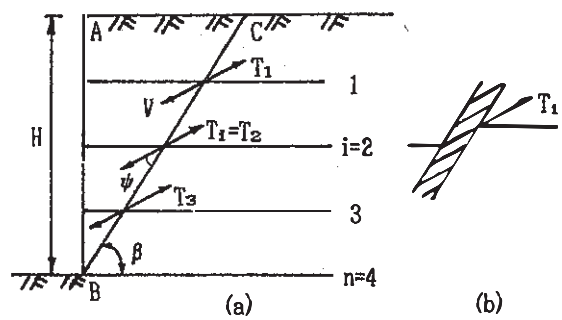


Fig.1.Deformation effect of flexible reinforcements under translational failure

2.2 Strength effect of flexible reinforcements

Based on soil plasticity and limit analysis theory, strength effect of reinforcements can be calculated by use of energy work rate form. As shown in Fig.1, strength effect of reinforcements includes two parts: the first is frictional dissipated energy work rate produced between the reinforcements and its surrounding soil,its value is equal to $\sum_{i=1}^{n}T_iV\cos(\beta-\psi)$, n is number of reinforcements along the slope height; the second is tensile disspated energy work rate produced by reinforcements at the slip surface tc prevent soil mass moving down, its value is equal to $\sum_{i=1}^{n}T_iV$.

2.3 Determination about upper bound horizontal space S_{hmin} of flexible reinforcements

Horizontal space S_h of reinforcements is taken as calculating length of vertical slope, for slip wedge ABC shown in Fig.1, energy work rate done by soil weight is expressed by formula(2).

$$W_{ex}=0.5\rho\, S_h H^2 V ctg\beta\, \sin(\beta-\psi) \qquad (2)$$

If soil satisfies Mohr-coulumb failure criteria and obeys associated flowing rule, then interior dissipated work rate W_{in} is produced by cohesion C along slip surface BC and by reinforcements, it can be expressed as follows.

$$W_{in}=V[1+\cos(\beta-\psi)]\sum_{i=1}^{n} T_i+\frac{CHS_h}{\sin\beta} V\cos\psi \qquad (3)$$

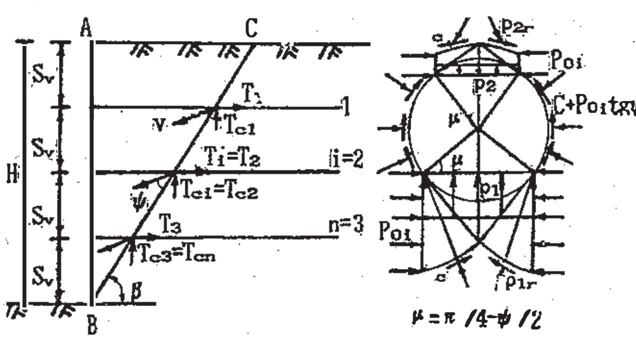
The flexbile reinforcements are placed at the same space along the slope height, so vertical distance from the ith-reinforcement to slope top surface is (i/n) H, and self- weight pressure on the ith reinforcement is $(i/n)\rho$ H, corresponding horizontal length of the reinforcement in the slip soil mass is (n-i)/n $Hctg\beta$. Supposed the width of single reinforcement is Δb, the cohesion and friction angle between the reinforcements and its surrounding soil are $C_b=\alpha_1 C$ and $\psi_b=\alpha_2\psi$, where α_1 and α_2 are some coefficient, and there is no surcharge on the slope top surface, then frictional force or tension force of the ith reinforcement at the slip surface is expressed as follows.

$$T_i=2\frac{i(n-i)}{n^2}\Delta b\rho H^2 tg\psi_b\, ctg\beta+2\frac{n-i}{n}\Delta bHC_b ctg\beta \qquad (4)$$

Putting formula (4) into formula (3) and making Wex equal W_{in}, then formula (5) can be obtained.

$$S_h=\frac{4\Delta b[1+\cos(\beta-\psi)][C_b H\sum_{i=1}^{n}\frac{n-i}{n}+\rho H^2 tg\psi_b\sum_{i=1}^{n}\frac{i(n-i)}{n^2}]}{\rho H^2\sin(\beta-\psi)-2cH\cos\psi\sec\beta} \qquad (5)$$

If given H, then S_h is a function of β , the range of β chosen is bigger than $(\pi/4+\psi/2)$, formula (5) can be calculated by trial and error, angle β corresponding to S_{hmin} is called critical failure angle β_{cr} of vertical reinforced slope, and S_{hmin} is called upper bound horizontal space of reinforcements.



(a) (b)

Fig.2. Strength effect of soil- nails under translational failure and flowing resistance mode of soil-nail

3 VERTICAL SLOPES REINFORCED BY SOIL-NAILS

3.1 Flowing resistance produced by soil-nails

Space of soil-nails is bigger and its diameter is smaller, when translational failure takes place, the soil mass near the planar slip surface BC often flows around the soil-nails. In order to calculate the flowing resistance produced by soil-nails, mode is established as shown in Fig.2. flowing resistance of per unit soil- nail's length is expressed in formulas (7) and (6).

$$\sigma_{bi}=(P_{oi}+c\, ctg\psi)D_g\{\frac{\cos(\pi/4-\psi/2)}{1-\sin\psi}e^{(\pi/2-\psi)tg\psi}-\frac{\sin(\pi/4-\psi/2)}{1+\sin\psi}e^{-(\pi/2+\psi)tg\psi}+tg\psi[\cos(\pi/4-\psi/2)+\sin(\pi/4-\psi/2)]+[\sin(\pi/4-\psi/2)-\cos(\pi/4-\psi/2)]\} \qquad (6)$$

$$P_{oi}=\frac{1}{3}(1+2K_o)\rho h_i \qquad (7)$$

Where D_g=the diameter of grouted soil-nails; K_o= static horizontal earth pressure coefficient.

3.2 Tranverse shear force of soil-nails

Soil flowing around soil-nails is taken place in a small region near the slip surface BC, as aparted from the small region, elastic contact is keeped between soil-nails and its surrounding soil. In order to calculate conservatively and approximately, soil-nail is taken as infinite long beam in the soil mass, by using of boundary conditions of the connected point between the ith nail and BC, which moment is equal to zero and σ_{bi} is given by formula(6), then transverse shear force T_{ci} is derived by formula(8) and (9).

$$T_{ci}=L_o\sigma_{bi}/2 \qquad (8)$$

$$L_o=\sqrt[4]{4EI/(k_s D_g)} \qquad (9)$$

Where Ks=modulus of subgrade reaction for the soil; E=Yang's modulus of grouted soil-nail; I=moment of area of grouted soil-nail.

Calculation results show that angle deformation of soil-nails at slip surface BC can be neglected. So horizontal soil- nails can be considered when translation failure happens.

3.3 Determination about upper bound horizontal space S_{hmin} of soil-nails

Horizontal space S_h of soil- nails is taken as calculating length of vertical slope, similar to vertical slope reinforced by flexible reinforcements, work rate done by soil weight Wex also is expressed by formula(2), the tension force or friction force T_i of the ith soil-nail is expressed by formula(10).

$$T_i=\pi D_s\frac{i[(n+1)-i]}{(n+1)^2}\rho H^2 ctg\beta\, tg\psi_b+\pi D_s\frac{(n+1)-i}{n+1}Hctg\beta\, C_b \quad (10)$$

Corresponding dissipated work rate produced by interior forces is expressed by formula(11).

$$W_{in}=2V\cos(\beta-\psi)\sum_{i=1}^{n}T_i+V\sin(\beta-\psi)\sum_{i=1}^{n}T_{ci}+\frac{CHS_h}{\sin\beta}V\cos\psi \quad (11)$$

Making W_{ex} equal to W_{in}, formula (12) can be obtained.

$$S_h=\{4\pi D_s\cos(\beta-\psi)[C_b H\sum_{i=1}^{n}\frac{n+1-i}{n+1}+\rho H^2 tg\psi_b \times \sum_{i=1}^{n}\frac{i(n+1-i)}{(n+1)^2}]+2\sin(\beta-\psi)tg\beta\sum_{i=1}^{n}T_{ci}\}/[\rho H^2\sin(\beta-\psi)-2CH\cos\psi\sec\beta] \quad (12)$$

Formula (12) can be calculate by trial and error, angle β corresponding to the S_{hmin} is called critical failure angle β_{cr} of vertical slope reinforced by soil-nails, and S_{hmin} is called upper bound horizontal space of soil-nails.

4 DESIGNING METHOD OF VERTICAL REINFORCED SLOPES

4.1 Determination about value of safety factor

The S_{hmin} can be derived by formulas(5) or (12) by use of upper bound solution method, in fact, the given slope height H in formulas (5) or (12) also is the upper bound Hu of slope. Obviously, we can not directly use n and H and S_{hmin} to design reinforced slopes, so how to design reinforced slopes under working load still need to discuss, this is related to safety factor chosen and its value used. Safety factor is defined as $\tau=c/k+\sigma\,(tg\psi/k)$, which cohesion C and friction angle ψ of soil will be dropped to $c_s=c/k$ and $\psi_s=arctg(tg\psi/k)$, respectively. Next, we discuss the value of safety factor.

Chen[1] gives low bound Hcr of vertical cohesive slope, as expressed by formula(13).

$$H_{cr}=\frac{2c}{\rho}tg(\pi/4+\psi/2) \quad (13)$$

The Hcr is similar to Pcr of shallow foundation engineering, Pcr also is the low bound solution of limit bearing pressure, So Pcr can be taken as designing pressure conservatively under working load. Similar to Pcr, the Hcr can also be taken as designing height of vertical cohesive slope.

If low bound Hcr is given out by upper bound Hu, c and ψ in the formula (1) must be reduced, corresponding safety factor is defined as standard safety factor K_k, then formula (14) is set up.

$$\frac{4C}{\rho K_k}tg[\pi/4+0.5arctg(tg\psi/K_k)]=\frac{2C}{\rho}tg(\pi/4+\psi/2) \quad (14)$$

Rearranging formula (14), then formula (15) will be obtained.

$$\frac{2}{K_k}tg[\pi/4+0.5arctg(tg\psi/K_k)]=tg(\pi/4+\psi/2) \quad (15)$$

K_k is the function of ψ. when $\psi=0, K_k=2$; when $\psi\neq0, K_k<2$, and K_k is decreased as ψ increased.

The K_k can be taken as initial value of reforced slope, because reinforments make C and ψ increased, by formula (15) we know that the k of vertical reinforce slope is smaller than K_k of cohesive vertical slope, it is shown that difference between upper bound Hu and low bound H_{cr} of vertical reinforced slope will be reduced, so by use of coefficient α_3, safety factor k of vertical reinforced slope is expressed in formula (16).

$$K=\alpha_3 K_k \quad (16)$$

α_3 can be affected by many factors and is difficult to be determined, in order to be briefty, we take $K=K_k$.

4.2 Designing procedure of vertical reinforced slope

Reinforcements are placed in horizontal and have enough anchorage length, in order to prevent reinforments pulled out from anchorage soil mass, anchored length of reinforcements should be equal to or bigger than reinforment's length in slip soil mass, so ith flexible reinforment's length can be expressed by formula (17).

$$L_i>2\frac{n-i}{n}Hctg\beta_{cr} \quad (17)$$

β_{cr} can be gotten by putting C_s and ψ_s into formula (5).

The ith soil-nail's length can be expressed by formula (18).

$$L_i>2\frac{n+1-i}{n+1}Hctg\beta_{cr} \quad (18)$$

β_{cr} of formula (18) can also be obtained by putting C_s and ψ_s into formula (12).

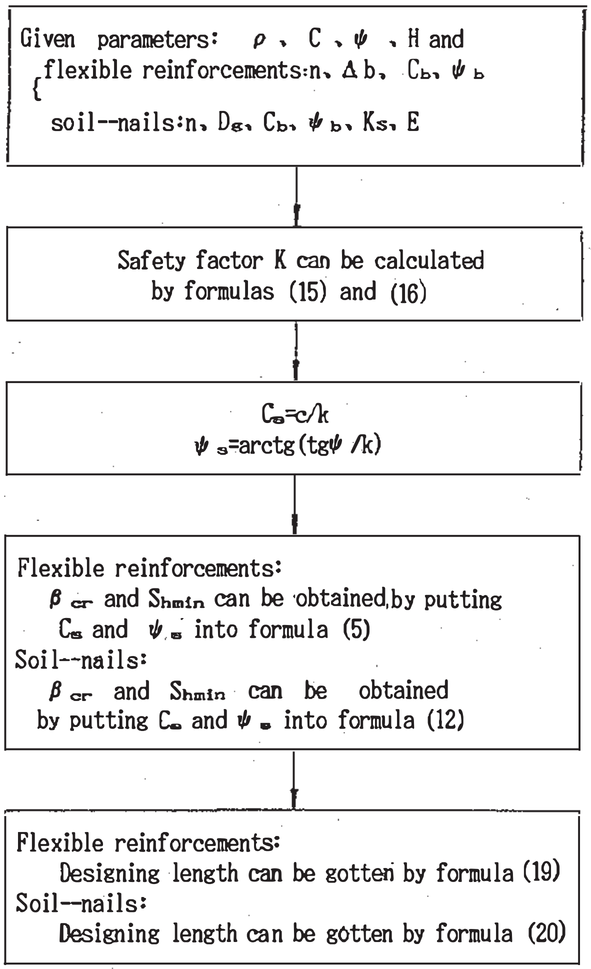
Because the L_1 is maximum, in order to construct conveniently, L_1 is defined as general reinforcement's length. For flexible reinforcements, L_1 is expressed by formula (19)

$$L_1=2\frac{n-1}{n}Hctg\beta_{cr} \quad (19)$$

For soil-nails, L_1 is expressed by formula(20).

$$L_1=2\frac{n}{n+1}Hctg\beta_{cr} \quad (20)$$

Designing procedure diagram of vertical reinforced slope is shown as follows.



5 CALCULATION EXAMPLE

5.1 Calculation example about vertical slope reinforced by flexible reinforcements

Some vertical slope, ρ =18KN/m^3, c=15kPa, ψ =25°, H=4.10m, Δb=0. 03m, n= 6. In order to consider different effects, two plans are adopted: the first is C_b=C and $\psi_b=\psi$; the second is C_b=0 and $\psi_b=\psi$. Calculation results of the two plans are listed in table 1.

Based on the results of table 1, the following conclusions can be obtained.

① Reforcements increase critical slip angle β_{cr} and make slope shallow translational failure.

② Cohesion C_b betweem reinforcements and its surrounding soil has bigger effect on S_{hmin}.

③The nth flexible reinforcement also is important, it increases the low bound Hcr and stability of vertical reinforced slopes.

Table 1 Calculation results

Result / Plans	k	β_{cr}	Designing S_{hmin}	Designing L_1
C_b=c $\psi_b=\psi$	1.68	60°	0.50m	3.94m
C_b=0 $\psi_b=\psi$	1.68	60°	0.24m	3.94m

5.2 Calculation example about vertical slope reinforced by soil-nails

Some vertical slope, ρ =16.3KN/m^3, c=19kPa, ψ =36. 5° K_s=50000KN/m^3, H=8.0m, n=3, diameter D of steel bar =0.025m, Dg=0.10m, modulus E of steel=210x10^{6}KN/m^2, modulus E of concrete=2.6x10^{7}KN/m^2, In order to consider different effects, two plans are adopted: the first is $T_{ci}\neq 0$; the second is T_{ci}=0. Calculateion results are listed in table 2.

Calculation results show that the designing horizintal space S_{hmin} of soil- nails will be increased if tranverse shear force T_{ci} and bend stiffness are considered, S_{hmin} is conservative when T_{ci} is equal to zero, conservative degree is (2.02-1.76)/1.76=14.8%, thus the plan which T_{ci} is equal to zero is approximate reasonable designing method for vertical slope reinforced by soil-nails.

Table 2 Calculation results

Result / Plans	K	β_{cr}	Designing S_{hmin}	Designing L_1
$T_{ci}\neq 0$	1.58	60°	2.02m	6.93m
T_{ci}= 0	1.58	60°	1.76m	6.93m

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