International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

2010 - Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

26 May 2010, 4:45 pm - 6:45 pm

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Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

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ABSTRACT

Soil nailing technology can be successfully applied to strengthen natural soil massifs in seismic regions, provided adequate analysis is available. Conventionally, the design of soil nailing is performed iteratively: firstly parameters of nailing and their distribution are assigned, the safety factor of the nailed massif is calculated, if its value is less than 1 then nailing parameters are reassigned, etc. Such "trial and error" approach is laborious and especially so, because different types of ULSs shall be analyzed. The method, discussed in the paper, is based on assumption that the effect of nailing in soil with internal cohesion c=c(x,y) could be simulated by equivalent internal cohesion *Δc=Δc(x,y)* (deficit) of unreinforced massif. Formulae for calculating nailing parameters are determined on the basis of deficit distribution. A MathCad code has been developed, examples are given. The method can be easily applied to assess seismic stability of nailed soil massifs.

SOIL MASSIF STRENGTH DEFICIT CONCEPT

There is essential difference between stability analysis of an existing soil massif (e.g., a slope) and that of a virtual paper-bound slope yet to be cut and reinforced by nails. *Instability* of an existing slope can be proved by existence of just one potential critical slip line (one ULS), while *stability* of a virtual nailed slope can only be proved by multiple checks, showing that none of different slip-line families contains a critical slip-line i.e., different ULS's shall be analyzed.

The nails are usually applied to compensate for the global slope strength deficit. Stability of a nailed slope is checked by comparing the sum of retaining resistances *R* (including nail resistances) and the sum of shearing forces S along all potential slip-lines to find *K=min(R/S)*. If *K>1* then the slope is stable. Another approach: moments of R and S, rotating the sliding block around a certain point can be compared in the same manner, as is done for circular slip-lines.

This approach, however, is not always adequate, because global stability evaluation misses the fact that nails do not have residual resistance in tension, shear or bending. If one nail is broken its resistance drops down to zero. It is not so for soil, which always has some residual resistance in shear. But if one nail breaks then its resistance will be distributed among other nails, whose strength could be insufficient to bear, and they would fail, then other nails … and so on and so forth, until the slope collapses because of *progressive failure of nails*.

Beside virtual stable slopes there exist real potentially unstable ones that could become unstable later, e.g. due seismic or any other accidental action. A currently stable but seismically unstable slope can be reinforced by nails to make up for its strength deficit.

The easiest and most explicit way to express the strength deficit of a soil massif is to consider it as the deficit of soil cohesion *Δc*. Having found *Δc* distribution in a virtually unstable slope (soil massif) it is possible to determine the parameters of nailing (or other types of reinforcement) equivalent to *Δc*.

In order to design a nailing system for a potentially unstable slope, it is necessary to find all slip-lines, characterized by stability factor $K<1$. If there are no such slip-lines found then the slope is stable. Otherwise, there is a family (or families) of unstable slip-lines, each of which features a certain distribution of $\Delta c=\Delta c(x,y)>0$ along it.

According to Sawitcky (2000) soil and discrete reinforcement (nails incl.) can be *homogenized* i.e., reinforced soil can be represented as a *homogeneous composite* material, in which a nailing system compensates for deficit $\Delta c=\Delta c(x,y)$. But, typically, nails, crossing the slope, have equal strength along their lengths, therefore, there is a *conservative* option: they all could be designed as adequate to compensate for $max(\Delta c)$, located at a point on the *worst slip-line*, whose stability factor K_w is equal to absolute minimum of all K's i.e., $K_w=min\ (K)$. Less conservative solutions require multiple types of nails or different spacing between them. The level of conservatism could be reduced if nails had non-uniform strength parameters distribution along their lengths. This design solution, however, is not technically feasible.

ENVELOPE OF ALL CRITICAL SLIP-LINES

Such envelope is a critical line albeit a boundary of the family of slip-lines. Evidently, the nails shall be designed to cross this boundary, otherwise, the zone of deficient soil strength would not be covered completely. Another requirement to nails: they should have adequate pullout strength i.e., they should extend beyond the envelope to have adequate fixture length.

ΔC IN SIMPLE HOMOGENEOUS SLOPES

Vertical wall with a horizontal bench, on which a uniformly distributed load q is applied. Such wall is stable if its height

$$H_0 \le \frac{2c\cos\varphi}{\gamma(1-\sin\varphi)} - \frac{q}{\gamma}, \qquad (1)$$

where c, φ and γ are soil parameters. If the height of the wall $H>H_0$ then

$$\Delta c = \frac{1-\sin\varphi}{2\cos\varphi}\gamma(H-H_0) = \frac{\gamma(H-H_0)}{2\sqrt{K_a}}, \qquad (2)$$

If a slope face is tilted at angle β (with $\beta>0$ for the wall tilting away from the soil massif) and the bench is inclined at angle α, then active pressure coefficient K_a in equation (2) can be calculated with the help of the well-known equation:

$$K_a = \frac{\cos^2(\phi-\beta)}{\left[1+\sqrt{\frac{\sin(\phi+\delta)\cdot\sin(\varphi-\alpha)}{\cos(\delta+\beta)\cdot\cos(\beta-\alpha)}}\right]^2 \cos^2\beta\cdot\cos(\delta+\beta)}, \qquad (3)$$

Infinite slope

A slope inclined at angle α is stable if $\varphi\geq\alpha$ for any value of c. The upper layer slips down if $\gamma\cdot h\cdot\cos\alpha\cdot\mathrm{tg}\varphi+c < \gamma\cdot h\cdot\sin\alpha$. Hence, stability can be ensured if deficit $\Delta c=\gamma\cdot h\cdot(\sin\alpha-\cos\alpha\cdot\mathrm{tg}\varphi)-c$ is compensated by nailing.

LIMIT STATE ANALYSIS OF NAILED SOIL MASSIF WITH FORMATION OF SLIP-LINE

If a slip-line R, formed up in a nailed soil massif (NSM), crosses a nail then its action on this nail at the intersection point is equivalent to combination of tensile force T and shear force Q (Fig. 1), applied to the nail.

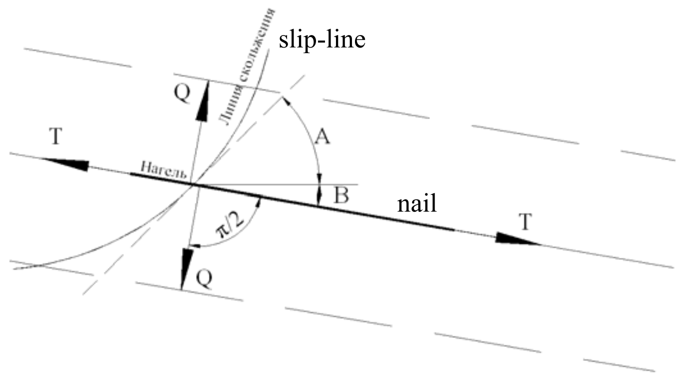


Fig.1. Relative location of a nail versus slip-line
(Note. Compressed nails, i.e. $0<A+B<\pi/2$, are not discussed here)

Consider nailed soil as a composite material, as is proposed by Andrzey Sawicki (2000). Assign $T=min(T_R,T_P)$ and $Q=min(Q_Q, Q_M)$ where T_R/T_P are nail extension/pullout strengths, Q_Q/Q_M are shear/bending strengths. Assign b and h as nails horizontal and vertical spacings in vertical plane, and $\beta=\pi/2-A-B$. Replace point forces T and Q by equivalent distributed loads:

$$t = \frac{T}{bh\cos B}$$
$$q = \frac{Q}{bh\cos B} \qquad (4)$$

It is assumed that ULS of NSM corresponds to formation of a slip-line and failure of all nails. Consider a Cartesian coordinate system (ξ, η), in which axis ξ is parallel to nail axis i.e., is inclined to horizon at angle B. Coaxial nail resistance can be expressed as tensile stress:

$$\sigma_\xi = -t, \qquad (5)$$

same as lateral nail resistance can be expressed as shear stress

$$\tau_{\xi\eta} = q \qquad (6)$$

In coordinate system (x, y) with axis x, being tangent to slip-line at the point of intersection with the nail, values of σ_x и τ_{xy} can be expressed, as follows: for normal stress σ_x in Cartesian system "normal-tangent"

$$\sigma = \sigma_x = - t \cos^2\beta, \quad \tau_{xy} = t \sin\beta \cos\beta,$$

and shear stress $\tau_{\xi\eta}$:

$$\sigma = \sigma_x = q \sin\beta \cos\beta \quad \tau = \tau_{xy} = q \cos^2\beta$$

Insert σ and τ in Coulomb law equation

$$t \sin\beta \cos\beta = - t \cos^2\beta \operatorname{tg}\varphi + \Delta c_t$$

and obtain deficit Δc_t equivalent to required nail extension/pullout resistance:

$$\Delta c_t = \frac{t \cdot \cos\beta \cdot \sin(\beta + \varphi)}{\cos\varphi} \quad (7)$$

Similarly obtain deficit Δc_q equivalent to nail resistance to lateral load q from Coulomb law equation:

$$q \cos^2\beta = q \sin\beta \cos\beta \cdot \operatorname{tg}\varphi + \Delta c_q,$$

$$\Delta c_q = \frac{q \cos\beta \cdot \cos(\beta + \varphi)}{\cos\varphi} \quad (8)$$

NAIL-SOIL INTERACTION

General case

Consider the problem of elastic bending of a nail in soil, whose length is $2L$. The solution of this problem boils down to solution of ODE (9), which describes lateral deflection function $s(x)$ of a nail (elastic bar with bending stiffness EJ) in Winkler medium:

$$EJs^{IV} + C_z \cdot d \cdot s = 0, \quad (9)$$

where x is coaxial with the nail;
z is mean nail depth from the surface;
d is nail diameter;
$C_z = K_0\, z$ is Winkler ratio along the nail at depth z;
K_0 is stiffness factor, depending on soil stiffness around the nail. K_0 values are borrowed from Russian Construction Code 50-102-2003 for laterally loaded piles as is shown in the following table.

Table 1.

Soils	K_0 kN/m^4	
	Driven nails	Injected nails
Very soft clays and clay loams ($0.75<I_L\leq 1$)	650-2500	500-2000
Soft clays and clay loams ($0.5<I_L\leq 0.75$)	2500-5000	2000-4000
Clays and clay loams ($0\leq I_L\leq 0.5$), sand loams ($I_L<0$), fine sands ($0.6\leq e\leq 0.75$), medium sands ($0.55\leq e\leq 0.7$)	5000-8000	4000-6000
Clay and clay loams ($I_L<0$), gravely sands ($0.55\leq e\leq 0.7$)	8000-13000	6000-10000
Gravely sands ($0.55\leq e\leq 0.7$), gravel and pebbles and pebbles with sand fill	-	10000-20000

Equation (10) with boundary conditions $s(\pm L) = \pm S$, $s^{II}(\pm L) = s^{III}(\pm L) = 0$ can be solved with the help of well-known ODE solution technique.

Numeric simulation of this solution yielded two facts:
a) large scatter of tabulated values of K_0 results in minor scatter of the solutions of equation (9), because they depend on $\alpha = \sqrt[4]{\frac{K}{EJ}}$, where EJ is nail bending stiffness;
b) for real nails their length can be assumed to be infinite.

The last assumption made it possible to present the above solutions in the following form:

$$\begin{aligned} &s(x) = S_0 e^{-\alpha x} \cos(\alpha x); \\ &\delta(x) = s^{/}(x) = S_0\, \alpha\, e^{-\alpha x} [\cos(\alpha x) + \sin(\alpha x)]; \\ &M(x) = 2EJs^{//}(x) = 2\, EJ\, S_0\, \alpha^2\, e^{-\alpha x} \sin(\alpha x); \\ &Q(x) = EJs^{///}(x) = S_0\, EJ\, \alpha^3\, e^{-\alpha x} [\sin(\alpha x) - \cos(\alpha x)]; \end{aligned} \quad (10)$$

where $s(x)$ is (see above); $\delta(x)$ is angle of tangent to $s(x)$; $M(x)$ and $Q(x)$ are bending moment and shear force at point x respectively. From (10) follows that

$$max\ Q(x) = Q(0),\ M_{max} = M\left(\frac{\pi}{4\alpha}\right) = \frac{Q(0)\sqrt{2}}{\alpha}, \quad (11)$$

Below an example of solutions (10) in graphical form is given.

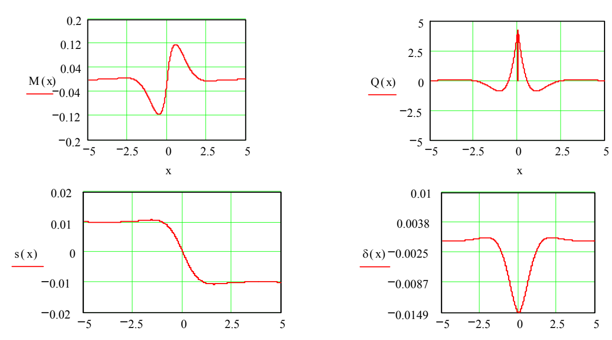


Fig. 2. Graphs of bending moments M(x), shear forces Q(x), displacements s(x) and tangent tilts δ(x) for a nail, having

diameter d=0.08 m, made of ferroconcrete, having elasticity modulus E=20000 MPa, in soil with K_0=2 MPa/m^2).

Numeric simulation showed that at limit state nail inclinations can not exceed 0.05 prior to failure i.e., geometric non-linearity of nail deformations is negligible. Another conclusion is that nails can be broken by tension and shear. Bending moment failure is only possible for nails in very soft soils, but soft soil massifs shall only be reinforced by anchored retaining structures rather than by nails.

SPECIFIC PROPERTIES, SEISMIC STRENGTH AND PROGRESSIVE FAILURE OF NAILING SYSTEM

As is mentioned above, nails have no residual strength in tension, shear or bending. Nails only have residual pullout strength. This circumstance can be used to design relatively stable nailed soil massifs, which do not collapse under unpredicted short duration actions, like seisms. Such NSM may change their geometry without collapsing and, therefore, may comply with the SLS requirements, without violating ULS requirements. In such case geometry changes may be repairable, and the NSM remains functional. In order to achieve it a nailing system shall be moderately overdesigned with respect to tensile rupture, shear and bending, while their pullout strength be adequate i.e., their fixture in soil outside the critical slip-line should be slightly shorter than that within the sliding block.

Condition $K>1$ is not sufficient for stating that the NSM is stable, because global stability does not mean that there are no overstressed nails, which could fail with their load being redistributed to other nails that could fail in turn and so on until NSM totally fail. Such *progressive failure* can be prevented if deficit Δc is *compensated by nails at any point of the slip-line*.

COMPUTER CODES FOR SOIL NAILING DESIGN ANALYSIS

Two MathCad codes were developed for soil nailing design analysis: the first one for computing the critical slip-line with Δc distribution along it and further nail parameters evaluation, corresponding to this distribution.

Another code was developed for checking if a slope with assigned nailing system is stable and if there are any nails that could fail, because their strength is less than Δc that could initiate progressive failure of the whole nailing system. The sliding block was considered as the system of vertical slices, sitting on slip-line, with no interactions between them, which assumption is conservative.

In both codes seismic action is defined as equivalent lateral static forces, applied to the gravity center of each slice.

The slip-line shape was defined as $y=Bx^b$ with free parameters B and b to be found by minimizing stability factor to achieve K_{min}. Any other slip-line definitions can also be used.

The analysis is carried out in two stages. At first the set of respresentative slip-lines is found, having safety factor $K=K(B,b)$ equal to the ratio of the sum of retaining forces to the sum of shear forces along the slip-line. Then absolute minimum $K=min(K(B,b))$ is found in the set. For unstable NSM $K_{abs}<1$. But beside K_{abs} other slip-lines in the set can have $K<1$ i.e, can be unstable, which fact is taken into account when parameters of the nailing system are assigned, as is described above.

The retaining and shear forces were determined with conservative assumption that the shear block is a system of slices formed up by vertical boundaries with no interaction between the slices. Calculated K values are partly given below.

KS =

	0	1	2	3	4	5	6	7	8	9
0	86.42	98.38	154.2	277.29	539.07	$1.1\cdot10^3$	$.33\cdot10^3$	$.08\cdot10^3$	$.13\cdot10^4$	$.54\cdot10^4$
1	25.16	24.52	31.68	45.53	69.1	108.4	174.04	284.41	471.6	791.72
2	11.15	9.83	11.44	14.81	20.29	28.79	41.81	61.77	92.43	139.69
3	6.14	5.05	5.47	6.59	8.4	11.1	15.03	20.7	28.87	40.65
4	3.85	3.01	3.09	3.52	4.24	5.3	6.78	8.83	11.65	15.52
5	1.32	1.3	1.42	1.64	1.96	2.4	3	3.79	4.83	6.23
6	0.86	0.88	0.95	1.08	1.25	1.49	1.8	2.19	2.71	3.37
7	0.69	0.7	0.75	0.82	0.93	1.07	1.25	1.48	1.76	2.12
8	0.6	0.61	0.64	0.69	0.77	0.86	0.97	1.11	1.28	1.48
9	0.56	0.56	0.59	0.62	0.67	0.73	0.81	0.9	1.01	1.13
10	0.54	0.54	0.56	0.59	0.62	0.67	0.72	0.78	0.85	0.93
11	0.54	0.53	0.55	0.57	0.6	0.63	0.67	0.71	0.76	0.81
12	0.54	0.54	0.55	0.56	0.59	0.61	0.64	0.67	0.71	0.74
13	0.54	0.54	0.55	0.57	0.59	0.61	0.63	0.66	0.68	0.71
14	0.56	0.56	0.57	0.58	0.6	0.61	0.63	0.65	0.67	0.69
15	0.57	0.57	0.58	0.59	0.61	0.63	0.64	0.66	0.68	0.69
16	0.59	0.59	0.6	0.61	0.63	0.64	0.66	0.68	0.69	0.71
17	0.61	0.61	0.62	0.64	0.65	0.67	0.68	0.7	0.71	0.72
18	0.62	0.63	0.64	0.66	0.67	0.69	0.71	0.72	0.73	0.75
19	0.65	0.65	0.67	0.68	0.7	0.72	0.73	0.75	0.76	0.77
20	0.67	0.68	0.7	0.71	0.73	0.75	0.77	0.79	0.8	0.82
21	0.69	0.71	0.73	0.75	0.78	0.8	0.83	0.85	0.87	0.89
22	0.72	0.74	0.77	0.8	0.83	0.86	0.89	0.92	0.96	0.99
23	0.75	0.77	0.81	0.85	0.88	0.93	0.97	1.01	1.06	...

Fig. 3. Tabulated field of K values. The absolute minimum K_{min}=0.54 (b=0, X=11). But there is a whole family of unstable slip-lines with $K<1$

The slip-line with K_{min}=0.54 can be used to obtain values of nail unit strength parameters t (unit tensile strength), q (unit shear strength) with the assumption that this slip-line is the worst among others i.e., such values will be sufficient to ensure integrity of the nails all over the failure zone. Nail strength in tension and shear is calculated with the help of equations (4) given above. Δc, q and t are given on Fig. 4.

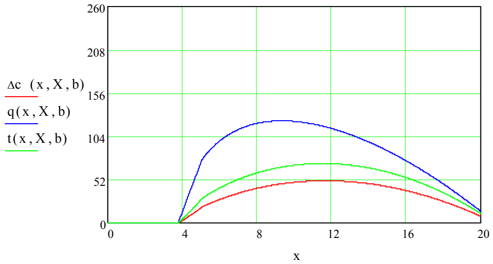


Fig. 4. Profiles of Δc (lower curve), t (middle curve) and q (upper curve).

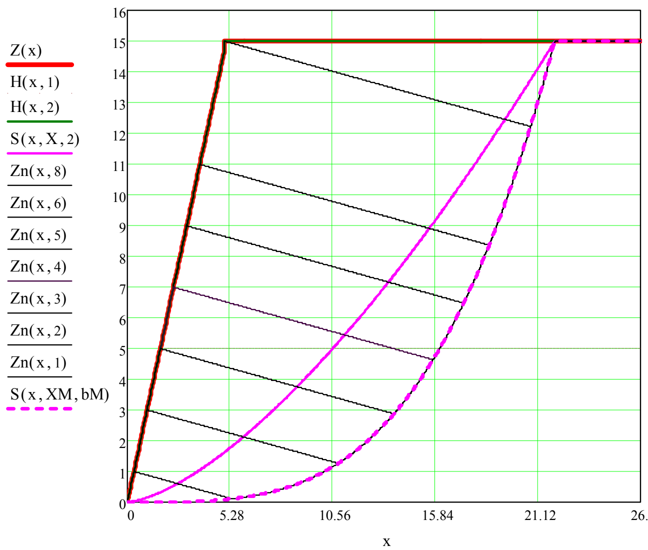


Fig. 5. Slip-line, enveloping the family of potential slip-lines with K<1 and nailing system configuration (not all nails are shown).

The curves in Fig. 4 show that if nails are designed by their tensile strength their shear strength is sufficient.

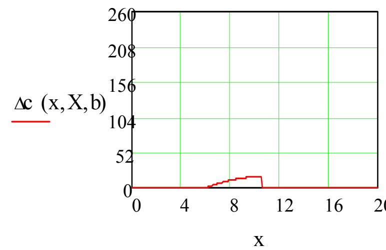
Diameters of nails to withstand tension and shear can be non-uniform along their lengths. It is shown on Fig. 6. However, it is not technically feasible to design a system with different nails, therefore, one diameter shall be chosen for all nails, i.e. 2.9 cm.

$$dq^T = (0\ \ 0\ \ 1\ \ 2.5\ \ 2.9\ \ 2.9\ \ 2.7\ \ 2.3\ \ 1.5)$$
$$dt^T = (0\ \ 0\ \ 0.9\ \ 2.1\ \ 2.4\ \ 2.5\ \ 2.3\ \ 2\ \ 1.3)$$

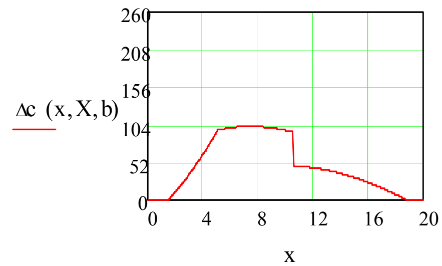
Fig. 6. Nail diameters (cm) versus height (from bottom up) for shear (dq) and tension (dt). Nail spacing is 1.5 x 1.5 m in vertical plane (computer output).

Seismic action in the above code is assumed to be a system of horizontal forces applied at the centers of gravity of the slices. Their values, according to Russian construction code, are 0.1; 0.2 and 0.4 for 7, 8 and 9 magnitudes of the Richter scale.

Below on Fig. 7 two *Δc* profiles are given for statically stable and seismically unstable slopes.



A slope with stability factor K=1.17 features local deficit Δc, which can initiate progressive failure.



Δc deficit along the whole length of seismically unstable critical slip-line with stability factor K=0.594 (Richter magnitude 9).

Fig. 7. Deficit Δc in statically stable and seismically unstable slopes to be compensated by nails.

CONCLUSIONS

1. An approach to evaluate static and dynamic stability of nailed soil massifs has been developed on assumption that such massifs may be homogenized and defined as composites.
2. Stability of existing and would-be nailed soil massifs shall be linked up with local deficit of soil cohesion along potential slip-lines. Nails shall be used to compensate for such deficit.
3. Global stability evaluation of nailed soil massifs, based on integration of retaining and shear forces along potential slip-lines is not sufficient, because nails do not have residual resistance to tension, shear or bending, and failure of just one nail can initiate progressive failure of all other nails one after another.
4. Nails have residual pullout strength.
5. Dynamic stability of nailed soil massifs can be evaluated on the basis of Russian construction codes by applying quasi-static approach.

6. In order to ensure dynamic stability of a nailed massif the nails shall be overdesigned with respect to their tensile, shear and bending strength. Their pullout strength shall be less than their tensile strength, especially in seismic design.

REFERENCES

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