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Fired soil nails

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ABSTRACT: A machine for firing soil nails has been devised and is described. Its speed and ease of use makes the activities required to execute the works simple and very economic. Of necessity stiff nails are used. The behaviour of stiff nails differs from pliable reinforcements which are regarded as acting in tension. The soil nails are orientated so as to contribute meaningful shear forces to the retained wedge of soil. The basic theory on which the strength assessment is based is described.

INTRODUCTION

The process of reinforcing earth has been used since ancient times and has several features which lead to the notion of soil nailing. The imported fill material used in building up the layered reinforced mass represents a substantial cost and so means of inserting reinforcement into existing undisturbed soil becomes an attractive option and has acquired the descriptive title of "soil nailing".

However, direct insertion demands a stiff nail. Traditional nails have been installed by placing them in pre–drilled holes and grouting or inserted by tip jetting or percussion. These techniques, often slow, involve a multiplicity of activities.

Firing stiff nails into earth is rapid and significantly reduces the activities involved. The machinery is not a major cost contributor and so fired nails offer an extremely economic soil reinforcement solution.

Soil nails have traditionally been treated as though they were pliable, as is the case with steel strips used in reinforced earth, and designed as though they were in tension. However, when the nails are stiff and offer less area to the vertical load they will generally generate less tension, nevertheless the nail stiffness can be utilized since when the nail deforms a useful shear force is generated which contributes significantly to equilibrium.

The Machine (1)

The nail is fired by a launcher which uses compressed air and consists of: Breech; "Breech interlock"; Barrel; "Release Valve" and Noise and Debris Shroud. The machine is illustrated in Fig 1. The nail is fired from its tip to which the force of the air pressure is transferred via a disposable plastic collet, in this way the nail is placed in tension in flight. The tension, induced by the tip firing ensures that the nail does not buckle on impact. Once the nail enters the ground it is supported by the earth and its straightness maintained. The launcher can be mounted on a standard wheeled or tracked vehicle with attachments capable of positioning the nail precisely at the required inclinations. The launching sequence is controlled by a microprocessor ensuring correct and safe operation. The launcher makes a sharp boom on firing but the noise is reduced by a baffled shroud which also captures any surface debris. The steel nails fired by the present launcher are 25mm and 38mm in diameter with nail lengths of up to 6 metres. Future developments envisage

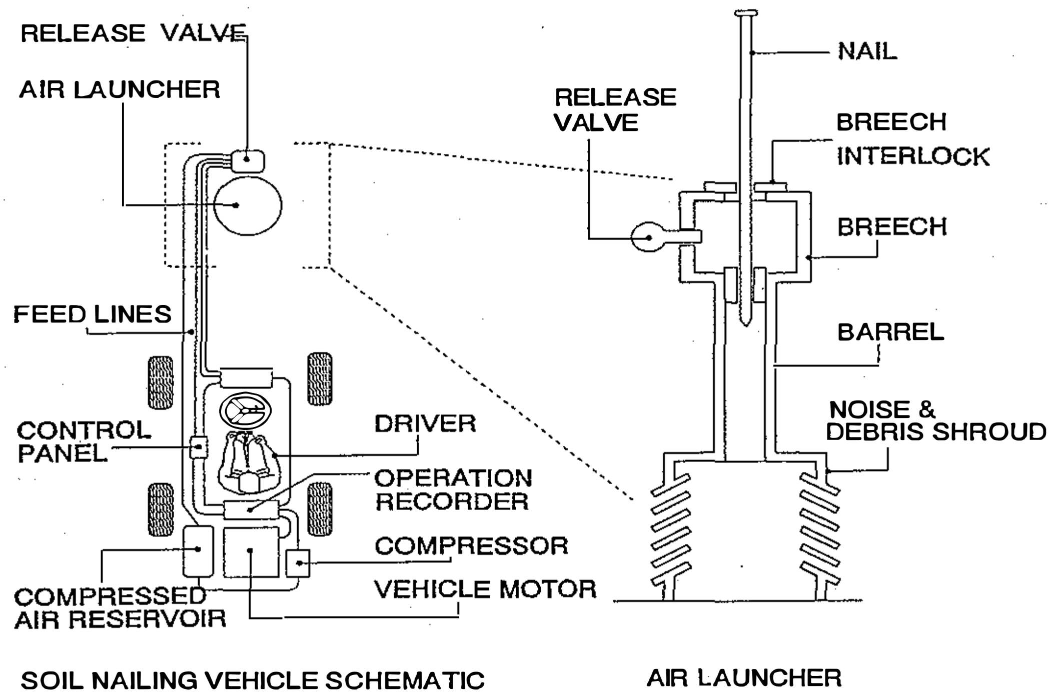

FIG 1. SOIL NAILING VEHICLE SCHEMATIC & AIR LAUNCHER

the adoption of anchorage arrangements and different shaped cross sections, increasing the perimeter/area ratio and the cross sectional stiffness, and synthetic nails. The head of the nail can be located at the surface or at specific depths by means of an arresting steel collar. The nail may also be a perforated tube for drainage or gas extraction. The nail can be protected by galvanizing or epoxy coating and the coatings are not damaged during penetration into the soil due to the wave produced by the nail tip. The head of the nail can be threaded to allow the attachment of facings, nail extensions or soil reinforcing strips and geotextiles.

THEORY

The difference in behaviour between a pliable and stiff nail was referred to in the introduction Fig.2 shows the model of collapse used in conjunction with limit state philosophy. The "disturbed wedge" slides by rotation over an "undisturbed zone".

The slip surface between the two has been observed many times and Wah Fah Chen [2] has shown that a log spiral is the best representation of the curve. A nail inserted across the slip surface will bend and elongate through soil deformation, this will induce a tensile force along its length up to the pull out resistance, after which it will start to move. The tensile force will be at its maximum at the slip surface.

The deformed shape of the nail is such that there is a point of centraflexure at the slip surface [3]. Therefore the bending moment in the nail is zero at this point but the shear force, at right angles to the bar, is at its maximum. Consequently the out of balance moment, OBM, between the disturbing and restoring moments about the centre of rotation Fig.3 has to be reconciled, at the point of collapse, by the moments of the shear and tension forces about the centre of rotation.

The limit state philosophy requires that the disturbing loads must be multiplied by a partial load factor, *fl*, and the material strength reduced by dividing by a partial material factor, *fm*, to allow for uncertainty in measurement and assessment and for reasons of safety. However, the assessment of the forces in an array of nails with the existence of both shear and tension renders the problem of their calculation statically indeterminate and additional equations relating to those of equilibrium must be sought for a complete analysis. Once this has been done a series of checks needs to be carried out to ensure each nail is capable of carrying its calculated loads.

Assessment process

1. Find the log spiral slip surface.
2. Propose an array of nails for assessment.
3. Find shear force S_i and tensile force T_i for each nail.
4. Check each nail's ability to carry the shear S_i and tension T_i.
5. If the array is shown to be inadequate, review the array of nails by modifying the transverse spacing and repeating the S_i T_i analysis.

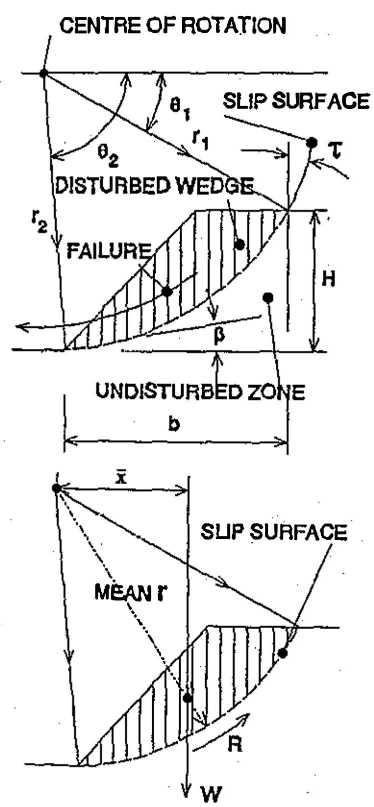

FIG 2. MODEL OF COLLAPSE

The Log Spiral Slip Surface

The symbols involved in the following are defined in Fig.3 and 4, and a computer program has been prepared which follows the above process for three types of problem:
Reinforcing an existing slope when the slip surface is known.
Building a wall where the critical slip surface must be found.
Strengthening a foundation.

The critical slip surface is that surface which requires the greatest nail shear. The difference between the wall and foundation is that for a wall the iteration takes place by varying the point of exit of the slip surface and for a foundation iteration takes place by varying the position of the toe of the slip surface.

The equation of the log spiral is

$$r = ae^{k\theta} \quad \text{------------------------------(1)}$$

where a and k are constants and r and Θ are the radius at a point and the angle the radius makes with the horizontal.

Fig.4 illustrates a log spiral and defines the symbols used. The log spiral is a curve which maintains a constant angle, ϕ, between the radius r and the normal to the slip surface.

The consequence is that the quadrilateral $ABCD$ is cyclic quadrilateral [1] whose perimeter is the locus of A, the centre of rotation between D and B. The particular values of b, H and the position of A, for given values of ϕ and β and τ and also values of $r1$, $r2$, $\Theta 1$, $\Theta 2$, β and τ can be found by iteration.

The iteration is carried out by using the sine rule for triangle ABD. Various slips can be found by varying $\beta + \tau$ and ϕ. Increasing $\beta + \tau$ will give a shallower curve, the effect of increasing ϕ is to make a deeper curve.

Forecasting T_i and S_i

The method of slices is used to find thc Out of Balance Moment (OBM) for the unreinforced condition however the determination of loads in an array of nails crossing the surface is a more difficult problem for the reasons given earlier.

Pull Out Relationship

In other work [4] it has been asserted that the shear stress in the nail, at the point of contraflexure, is a principal shear in the direction of the slip surface and represented by:

$$Ti = 2\, Si \tan 2\rho\iota \quad \text{-------------------(2)}$$

This assertion has been shown to be questionable by work at full scale in a large shear box at Cardiff University [4] However, this equation can be conveniently replaced to give a

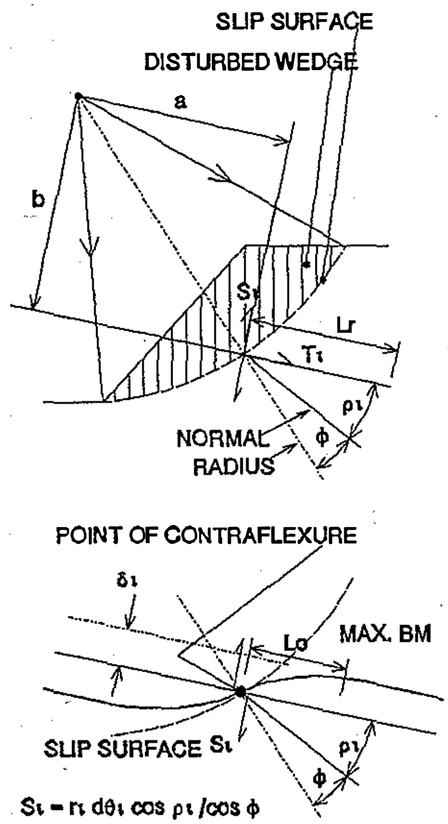

FIG 3. NAIL RESISTANCE

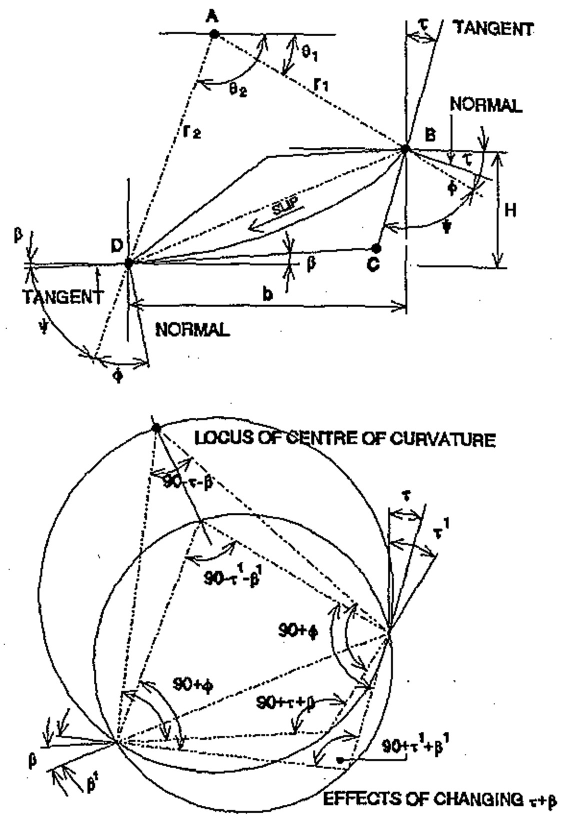

FIG 4. LOG SPIRAL AND SYMBOLS

relationship between T_i and S_i by using the pull out relationship.

All formula of the equation can be written in the form [1]

$$T_i = Ki\ Si + C_i \text{ --------------------(3)}$$

where Ki and C_i are constants for a particular reinforcement.

The first term represents the contribution to pull out by the frictional force due to S_i while the second term allows for the cohesion resistance and the frictional force due to overburden and other loads.

The C_i port of the equation can be treated separately and its moment deducted from OBM to give Out of Balance Moment, (OBMA), which is the moment to be balanced by the shear and the tension induced by the shear leaving the equation

$$T_i = ki\ Si \text{ --------------------(4)}$$

After Ti has been solved C_i is added to the result to give the tensile force in the nail.

End Deflection Equations

The deflection of the reinforcement at right angles to its length at the slip surface is denoted *Si.* and must be compatible with the Kinematic model [3] thus

$$S_i = \frac{r_i\ \delta\Theta_i\ \cos\rho i}{\cos\phi} \text{ ----------------(5)}$$

The symbols are defined in the figures and $\delta\Theta_i$ is the angle turned by the disturbed wedge at the point of failure.

The second equation for deflection is attributable to Matlock and Reese [6] They gave the deflection at the end of a long thin pile as

$$S_i = \frac{\alpha\ S_i}{(El_i)^{0.4}\ (KZ_i)^{0.6}} \text{ -------------(6)}$$

where El_i is the stiffness of the nail, KZ_i the modulus of soil reaction and α a constant equal to 2.5 for long piles (nails).

Equilibrium: The forces in the reinforcements must provide a moment about the centre of rotation equal to OBMA

$$OBMA = \sum i\ S_i\ r_i\ [\cos(\phi + \rho_i) + k\sin(\phi + \rho_i) + \tan\phi(\sin\rho_i + k\cos.\ \rho_i)] \text{ ---(7)}$$

$$OBMA = \sum S_i\ r_i\ A_i \text{ ----------(8)}$$

which also allows for the additional resistance on the slip surface created by the nail forces.

Solution: Simple manipulation of the above equations[3] leads to the solution

$$Si = OBMA\ r_i \cos\rho_i\ (EI_i)^{0.4}\ .\left(\frac{KZi^{0.6}}{EI\ Ai\ r_1^2\cos\rho_i(EI_i)^{0.4}(KZi)^{0.6}}\right) \text{--(9)}$$

and

$$Ti = kSi + Ci \text{ ----------------(10)}$$

which can be simplified to

$$Si = \frac{OBMA\ ri}{EA_i\ r_1^2} \text{ -----------------(11)}$$

Where KZi and ρ_i are all constant.

For a coheshive material where ϕ is zero, r constant, Ai will be 1.0 and the moment due to C is zero giving

$$Si = \frac{OBM}{Nr} \text{ --------------------(12)}$$

where N is the number of nails.

This result accords with common sense and allows an estimate to be made of the number of nails, basing Si on the ultimate BM of the nail. The number of nails can be used to suggest an array which is then subject to rigorous analysis and iteration using the transverse spacing thus leading to a practical design.

CHECKS

In the following checks, a material factor fm is applied to the fracture stress Ff and the ultimate moment Mu. Furthermore, the value then is reduced by the effect of the residual stress remaining in the nail at the point of the maximum bending moment. Where T_i and S_i assist resistance they should be divided by fi for the partial load factor.

The first check should be to ensure Ti does not exceed the Pull Out Resistance (POR). However, this relationship is integral to the solution of Ti and Si and thus is ensured as part of the process.

The second check is that the fracture stress of the nail should not be exceeded. The principal stress is computed and given as the ratio $Ti/"A".Ff$ where $"A"$ is the nail cross sectional area. In practice the ratio is always extremely small and fracture is not a feasible failure mode. Failure is most likely to be due to pull out or the formation of plastic hinges in the nails. So the checks in respect of bending and bearing are the most important.

Bending and Bearing are inter-related. A bearing failure below the nail will not lead to collapse nor would a plastic hinge in a single nail constitute a failure.

Fig 5 shows the deflected shape of the nail and the load intensity in various conditions. The distribution of load intensity is exponential unless the bearing capacity is exceeded at which stage

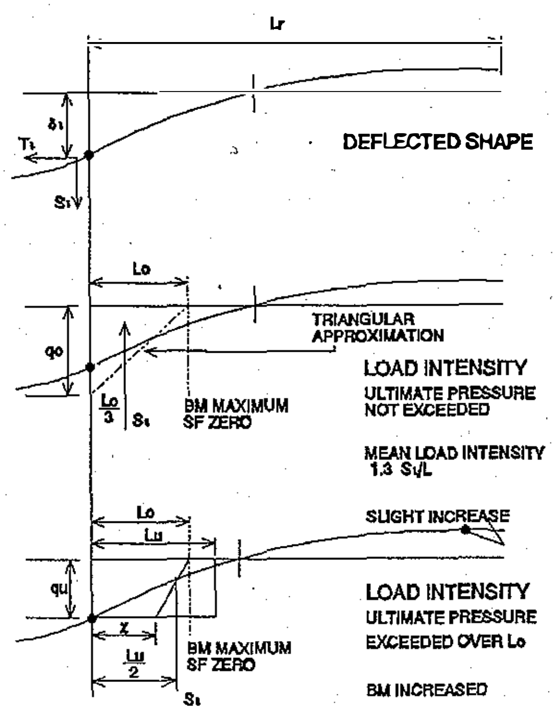

FIG 5. DEFLECTED SHAPE AND LOAD INTENSITY

the distribution becomes horizontal, the bearing pressure below the nail at the slip surface is q_o and the ultimate bearing pressure q_u is calculated using (8) Terzaglis bearing coefficients.

The three limits to check are:

When load intensity is elastic

$$Si\ limit_1 = \frac{3M_u^1}{Lo} \text{ -----------------(13)}$$

When load intensity has partially exceeding the ultimate bearing strength

$$Si\ limit\ 2 = 0.5q_d\ (\chi + L_o)/fm \text{ ---------(14)}$$

When the bearing strength is exceeded at the point of maximum bending moment.

$$Si\ limit\ 3 = q_u\ Lud/fm \text{ ------------(15)}$$

It is assumed, conservatively, that the distribution of load intensity, up to the point of maximum bending moment is triangular when the ultimate bearing is not exceeded.

Where:

M_u^1= the ultimate moment divided by *fm* the partial material factor.

$$L_o = \frac{2}{\alpha d}\left(\frac{Eli}{Kzi}\right)^{04} \text{ -----------------(16)}$$

L_o= the distance from the slip surface to the point of maximum bending moment

$$L_u = \frac{2M_u^1}{q_u d} \text{ ----------------------(17)}$$

L_u = the distance to the point of maximum bending moment when the bearing resistance is wholly exceeded

d = nail diameter

q_u = the ultimate bearing pressure.

$$x = \left(\frac{6M_u^1}{q_u d} - 0.75L_o^2\right)^{0.5} - 0.5Lo \text{ --(18)}$$

x = the distance over which the bearing resistance is exceeded.

(q_o = bearing pressure below nail)

CONCLUDING REMARKS

Using soil nails is a simple and economic method of strengthening walls and slopes; foundations may also be improved in strength by soil nails. The assessment method described provides a robust means if determining a practical array of nails taking advantage of their shear strength.

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