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Evaluation of Design Methodologies for Soil Nailed Walls

EVALUATION OF DESIGN METHODOLOGIES FOR SOIL-NAILED WALLS

VOLUME 3
AN EVALUATION OF SOIL-NAILING ANALYSIS PACKAGES

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16. ABSTRACT

Comparative evaluations of seven soil nail wall design computer programs are described and analyzed. The performance evaluations of the available programs (**SNAIL**, **NAIL-SOLVER**, **STARS**, **NAILM**, **GOLDNAIL**, **TALREN**, and **COLDUIM**) was accomplished by conducting a number of example analyses. Ten hypothetical cases and five case studies used in the analyses represented common design scenarios. Also examined were the magnitude and distribution of loads on the nails under normal working conditions. This was accomplished by observing the response of soil nails for a number of walls instrumented with strain gages. From this a general approach for estimating nail loads from strain history data was developed.

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Chapter 1
Introduction

1.1 Introduction

Soil nailing has become a viable and cost effective means of both temporary and permanent excavation support. Developments in soil nailing have come primarily from specialty contractors based on their own job experience. It is common for contractors and geotechnical engineering firms to develop methods or design packages based on a combination of classical soil mechanics and practical experience. Countless methods of describing nail/soil interaction, nail reinforcing benefit, and overall system behavior have been proposed. To date, there exists no standardized design methodology.

Many transportation departments and smaller design firms have been slow to accept the technique of soil nailing. The average designer faces a lack of consensus within the engineering community with regard to the appropriate way to model and design soil-nailed walls.

The purpose of this research is to evaluate six different design packages. Each of the six packages, or computer programs, make different assumptions about slip surface characteristics, nail reinforcing benefit, and nail/soil interaction. A set of objective criteria for the evaluation included: the program's degree of 'user friendliness', the flexibility of the data input, and the reliability of the results.

1.2 Organization of thesis

Chapter 2 contains a history of both soil nailing and the development of soil nailing design methodology. It includes a literature review from 1979 to the present, with summaries of most of the major papers and theories. In Chapter 3 the six evaluated design packages are presented and reviewed. The description of each of the programs involved includes a summary of the underlying principles, discussion of 'user friendliness', notable program features, and form and content of the final output. Chapter 4 describes the method of comparison and presents the results of the research, showing the predicted slip surfaces, as well as the effect of face pressure and punching shear on the results given by **Goldnail** and **Snail**, respectively. In addition, notes are given that discuss, case by case, any problems encountered, or restrictive input requirements made by a given program. Finally, Chapter 5 is a discussion of the results and the conclusions of the research. The input data used for the comparisons are presented in Appendix A.

Chapter 2

Current state of knowledge

2.1 Introduction

Soil nailing is the technique of stabilizing ground with passive inclusions or reinforcements, commonly known as soil nails. The inclusions can be fully bonded, (e.g. drilled and grouted nails), or simply driven into the ground. In either case the nails act to limit the soil deformations near the exposed face and to transfer the stress into a more stable zone behind the wall.

It is important to distinguish the practice of soil nailing from other similar methods of soil reinforcement, namely tieback anchors and reinforced earth. While tiebacks are grouted along only their bonded lengths, deep in the soil mass, soil nails are grouted along their entire length. Tiebacks are active inclusions in the sense that they are prestressed to reduce movement of the slope or wall. Soil nails are passive and rely on soil deformations to mobilize their reinforcement capabilities. Obviously tiebacks require a robust wall structure and bearing plate to accommodate prestressing. Soil nailed walls do not require such a wall structure and commonly utilize a wall facing only to reduce surface raveling and local instabilities. Here, shotcrete facing is sprayed on with minimal steel reinforcement. Structurally, soil nails require no more than small steel plates cast into the shotcrete facing.

With reinforced earth, the reinforcing strips are initially unstressed, and derive their stabilizing action from relative soil deformations. The load transfer mechanism in soil nailing and reinforced earth is therefore somewhat similar. However, reinforced earth utilizes a bottom up construction sequence, in contrast to the top down construction of soil nailing.

2.2 History of soil nailing

Soil nailing was introduced in Europe, specifically with the New Austrian Tunneling Method (NATM)(Jones et al.,1990). This method was initially used as a hard rock tunneling technique in Germany in the early 1960's, utilizing bonded steel bars and shotcrete facing. The same technique was applied to less competent formations, such as graphitic shales, and Keuper Marl (Bruce et al.,1986). Trials were also conducted in silts, gravels, and sands, with early applications in Frankfurt in 1970 with metro tunnels. The method gained respect in the early 1970's, especially in Germany. A French construction company, Bouygues, had experience in France with the NATM, and in 1972, in a joint venture with Soletanche, started construction on a 70 degree cut slope for a railroad near Versailles. Over 25,000 steel bars were used, and it is the first recorded application of soil nailing (Bruce et al.,1986).

In the U.S., the first recorded use of soil-nailing was in Oregon, with the construction of an addition to the Good Samaritan Hospital in Portland in 1976. Professor Shen at the University of California at Davis was involved in the construction monitoring program, and as a result of interest generated, conducted a program of research that included a full scale test wall (Shen et al., 1981a,b).

In West Germany, specialty contractor Karl Bauer AG led the developments in soil nailing in association with the Institut fur Bodenmechanik und Karlsruhe, and with support from the West German federal government (Bruce et al., 1986). Four large scale tests were conducted starting in 1975, the results of which were published by Stocker et al.(1979).

In France, the success of the Versailles project led Bouygues to construct a number of other soil nailed walls, both temporary and permanent, one of which was the Les Invalides Metro station in Paris in 1974. In this case the nails were driven, rather than grouted, and marked the development of the Hurpinoise system of soil nailing, named for its inventor. A number of specialty contractors, such as Bachy, Intrafor Cofor, SEFI, and Soletanche began to develop their own methods for nailing based on the drilled and grouted nail. In the mid 1980's a large testing program was organized under a French national project called "Programme Clouterre", the results of which were published in English in 1992 (Schlosser et al., 1992).

2.3 Development of design methodology

While specialty contractors in Europe and the U.S. were gaining practical experience with soil nailing, no consensus could be reached on the best way to model and design the walls. It wasn't until 1979 at the Paris conference on the reinforcement of soils that soil nailing design was provided any forum. At this conference, both the French and Germans presented design methods on which many of today's current designs are based.

2.3.1 German gravity wall analysis

Stocker et al. (1979) presented a design methodology based on a force equilibrium with a bilinear slip surface. The authors believed that soil-nailed walls should be designed as gravity retaining walls. The reinforced zone with soil nails was modeled as a single composite mass acting to retain the soil behind it. It was modeled with a bilinear wedge, and the location of the intersection of the two angled failure surfaces was to be behind the nailed zone.

The work presented by the Germans at this conference has evolved into the concept of the so-called soil-nailed gravity wall. Several improvements have been proposed to refine the original method since then. Experimental work by Gässler and Gudehus (1981) showed that two plane translational failure was the only failure mode that warranted consideration. Their research showed that all other modes of failure (deep slip surfaces, steep circular surfaces, and combined tilting failures) produced higher factors of overall safety. The definition of overall safety was given as the ratio of dissipative forces along the slip surface combined with the nail effects, divided by the external forces applied to the system. The procedure was to vary the first planar angle, measured from the horizontal at the wall toe, while keeping the second planar angle, also measured from the horizontal (starting from the back of the nailed zone), at $45° + \phi/2$, where ϕ is the friction angle of the soil. A further refinement came in 1983 with the adoption of a statistical design method to meet the new Eurocode 7 requirements (Gässler and Gudehus, 1983).

Gässler (1988) conducted another comparison and analysis and examined the four commonly assumed failure modes employed in soil nailing design: translation of a single rigid body, translation of two rigid bodies, rotation of one rigid body, and rotation of two rigid bodies. The results are summarized below, for different ranges of soil cohesion, C:

In C = 0 soils	Bilinear wedge is most critical case if the walls are near vertical. Slip circle is critical if the walls are angled at less than 80 degrees from the horizontal, or if longer nails are used in the upper rows.
In medium high C soils	Slip circle and bilinear wedge are equivalent.
In high C soils	Slip circle is critical.

Gässler (1988) also concluded that the simple wedge, bilinear wedge, and slip circle are the only relevant failure mechanisms.

Further conclusions of the paper were that only axial forces need be considered in near vertical walls and that the internal nail force is based on the mean shear per length of nail, T_m, which is constant with depth. The earlier gravity wall design method was refined by using a velocity hodogragh (velocity vector diagram) to obtain kinematical compatibility. As a final note, it was recommended that various partial material safety factors be used in a two step process for design. In the preliminary design one would examine various failure modes and varied surfaces to determine the most critical case. In the final design the most critical surface would be used to assess the suitability of the design reinforcement.

The gravity wall design concept was furthered by Riedinger and Stocker (1990) with the consideration of internal stability, that is the pulling away of a failure wedge of soil, leaving only the nails in place. It was concluded that external stability should be checked using a two part rigid body translation, with the second wedge angled at $45° + \phi/2$ to exert an active pressure on the back of the nailed zone. Internal stability should be checked using wedges angled at any inclination from the toe, with reinforcement contributions coming from that portion of the nail located between the failure plane and the wall face.

2.3.2 Schlosser's Multicriteria analysis

The French developed a somewhat different method of analysis that considered the contribution of nail shear strength as well as tensile strength to the overall wall stability. Early work by Schlosser and Juran (1979) identified the need to delineate between excavation support and slope stability. According to their work, it was important to distinguish between the two applications. The excavations were to be designed considering nail tension, as is done in Reinforced Earth (RE), and the slope stability cases were to require nail designs modeled after laterally loaded piles. The other conclusions of this paper were that the slip surface should follow the line of maximum tensile forces from RE, and that failure of the wall was of a rotational nature.

Further work by Schlosser et al. (1983) resulted in a soil/grout interaction model based on the overburden stress, with a coefficient that attempted to correct for dilation of the soil during shearing. They presented the following equation:

$$\tau = C_o^* + \sigma' \tan \phi' + \Delta\tau \qquad (1)$$

Where τ = shearing resistance of the nailed-soil

C_o^* = apparent cohesion due to the mobilized shear force in the bars

σ' = effective normal stress acting on the bar

$\Delta\tau$ = variation of the shear stresses in the soil due to the effect of the reinforcing bars

The conclusion of the paper was that tensile forces in the nail are efficiently generated with small relative soil/grout deformations, but that shear and moments in the nail are only efficiently generated with large soil deformations.

Schlosser (1985) presented the Multicriteria theory for soil nailing. The delineation between excavation and slope stability applications was no longer necessary with the presentation of a limit envelope in normal and shear space that considered the tensile strength of the nails, the shear strength of the soil, the soil/nail friction, and the limiting lateral earth pressure acting on the nail. The method used a circular slip surface with a method of slices, but considered also the mobilization of the lateral earth pressure on the inclusions, as it controlled the maximum shear force developed in the nails. The basis for the limit criteria came from work by Baguelin and Jezequel (no reference given), modeling the nail as a laterally loaded long elastic pile with a constant K_s of the soil, where K_s is the modulus of subgrade reaction of the soil.

Schlosser and DeBuhan (1990) presented research on the composite behavior of nailed soil. They concluded that the design of soil nailed walls has been oversimplified by not considering the soil/nail interaction on the stress/strain patterns of the soil. They suggested that failure planes in the reinforced soil were very different from the Mohr-Coulomb failure planes of the unreinforced soil. Furthermore, they concluded that tensile forces in the nail are rapidly mobilized and that nail shearing resistance is not efficiently mobilized until there have been significant displacements. Various assumed failure planes were rated in order of decreasing accuracy: log spiral, circular with slices, and bilinear wedge. The final recommendation was that a method like Juran's Kinematical method, described in the following section, be used.

2.3.3 Juran's kinematical limit analysis

Juran and Elias (1988) proposed a "Kinematical Limit Analysis Approach". They departed from methods developed by Schlosser and DeBuhan (1990) and Stocker et al.(1979) claiming that they could not be used to adequately assess the global safety with respect to shear strength characteristics of the soil and the soil/inclusion lateral friction. According to the authors, these methods do not allow for evaluation of the local stability of the reinforced soil mass, or determination of the forces in the nails, which they claimed were often critical. A log spiral slip surface was used with a method of horizontal slices. The horizontal components of the interslice forces were assumed to be equal. The yield criterion for the nails was based on Schlosser's earlier Multicriteria envelope (Schlosser, 1985). Juran's method used Kotter's equation (no reference given) to determine the distribution of normal forces on the slip surface. Nails were modeled as rigid laterally loaded piles, based on work by Hansen and Lundgren (no reference given). Furthermore, nail forces were determined by considering the equilibrium of a given horizontal wedge of soil surrounding a nail.

Juran and Elias (1990) further developed the kinematical limit analysis with additional discussion of the failure envelope and the added suggestion that the value of K_S could be found from the Soletanche charts developed by Pfister et al. (1982). The benefit of this method according to authors, is that by analyzing every nail level, and avoiding a global safety factor, the procedure guards against progressive failure.

The finalized version of the method involved four specific design steps (Juran and Elias, 1990). First, estimate the location and magnitude of the maximum working stresses. Second, analyze local stability at each nail level. Third, look at overall or global stability. Finally, consider the adequacy of the facing. The major point to this approach is that local nail stability can be far more critical than global stability in the consideration of progressive failure. Juran and Elias recommended that the local stability be analyzed using their kinematical method, and global stability be analyzed with a method like that developed at Davis by Shen et al. (1978) and extended by Bang and Erickson (1989), or Schlosser's Multicriteria method, (Schlosser, 1985). The Davis method was favored due to its simplicity and consideration of nail tensile forces alone, which the authors claimed to be the most accurate representation of the wall's behavior. The paper also discussed the observation that the behavior of a nailed wall is similar to that of a braced cut, and therefore it may be possible to use semi-empirical earth pressure diagrams in future developments.

2.3.4 The Davis method

The Davis method, developed at the University of California, Davis, was originally presented at a symposium on earth reinforcement (Shen et al., 1978). Soil nailing was described as the use of non-pretensioned inclusions to be used for temporary excavation support. The bond stress was given as:

$$\tau_{max} = C + \sigma_v \tan\phi \qquad (2)$$

where τ_{max} = maximum shear stress between soil and nail

C = cohesion of soil

σ_v = vertical overburden stress acting on nail

No yielding of the reinforcement was mentioned. The entire system was considered as a composite material, and the solution to the overall stability was found by minimizing the incremental potential energy. The failure surface was given as a parabolic surface, the result of finite element work conducted on in-situ reinforced soil at Davis and a full scale test wall (Shen et al., 1981a,b).

Bang et al. (1980) expanded on the Davis method by describing the assumed soil failure parabola as being divided into two sections, one with reinforcement, one without. The design method was limited to vertical walls, horizontal back slopes, and homogeneous soil profiles. Bang and Erickson (1989) modified the method to handle irregular ground surfaces, wall inclinations, and up to two layers of soil.

The method is based on a force equilibrium with a parabolic slip surface. The resisting force, F_R, is defined as:

$$F_R = C'L + T_f \tan\phi' + T_t \quad (3)$$

where C' = developed cohesion (C/material safety factor)

L = length of potential failure surface

$T_f = F_n + T_n$

F_n = normal force acting on the base of a given vertical slice

T_n = normal component of the resultant of the axial forces in the nails

T_t = tangential component of the resultant of the axial forces in the nails

Pullout stress is based on overburden stress and limited by the yield strength of the nail.

2.3.5 Bridle's log spiral analysis

The soil nailing debate was brought to the UK with a publication by Bridle (1989) in which he presented a method of soil nailing design using a log spiral failure surface with a moment equilibrium. Both tension and shear contributions from the nail are considered, with a composite failure envelope based on the nail's material capabilities and the bearing pressure under each nail. Equations were presented to define the log spiral's exit angle and its angle with the horizontal at the wall toe. According to the author, the exit angle, α, was found from the author's research to be about 3 degrees. β, the angle of the slip surface at the wall toe was defined as:

$$\beta = 0.5\phi + 0.201\alpha\phi + 0.265\alpha + 0.087 \qquad (4)$$

The purpose of the reinforcement in this method is to take up the Out of Balance Moment, or OBM. The OBM is defined as the difference between the driving and resisting moments. The method utilizes two existing relationships. The first is from Juran (1990), and relates the normal force, σ, and shear force, τ, present in the nail:

$$\sigma = \tau \tan(2\rho) \qquad (5)$$

where ρ = angle of inclination of the nail with the normal to the slip surface.

The second formula is from Matlock and Reese (1962), based on their work on laterally loaded piles, and allows the calculation of a nail deflection on either side of the slip surface. The bearing pressure under the nail is given by Terzaghi's general bearing capacity formula (Terzaghi, 1943).

2.3.6 Jewell's tension only model

The preceding log spiral analysis (Bridle, 1989) touched off a debate centered around the contribution of nail shearing resistance to overall wall stability. Pedley and Jewell (1990) addressed the issue of shearing by carefully showing its contribution to be negligible. Their analysis starts with the Tresca criterion of failure for combined shear and tension. The combined moment and tension is limited by an equation the authors derive for a rectangular bar:

$$(M/M_p) + (P/P_p)^2 = 1.0 \qquad (6)$$

where M = nail bending moment

M_p = maximum plastic moment

P = axial nail force

P_p= maximum plastic axial nail force

This equation is conservative for bars of circular cross-section but offers more benefit from shear than the current British structural steel codes, such as BS5950(1985). An upper bound for the determination of the effect of shear is given by Schlosser's elastic analysis (Schlosser, 1985):

$$P_s = 4.9\ M_{max}/L_s \tag{7}$$

where P_s = maximum nail shear force

L_s = distance between two points on either side of the nail centerline, experiencing the maximum moment

A simple limiting plasticity model developed by the authors acts as an example lower bound:

$$P_s = 2M_{max}/L_s \tag{8}$$

With further manipulation, the conclusion is drawn that the shear width L_s must be minimized in order to maximize the mobilized shear. Using the range of analysis methods presented in preceding sections, the authors show that the practical range of shear widths is very limited. Using nails perpendicular to the slip surface for maximum benefit from shear, and both plastic and elastic analyses, the authors found that a relatively small nail shear force is mobilized compared to the nail tensile force. They conclusions were that the benefit to overall stability from nail shear is minimal, and more importantly, that Schlosser's

Multicriteria analysis method was based on an incorrect relationship:

$$(P/P_p)^2 + (2P_s/P_p)^2 = 1.0 \quad (9)$$

The authors claim that the above relationship is valid only for combined axial force and torsion. They also claim that the analysis includes an assumption that $M_{max} = M_{plastic}$, regardless of the applied axial force.

In a discussion of Pedley and Jewell's analysis, Bridle and Barr (1990) point out that the plasticity model used by Pedley and Jewell to determine the ultimate lower bound (Eq.8) is erroneous. Jewell and Pedley (1991) subsequently explained that the plastic hinge model was merely meant to provide a lower bound and was not considered again in their paper. It was Schlosser's elastic analysis (Schlosser, 1985), and Jewell and Pedley's plastic analysis that were used to discount the effect of shearing resistance.

2.3.7 The Glasgow conference

The 1990 Glasgow conference was an opportunity for all the members of the debate to voice their opinions in a single forum. The contribution of Juran and Elias (1990) was discussed earlier in Section 2.3.3.

Two papers are particularly noteworthy. Bastick (1990) recommended that one should avoid Schlosser's (1985) equation for unit soil/grout shear stress that includes an apparent coefficient of friction term for soil dilation. His alternative was to use a τ_{max} along the soil/grout interface. Furthermore, Bastick argued that local equilibrium methods such as Juran's should be avoided, and full-scale pullout tests should be conducted.

Plumelle and Schlosser (1990) presented the results of Clouterre, the French soil nailing research program. The conclusion was that although bending stiffness can play an important practical role in maintaining face stability, it is axial reinforcement force that provides the main stability.

Bridle presented the final version of his work in the form of the computer program, **Cresol** (Bridle, 1990). Use of the log spiral failure surface was defended by citing work by Chen (1975), and the empirical formula for determining the angle, β, at the toe of the wall was not fully substantiated. The relationship given by Juran (Eq.5) was used, relating the shear and tension forces in the nail. Pullout was based on overburden stress, and bearing capacity of the soil under the nail was unchanged from before and limited by Terzaghi's general bearing capacity formula.

At the conference, it was Jewell who attempted to provide a definitive analysis of the various design methods. This paper discussed lateral nail stresses, axial nail force only methods, and Juran and Schlosser's approaches linking lateral soil stresses and the nail forces. Through Jewell's analysis, the conclusion was reached that in order for the combination of forces at the point of maximum shear to become critical, the maximum bearing stress in the soil would have to be on the order of the yield stress of the bar. Jewell also pointed out that nail reinforced walls fail long before the limiting shear force in the nail can be mobilized. Jewell cited Gässler's (1987) test wall data to show that at failure, defined as the point of maximum overall soil shearing resistance, no displacements were measured along any one slip surface, only local shear displacements. It wasn't until well after failure that any displacement was recorded along a slip surface, therefore no shear contribution from the nail was effectively mobilized. It is therefore prudent to rely solely on the axial capacity of the bar. It was noted that this was also the recommendation made by Nielson (1984) for the dowel action of reinforcing steel in concrete. The Gässler-Gudehus (1981), Shen et al (1981), Gässler (1988), and Stocker-Riedinger (1990) methods were all recommended. Acceptable failure surfaces were considered to be log spiral rigid body rotations and two-part wedges. The method of slices was not highly recommended due to the questionable allocation of reinforcement forces to the individual slices. For safety factors, Schlosser's (1985) method of partial material factors was considered attractive, as was the more rigorous analysis presented by Gässler (1988) that utilized a statistical approach.

2.4 Overview of current design methodology

It is easy to see from the brief review of the development of soil nailing design that there remain a number of issues yet unresolved. Many of the methods and theories presented share common elements, but for every common element there are as many differences. Most of the methods utilize standard slope stability analysis concepts with varying assumptions about the incorporation of interslice nail forces and the application of the reinforcing benefit to each slice. Some of the methods arguably claim that the adopted failure mode is kinematically admissible without presenting any rigorous proof. The benefit of the reinforcements is the major point of divergence. Some of the methods combine the contributions from nail shear and axial forces, while others simply utilize the effect of nail tension. Some methods consider internal equilibrium with the aid of face pressure or simply bond stress, while others do not. Considering the number and variation between methods, it is important to determine the effect of the underlying assumptions on the results of the analysis.

Chapter 3

Description of analysis packages

3.1 Introduction

The analysis packages reviewed in this chapter include the programs, listed below with their sources. Some of these are used for in-house design, others are currently available commercially:

Snail -	Caltrans, Sacramento, CA, USA.
Nail-Solver -	Oxford Geotechnical Software, Oxford, U.K.
Stars -	L'ecole Nationale des Ponts et Chaussees Paris, France.
NailM9 -	Bang, S., South Dakota School of Mines and Technology, S.D., USA.
Goldnail -	Golder Associates, Redmond, WA, USA.
Talren -	Terrasol, Montreuil, France.

3.2 Description of Programs

3.2.1 Snail

Snail is a soil-nailing design and analysis package developed by Caltrans, and the currently available version of the program is **Snail** 2.08. Due to time limitations the preceding version, **Snail** 2.07, was evaluated. Version 2.08 corrects difficulties with multiple soil layers and user-defined linear failure planes that in earlier versions produced unconservative results. It also corrects errors with failure planes passing below the toe when the soil type at the toe is cohesive. As neither of these cases were ever encountered in the evaluation, the analysis contained herein would also appear applicable for version 2.08.

The program uses a two or three part wedge analysis to determine the minimum global factor of safety for a given wall cross-section. It can be used with both passive soil nails, and active tie-backs. In addition, although not actually part of the **Snail** program, it is coupled with a program called **Naildesign,** also developed by Caltrans, which can be used with the data from **Snail** to predict nail loads.

Snail analysis begins by allowing the user to enter a number of different wall parameters and loading scenarios. It is extremely flexible in this respect and can accommodate cases such as benched walls, two slope angles below the wall toe, varying distributed surcharge loads, water table, earthquake loading, failure surface emanating from points below the toe of the wall, horizontal forces applied to the wall face, and varying reinforcement parameters such as length, grout diameter, and bond stress. It is limited to two soil types, and the soil boundaries are specified with two sets of x and y coordinates, requiring that highly variable profiles be approximated by the user. Furthermore, the program looks at internal and external wall stability, i.e., a soil wedge pulling away from the nails (which remain in place), and a soil mass pulling away along with the nails. This is achieved by comparing the required forces for internal stability with an input value for punching shear, expressed in kips. Punching shear is the resultant of the face pressure acting on a section of the wall face, the dimensions of which correspond to the horizontal and vertical spacing between nails. Both punching shear and face pressure are a measure of the structural capability of the facing to resist internal soil failure, through pull-away of the wall from the nails and the subsequent failure of a wedge of soil. The parameter of punching shear is used exclusively in **Snail**; its counterpart, face pressure, is depicted in analysis plots (see Section 4.3) to facilitate comparisons. The parameter of face pressure is used in the program **Goldnail** (see Section 3.2.5). **Snail**'s user's manual is straightforward and includes easy to understand definitions of the required input parameters.

The following method is used with a homogeneous soil profile to determine the global factor of safety. **Snail** divides the user entered search range (see Fig. 3.1) into ten equal parts, or ten nodes. In the case where there is a wall batter, the horizontal distance from the wall toe to the wall crest is subtracted from the search limit, and the remainder is divided up into ten parts. The search intervals begin from the wall crest, if not otherwise specified by the user. For a given node, **Snail** divides the cross-section into a ten by ten grid, and this is done for every one of the ten nodes, unless otherwise specified. The lines are drawn from the toe and the backslope node to every intersecting grid point; each point represents a possible failure plane. A quick check will prove that there are 56 possible grid points, or 56 possible failure planes. Therefore, **Snail** checks a possible 560 failure planes with the ten nodes.

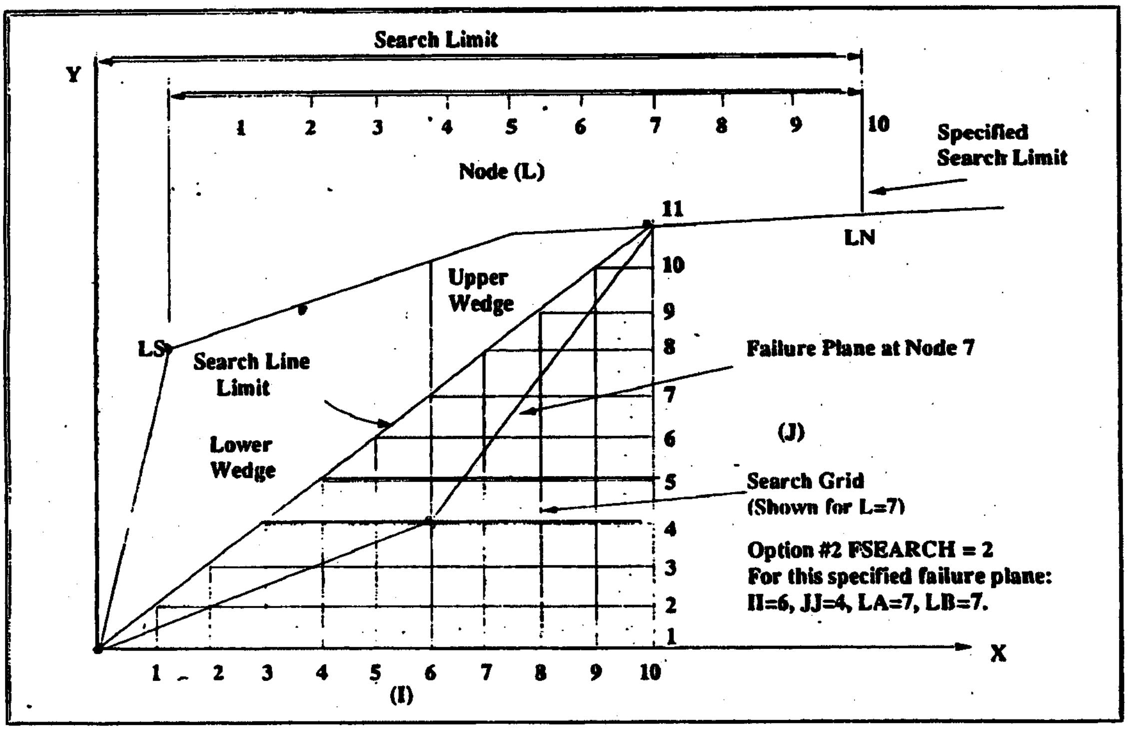


FIGURE 3. SEARCH GRID PATTERN FOR NODE 7.

Figure 3.1 **Snail** Search Grid

The bilinear wedge analysis is comparatively simple and involves a simple summation of forces in the normal and tangential directions for each of the two wedges (upper and lower). The forces acting on a given wedge are as follows: the weight of the wedge, including the water table and any surcharge; earthquake force; mobilized cohesion on the lower surface, as well as the interslice cohesion; the resultant frictional forces on the base of the wedge; the resultant interslice frictional force including interslice nail forces; and, the sum of mobilized reinforcement friction forces acting on the wedge. The contribution of the reinforcement to overall stability assumes that the reinforcement acts only in tension, and that the role of bending stiffness is minimal.

Snail is based on an ultimate or limit state definition of the factor of safety; however it has two modes of operation that differ in their analysis/application of the factor of safety. In mode one, ultimate values of bond stress, yield stress, and punching shear are used. The program iterates on a safety factor which it applies to the material properties C, and ϕ, and to T, the sum of the mobilized reinforcement tension acting on the wedge. The mobilized tension is defined as the lesser of either the nail force developed on the portion of the nail outside the slip surface, or the force developed on the portion of the nail inside the slip surface combined with the user specified value of punching shear. By using the lesser of these two values, **Snail** examines internal and external stability in one pass. Stability is assessed by calculating the resultant interslice friction force, which includes the contribution from the interslice nail forces, for both bilinear wedges (upper and lower). The program then iterates with the material factor of safety until the difference between the two is essentially zero.

In mode two, the calculations and iterations are similar, but the values of bond stress, yield stress, and punching shear are entered pre-factored by the user. In this way, different factors of safety with respect to each of the three quantities can be used. If the ultimate values of bond stress, yield stress, and punching shear are prefactored with the factor of safety obtained from a mode one run, then the obtained mode two factor of safety is the same as that obtained from Mode one. This is because the program iterates by changing only the factor of safety on soil strengths. In our comparison, mode two was used so that the material factors of safety on the bond stress and yield strength remained constant at 1.5.

Snail output includes a graphical representation of the wall cross-section displaying the slip surface with the lowest overall factor of safety. This can be printed using the printscreen utility of DOS (Disk Operating System). The results of the calculation along with the input parameters can also be output.

As a final note, a math coprocessor will significantly reduce the time required for calculation with **Snail**. Complicated walls may take up to twenty minutes to run without the coprocessor.

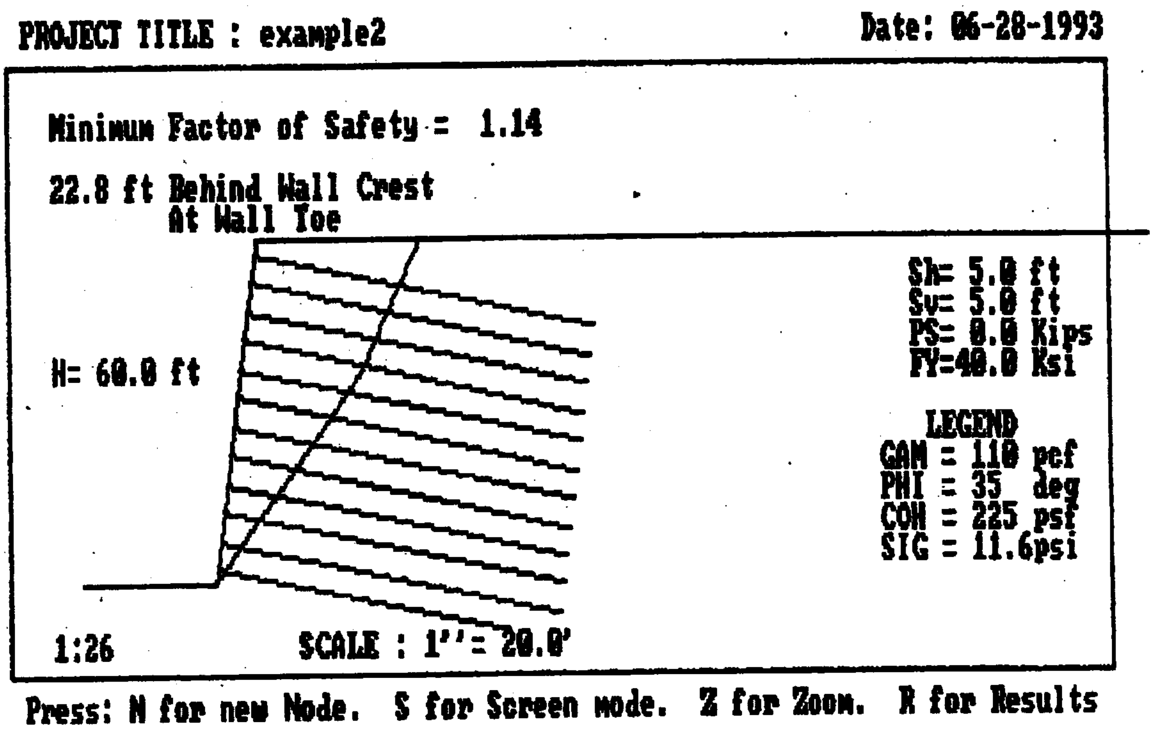


Figure 3.2 **Snail** Output.

3.2.2 Nail-Solver

Nail-Solver is a computer design package developed by Oxford Geotechnical Software and is based on work by Jewell and Pedley at the University of Oxford. It is currently available as version 1.1. **Nail-Solver,** like **Snail,** uses a bilinear wedge analysis to evaluate both internal and overall stability of a given soil-nailed cross-section.

The program is somewhat limited in the cross-sections and loading conditions that it can handle. The wall must be a single element, without benches, and there can be no toe slopes, or more than a single slope above the wall. Varying reinforcement parameters, such as spacing, length, grout diameter, bar diameter, etc., cannot be accommodated. The pullout resistance is calculated using nail overburden stress, and a dimensionless bond coefficient, f_b, which represents a percentage of the factored soil friction angle (the given range of f_b is from 0.4 to 1.0). There is no allowance for actual pullout data. The horizontal and vertical nail spacing is entered by the user, but if the program reaches the bottom of the wall and finds a space of more than one half the vertical spacing, it will automatically add an additional row of nails.

Nail-Solver allows the use of point loads and uniformly distributed loads, but is unable to handle varying distributed loadings. Pore pressures can be input using a non-dimensional pore water pressure coefficient, r_u, which represents a percentage of the soil overburden stress. A single r_u value describes a distribution of pore pressures that increases with depth. It should be noted that **Nail-Solver** uses effective parameters for ϕ and C. The soil shearing resistance is described by a secant angle of friction relevant to the effective stress range for the soil in the cross-section. For this reason it is necessary to prefactor the effective cohesion, as the factor of safety on peak soil shearing resistance is not automatically applied to the cohesion.

Nail-Solver starts the computational process with a calculation of 120 unreinforced trial failure wedges to determine the maximum required forces for internal equilibrium. The program examines wedges intersecting the wall at ten different elevations below the crest. Required forces for the internal equilibrium are derived from a simple summation of forces, which can be approximated with the use of Coulomb's formula,

$$P_a = 0.5 K_a \gamma H^2 \qquad (10)$$

where P_a = active soil force

K_a = active earth pressure coefficient

γ= soil unit weight

H = depth below the wall crest

The reinforcement parameters, such as nail length, grout diameter, spacing, etc. are then entered by the user and the program calculates the maximum required forces for overall equilibrium using a two part failure mechanism. For each of the bilinear wedges passing from the toe to ten different elevations at the back of the reinforced zone, a search is made to find the worst inclination of the back wedge. The required forces are calculated using a summation of forces on the two wedges, with the condition of horizontal and vertical equilibrium. They are assessed first by determining the vertical spacing of the nails, based on the entered 'trial' spacing. Next, bond strength is calculated based on the bond coefficient, f_b, and the average of the vertical effective overburden stress and the lateral effective stress acting parallel to the slope. Reinforcing benefit is derived from the portion of the nails outside the slip surface. If a nail passes through the failure plane and into the soil beyond, it is assumed to be able to contribute the lesser of the total yield strength of the nail, or the bond stress integrated over that portion of the nail outside the failure plane. Next, two passes are made comparing the required and available forces for internal equilibrium, one during construction (without the next nail installed), and one at the end of construction. Finally, two more passes are made to compare required and available forces for overall equilibrium, during and after construction.

Nail-Solver, for the purpose of comparison, has the added complication of bond stress calculated from overburden stress. The problem is twofold. First, without a strictly specified value of bond stress the program comparisons are not exact. Second, the material factor of safety applied to ϕ for the soil is also applied to the calculations of bond stress through the use of the factored soil ϕ value. In order to allow the comparison, a procedure had to be developed that could approximate the design bond stress using nail overburden stress, a lateral earth pressure coefficient, and a bond coefficient. A point was chosen half-way along the length of the middle nail (or between the nails, in the case of an even number of nails). The overburden stress was calculated at this point. **Nail-Solver** uses the following formula to calculate the bond stress at a given depth:

$$\tau = \sigma_v' (1+k_L) f_b \tan \phi_d' \qquad (11)$$

where k_L = lateral earth pressure coefficient

f_b = bond stress coefficient

ϕ_d' = effective soil friction angle for design.

This formula was set equal to the allowable bond stress used in the other programs, at this middle nail depth, and solved for k_L. This value of k_L was used in the subsequent run, although in a number of cases its value exceeded one. This was the only way to modify the equation to produce the desired results, as the bond stress coefficient f_b was limited to a maximum value of one. In this way, the specified bond stress was approximated for all the nails. The value of k_L is used only to compute bond stress, and therefore artificially high values have no effect elsewhere in the calculations.

The program allows the user to enter both ultimate and allowable values of yield stress and the soil properties C' and ϕ', and displays on-screen the calculated material safety factor. In this way it does utilize individual material factors of safety, providing the user with an overall global safety factor at the end of calculations. It should be reiterated that the bond stress is computed using the design value of ϕ', and therefore carries with it the factor of safety on soil strength. This was not an issue with our comparison, however, as the average value of bond stress calculated with an artificial k_L, included only the safety factor of 1.5 used on bond stress.

Nail-Solver output is in the form of graphs of force vs. depth below crest, showing maximum required and minimum available forces previously calculated for both internal and external stability, both during and after construction. Depth below crest refers to the depth below the crest at which either the internal wedge intersects the wall facing (in the case of the internal equilibrium plot), or the depth below the crest at the back of the nailed zone that delineates wedge one from wedge two (in the case of the overall equilibrium plots). In order to ensure that the global factor of safety was equal to one, the curve of required forces was made to just 'touch' the curve of the available forces, either those limited by the bond stress, or those limited by the steel, depending on the individual case. In all cases, the most critical case (either internal stability at the end of construction or overall stability at the end of construction) was used to achieve this global factor of safety equal to one. No output specifying the location of a failure surface is given, and therefore no failure surface for **Nail-Solver** is depicted on the comparison plots (see Section 4.3).

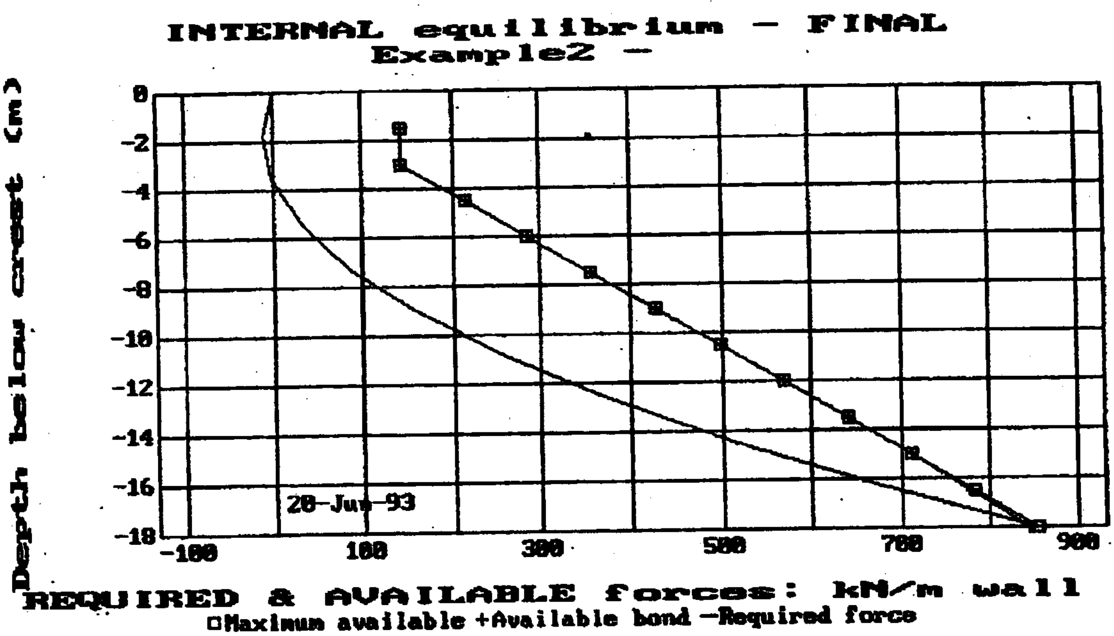


Figure 3.3 **Nail-Solver** Output.

3.2.3 Stars

Stars is a program developed by a joint venture known as C.N.R.S., which includes the Laboratoire Commun a l'Ecole Polytechnique, l'Ecole Superieure des Mines de Paris, and l'Ecole Nationale des Ponts et Chausses. It is currently available in a version 2.0.

Stars uses a moment balance coupled with a log spiral failure surface to calculate an overall, or global, safety factor. The program has an excellent user interface with on-screen graphics and brief descriptions for all entered parameters. Since much of the terminology and all of the user's manual are in French, these on-screen attributes are particularly useful. The program can handle different reinforcement parameters, allowing the user to enter individual nail properties. It can handle varying distributed surcharges, point loads, wall toe slopes, multiple sloping soil layers, and a simple non-sloping bedrock surface. It can also be used with tie-backs or a combination of tie-backs and nails. The program is limited, however, in that water tables and multiple ground surfaces behind the wall are not accommodated. Furthermore, the program will not allow backslopes with angles greater than the allowable ϕ value of the top soil layer. A significant advantage of the program, however, is that it will directly assess overall stability during construction and after construction, and the stability of deep-seated failure surfaces not passing through the toe.

Stars uses a log spiral slip surface and therefore no assumption of the distribution of the normal forces along the slip surface is needed. The program starts at the upper nail level, and hunts for surfaces that intersect the wall face just below the nail, with no assumed benefit from the nail. This is often a critical case during construction, when the cut has been made, and the nail is not yet installed. The program then proceeds to the next nail level, until it reaches the bottom of the wall where the final or End-Of-Construction safety factor is determined. Different soil layers with different ϕ values produce slightly different log spirals, so **Stars** creates a composite surface.

Stars calculates a resisting and a driving moment for each trial slip surface like many slope stability programs. The driving moment is calculated considering the weight of the soil and any surcharges present. Surcharges at the toe of the slope that increase resistance are considered as negative driving moments. The resisting moment is calculated by integrating the contribution of the soil shearing resistance to the resisting moment along the length of the slip surface. The result of the frictional forces acting on the slip surface, both normal and shear, passes directly through the center of the log spiral, negating its effect on the moment. The component of the remaining resisting force perpendicular to the moment arm (Ccosϕ; see Fig. 3.4) is then multiplied by the moment arm and integrated along the slip surface.

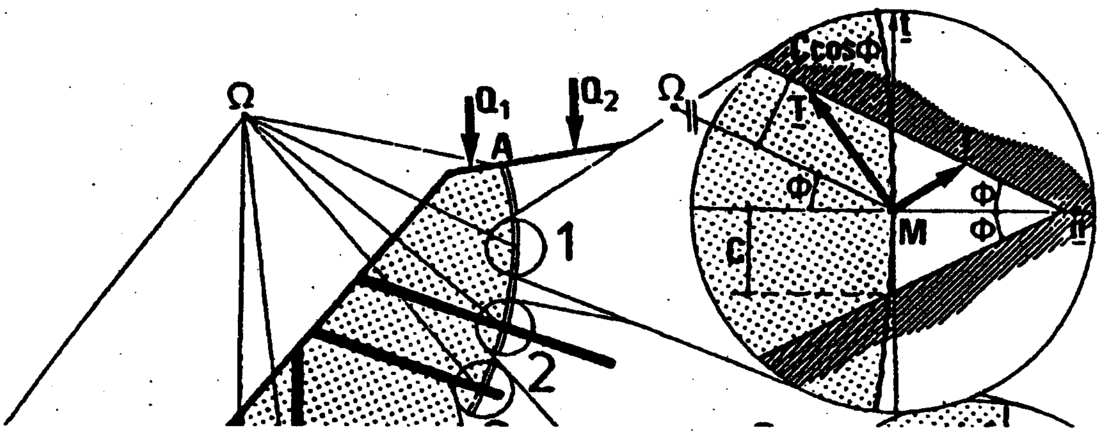


Figure 3.4 Tension and Cohesion Forces Acting on a Log Spiral Surface-**Stars**.

Every time reinforcement is encountered, **Stars** simply adds its contribution to the resisting moment in the following way. If the reinforcement is positioned in such a way across the slip surface that it is working in compression, or if it is aligned along the ray of the log spiral, its contribution is considered to be zero. If the reinforcement is positioned to be working in tension, it is assumed to be contributing the lesser of either the maximum yield stress of the nail, or the lateral soil/grout interface friction over the length of the nail outside the log spiral. The contribution perpendicular to the log spiral radius of this vector N is multiplied by the moment arm to give its resistance. Internal stability is not checked with the current version of **Stars**.

The overall factor of safety **Stars** displays after calculation is a straightforward M_r/M_d, where M_r is the resisting moment and M_d is the driving moment. **Stars** does allow the user to enter individual material safety factors on lateral interface friction, yield strength, soil strength, and surcharges.

The output of **Stars** consists of a DOS printscreen capture of the wall cross-section depicting the various critical slip surfaces intersecting the slope at each of the nail levels and at the toe. In addition, if previously calculated, the critical deep-seated slip surface will be shown. Also output is a summary of the input data and the results of the calculations. The output results are limited to the depth below the crest of the failure surface intersection and overall or global factor of safety ("factor of confidence" in Fig. 3.5).

It should be noted that at present a math coprocessor is required to run **Stars**.

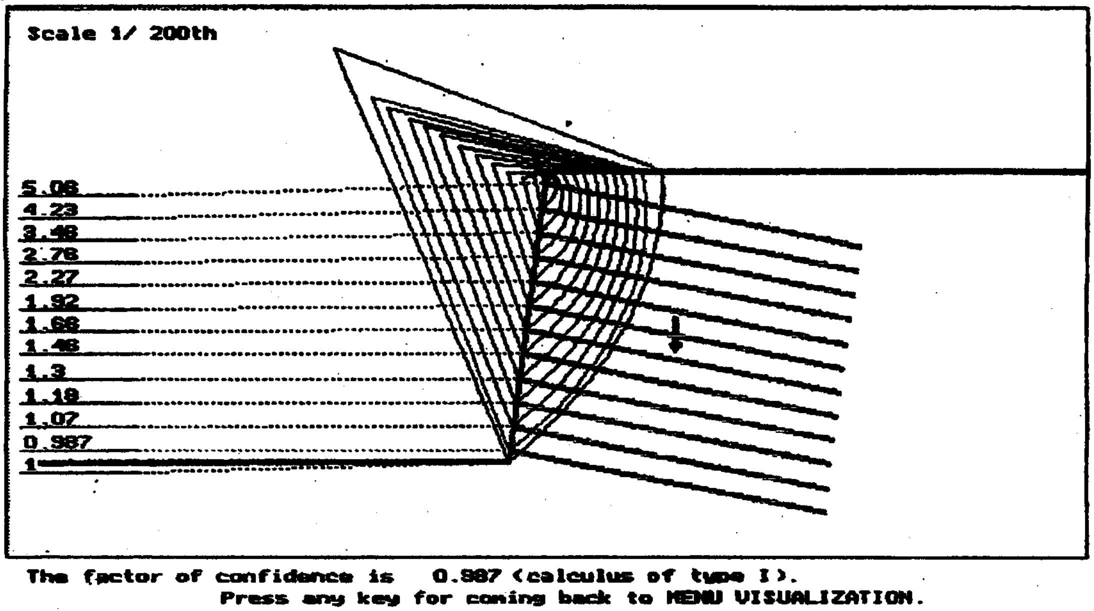


Figure 3.5 **Stars** Output.

3.2.4 NailM9

NailM9 was developed by Bang at the South Dakota School of Mines and Technology. It is unique in that it uses a parabolic slip surface to describe the failure, based on finite element studies of in-situ reinforced soil (Shen et al., 1981a,b). The program has limited input options, and minimal user interface complicates data entry. Data are entered in response to program prompts, and are stored in a data file. There are separate files for data entry and output; viewing the input or output files requires exiting to the text editor.

NailM9 can handle different horizontal soil layers, simple distributed surcharges that act over the entire backslope, point loads, earthquake loading, and varying nail length. The program allows one to use either pullout test data or a bond stress calculated from overburden stress. It cannot accommodate varying nail pullout resistance or varying nail parameters such as grout diameter, yield stress, and bar cross-sectional area. It is also unable to handle water tables, stepped walls, or toe slopes.

For each program run, use of an existing data file must be specified or data must be entered manually. Subsequent runs involving only minor changes to entered data require re-entry of much of the original data. This is because the data modification part of the program works with segments of data, not individual parameters. As an example, changing the grout diameter after completing an initial run would require re-entering all other nail data. Furthermore, once this modification has been made, changes to the existing data file cannot be stored without exiting to the DOS text editor and modifying the entry file.

The program asks for a user-input search limit. It then divides this distance up into even increments and proceeds to run parabolas from the toe to each of these points. Each parabola is divided into two parts--a reinforced slice, and an unreinforced slice (see Fig. 3.6). If the parabola passes beyond the length of the uppermost nail, the X coordinate of the division between the reinforced slice and the unreinforced slice is the coordinate of the end of the uppermost nail. If the parabola passes completely through the nailed zone, the X coordinate of the slice division is that point where the failure parabola intersects the uppermost nail.

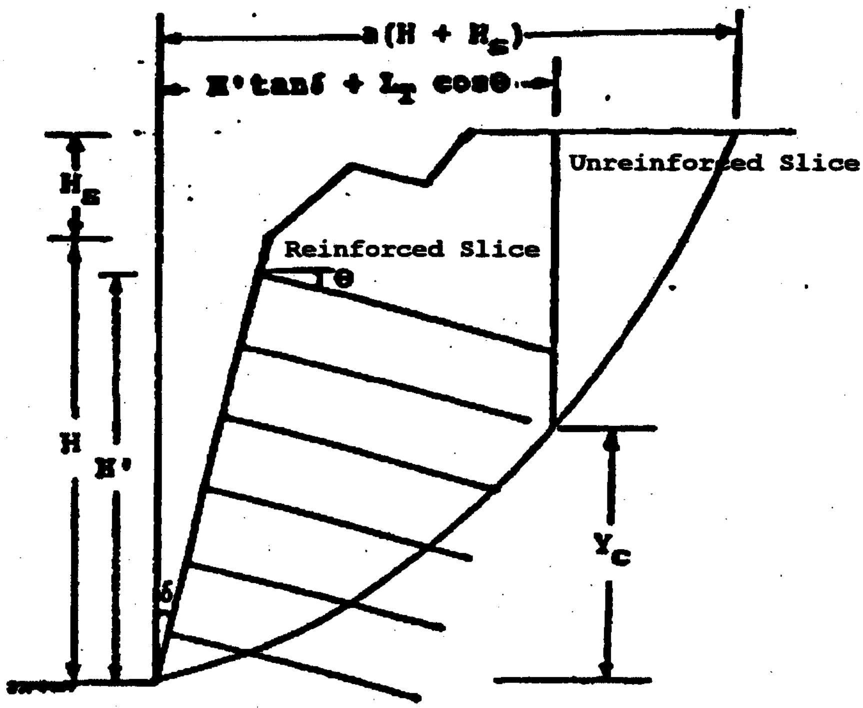


Figure 3.6 **NailM9** Assumed Failure Surface.

The reinforcement contribution is determined simply as the pullout resistance developed over the length of the nail beyond the slip surface. The stability calculation involves a straightforward summation of forces with a slight difference in the definition of the factor of safety. Instead of the standard resisting forces divided by the driving forces, **NailM9** defines the overall or global factor of safety as the component of the total resisting force in the direction of the driving force divided by the total driving force, resulting in a consistently lower value compared to the standard approach.

NailM9 does not make direct allowances for individual material factors of safety; however, to allow comparison with other programs, the entered values of bond stress and yield stress were prefactored, and the overall factor of safety was made to equal one by changing the material factors of safety on the soil.

Output is a standard printout of the input parameters, the slip surface and lowest safety factor from the results of the parabolic searches, and the location of this surface behind the crest. In order to compare the surface with that of other programs, hand calculations were made using formulas given in Bang et al. (1991) to delineate the parabolic surface on the cross-section.

3.2.5 Goldnail

Goldnail is a program developed by Golder Associates and is based on limiting equilibrium using a circular failure surface and the Janbu method of slices (Janbu, 1973). It can accommodate passive soil nails as well as active tiebacks. **Goldnail** has the capability not only of checking possible designs, but also of actively designing walls and predicting nail loads.

Goldnail can accommodate widely varied back slope geometry through the entry of single points and subsequent user input connecting lines. It can handle multiple and varied soil layers, water tables, earthquake loadings, varying distributed surcharges, point loads, and varying nail parameters such as adhesion, length, and yield strength. It is unable to directly handle benched walls or toe slopes. These last two can be accommodated by making certain assumptions about the wall modeling, such as using an equivalent sloped wall facing to model a benched slope. This is true with many of the other programs that cannot directly accommodate benched walls (**Nail-Solver, NailM9,** and **Stars**).

The user interface is somewhat tedious in **Goldnail.** Although all input data can be viewed on-screen in the program, in order to view or print a given output file, one must enter the DOS text editor and edit the output file. **Goldnail,** like **Snail,** is able to examine the internal stability of the wall and incorporates the use of a face pressure value, entered in psf by the user. This face pressure value (previously described in Section 3.2.1) is a measure of how resistant the facing is to having the bar punch through the wall. This is important because the adhesion between the nail and a thin failure wedge behind the wall is minimal.

It is important at this point to distinguish between **Goldnail**'s two modes of operation. In mode one, the design mode, all information about the wall geometry, soil properties, and desired factor of safety on the soil is entered. The program then determines the required nail lengths, loads, and face pressure required to meet this factor of safety. The program does this by stepping through a number of slip surfaces that pass through the wall toe, or through a user-specified point. The circles are bounded by the inclination of the wall facing, and by the two minimums of the parameters α and β specified by the user. α is the minimum tangential orientation of the slip circle at the wall toe. β is a minimum angle measured from the horizontal, at the wall toe, whose intersection with the back slope specifies the search limit. This value is used to define a range for the radii of the trial slip circles. The program then steps through the angles α and β and begins to construct circles from the toe to each node. The first pass assumes that the nails have sufficient pullout capacity beyond the failure surface, and is used to determine the minimum value of face pressure necessary to obtain the user-specified factor of safety on the soil. The second pass then uses this value of face pressure to determine the length of nail required, by systematically adding an incremental length to each nail until the specified factor of safety is met. Finally, using the determined values of face pressure, nail length, and factored adhesions, the program calculates the nail loads.

In mode two, or the factor of safety mode, a given wall geometry and soil properties are entered, as well as the nail properties such as length and maximum load, values for face pressure, and desired factor of safety. Here the object of the program is to identify any slip surfaces that have a factor of safety lower than that of the user-specified safety factor. The maximum nail load is simply entered as the product of the factored yield strength of the steel and the nail's cross-sectional area. It is important to note here that with any limit equilibrium method, assumptions have to be made regarding the distribution of nail forces along the nail. **Goldnail** computes each nail's contribution to stability by using a triangular distribution of forces along the nail. If face pressure is included the nail sees a jump in the force applied at its head. Depending on the specified adhesion values for the soil, the force distribution then increases linearly toward the middle of the nail. Starting from the other end, the same linear increase occurs, without the additional value of face pressure. The maximum value of the force is obtained when the two force distribution lines intersect. As **Goldnail** considers only tension in its analysis, the value used to determine overall stability is that value of tension present in the nail where it crosses the trial failure surface. By using this value, **Goldnail** eliminates the practice of using the entire length of the nail outside the slip surface as the contribution to stability. The difference is most evident when one looks at the lower nail in a given wall. Conventional methods would dictate that any extensive length of nail outside the slip surface would contribute a great deal to the stability; however, it is widely known that the bottom nail has little applied force. **Goldnail** predicts this, as the nail force contributing to stability is limited by the bond stress acting on the nail between the slip surface and the wall facing. In this way, the program considers face pressure and

its effect on the force distribution on the nail. It also eliminates the need for a separate step to check internal stability, as it can consider pullout of the bars and the pull-away of the soil simultaneously.

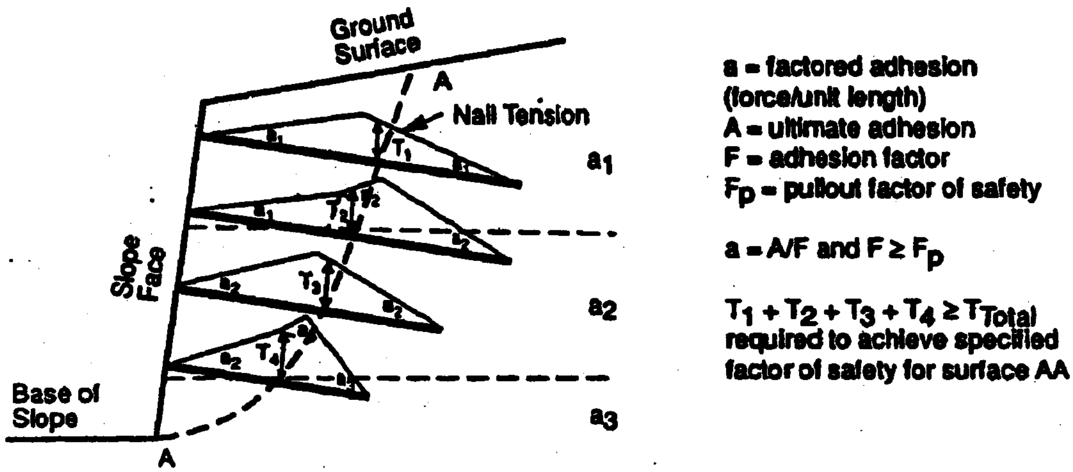


Figure A-1. Nail Tension Distribution - Limiting Equilibrium Analysis

Figure 3.7 Nail Tension Distribution - **Goldnail**

Equilibrium of the system is analyzed with a Janbu method of slices approach. Each slice must satisfy horizontal and vertical equilibrium. The total nail force contributing to equilibrium is known, but how that force is distributed throughout the various slices is not known. **Goldnail** places fictitious nails so that one nail passes through the center of the base of each slice. Using the same procedure as before, it determines a distribution of nail tension forces. It then divides the actual total nail force into components applied to the base of each slice, based on this computed force distribution. The same process is used with interslice nail forces. Three fictitious nails are run through each slice to determine relative magnitudes of the nail interslice forces. All forces acting on the base of a given slice are known, as well as the interslice forces and the relative magnitudes of the nail forces. In order to reduce the number of unknowns, the assumption is made that the interslice soil shear forces acting on either side of a slice are equal and opposite in direction, and therefore cancel.

Goldnail defines its overall factor of safety as a material strength factor applied to the soil strength parameters. The traditional overall safety factor of F_r/F_d (resisting forces divided by the driving forces) is internally set equal to one. There is no specific allowance for individual material strength resistance factors in **Goldnail**, but as in many of the programs,(**Snail**, **Nail-Solver**, **Stars**, and **NailM9**) the user can simply pre-factor the values of soil adhesion and yield strength of the steel. **Goldnail**'s definition of its output factor of safety was totally compatible with the procedure adopted for the comparison. It did not require multiple runs per wall to iterate to a value of 1.0 for the overall or global safety factor. In order to view the slip surface with the lowest factor of safety, it was necessary to lower the factor of safety applied to the soil to just above the lowest factor calculated. This is because, as was mentioned before, the program will only display circles with a safety factor lower than that specified.

Output from **Goldnail** includes a DOS printscreen capture of the wall cross-section and failure surfaces (see Fig. 3.8). Also output through the print utility of the DOS text editor is a printout of the input parameters and results for each of the weakest slip surfaces run through a given node.

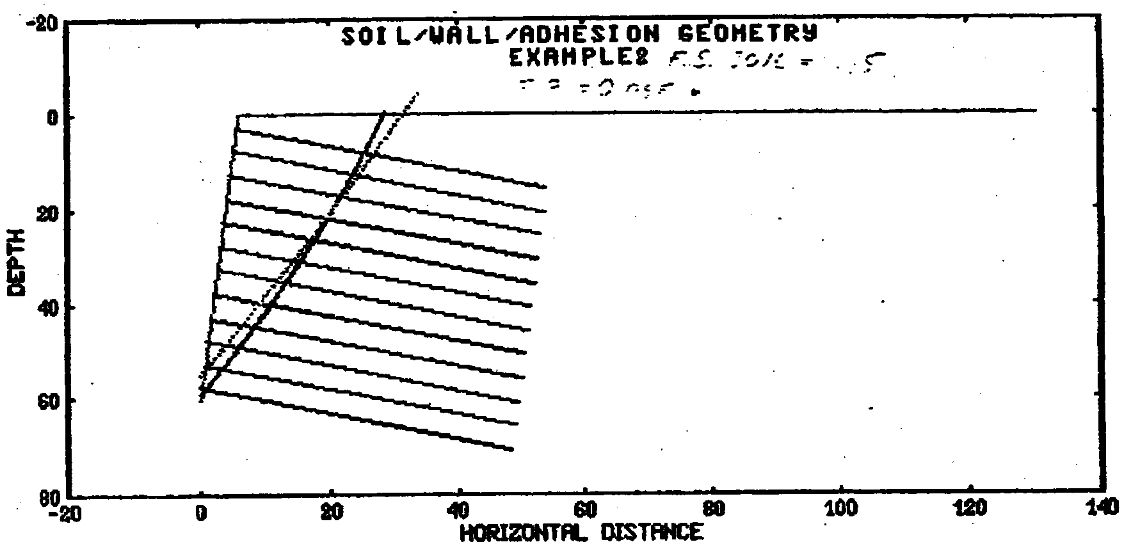


Figure 3.8 **Goldnail** Output.

3.2.6 Talren

Talren is a general slope stability and reinforced soil design package developed by the French company Terrasol. It is a much more comprehensive program than the other five programs being evaluated herein and in addition to soil nails, can handle tie-backs, struts, Reinforced Earth strips, geotextiles, piles, micropiles, and retaining walls. It is currently available in version 2.3 as of 6/29/93.

The program can handle any one of a number of inputs for hydraulic conditions including user specified points on a phreatic surface, specified pore pressures, or a triangular mesh with pore pressures defined at every point. Any cross-sectional geometry with the exception of overhangs can be accommodated, as can varying distributed surcharges, linear surcharges, additional applied moments, and seismic loadings. Intrinsic strength curves can be input for a given soil, as well as curves for cohesion anisotropy.

User input is complicated by the fact that prompts for data entry are given by a shortened French term, (e.g. ESP for horizontal spacing, short for espace in French). Many of the terms in the program have poor descriptions given in the user's manual. The manual is poorly laid out, and descriptions of a given input parameter are often hard to find.

Talren utilizes classical limit equilibrium methods of slope stability to calculate its overall safety factors for a given cross-section. User defined calculation methods include the simplified Bishop method of slices, Fellenius' method of slices, or the perturbations method. For our comparison, the simplified Bishop's method was used. As is standard with this method, the soil is divided into infinitesimally small vertical slices, and the static equilibrium of these slices is evaluated. The global safety factor is assumed constant along the length of the failure surface, and is defined as the ratio of the maximum shear strength, τ_{max}, to the mobilized shear stress, τ, along the failure surface.

Talren is divided into different modules. A separate module allows data entry and provides the data entry format. Another module calculates the stability, yet another provides the graphical representation of the results, and another serves as the 'home' menu. **Talren** is the only program considered in this comparison that can calculate the bending and shearing resistance of the soil nails. The calculation requires the user to input a large number of terms to describe not only the nail properties, but the soil and the nail/soil interaction properties. Among the complicated input parameters are the following terms:

P_L, the limit pressure of the soil

K_{sb}, the horizontal soil modulus

L_b, the width of the base of diffusion for the nail shear and tension forces

ALB, the angle of diffusion for the above mentioned forces

ANGC, the critical angle for the soil-nail interaction

M_{max}, the plastification moment of the nail

Any potential gain in accuracy of modeling is offset by the following:

1) no guidelines for the selection of these parameters is given in the manual;
2) there is no evidence that varying these parameters had any impact on the results of this comparison.

Failure of the nail is calculated using Schlosser's Multicriteria analysis (Schlosser 1985), where a limit envelope for the nail is constructed using the curves for the plastification of the soil, plastification of the nail, limit lateral friction, and yield stress of the steel.

The critical slip surface is determined through a classical grid of circle centers where the grid parameters such as location, size, angle between adjacent centers, and number and increment of radii to be searched are entered by the user. A given circle is then divided into slices and the corresponding assumptions regarding interslice forces are made. If the Simplified Bishop Method has been selected, the interslice shear forces are assumed to be equal and opposite, and therefore cancel. If the center of the circle is below the wall crest, the program will create a composite surface, rather than allowing an overhang. The composite surface will simply consist of a vertical portion grafted onto the remaining 'allowable' surface (see Fig. 3.9). It should be noted here that the program conservatively assumes the shear forces acting on the vertical section of wall are zero. The manual indicates that in later versions this assumption may be replaced by an active soil pressure distribution acting on the vertical section of the slip surface.

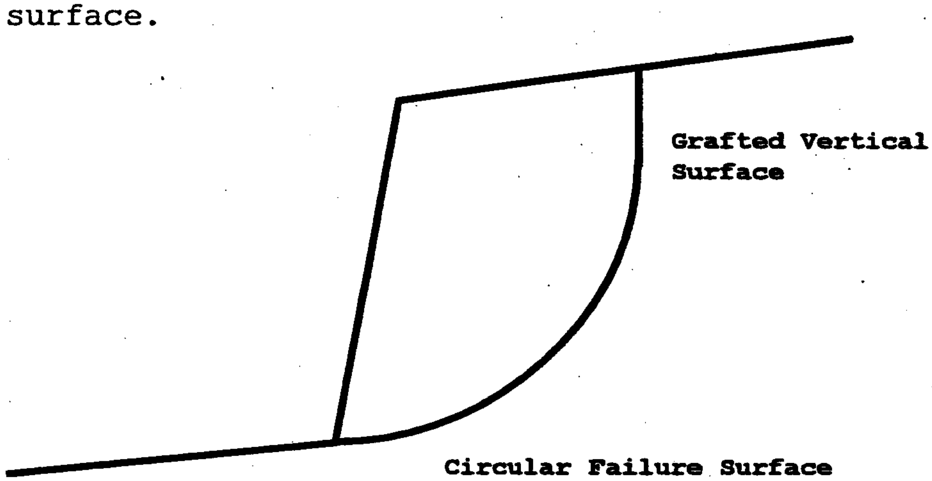


Figure 3.9 **Talren** composite failure surface

With soil nails, the inclusion is assumed to be working in a combination of tension and shear. As with all limit state analyses the nails are evaluated using their at-failure strengths. These strengths, as was mentioned before, are determined using Schlosser's Multicriteria envelope. The nail is modeled as an elastically supported beam. In shear and normal space, the Tresca criterion provides a limiting envelope equal to:

$$(T_n^2/R_n^2) + (T_c^2/R_c^2) \leq 1.0 \qquad (12)$$

where T_n = tension force in the nail

R_n = ultimate tension force in the nail

T_c = shear force in the nail

R_c = ultimate shear force in the nail = $R_n/2$

At the point of maximum moment the nail works in combined bending. Here the developed envelope has the form

$$M_{max} = M_{max0}(1-(T_n^2/R_n^2)) \qquad (13)$$

where M_{max0} = maximum bending moment of the nail in simple flexure.

This equation is only valid for a rectangular bar, and is conservative for circular cross sections such as nails. The soil/inclusion lateral friction is limited by:

$$T_n \leq L_a f_{lim} \qquad (14)$$

where L_a = length of the nail outside the slip surface

f_{lim} = limiting shear force/length of nail

The nail normal reaction is limited by the elasto-plastic rule:

$$P = K_s y \qquad (15)$$

where P = soil pressure under the nail

K_s = soil modulus of subgrade reaction

y = deflection of the soil

and

$$P \leq P_L \tag{16}$$

where P_L = limit pressure of the soil.

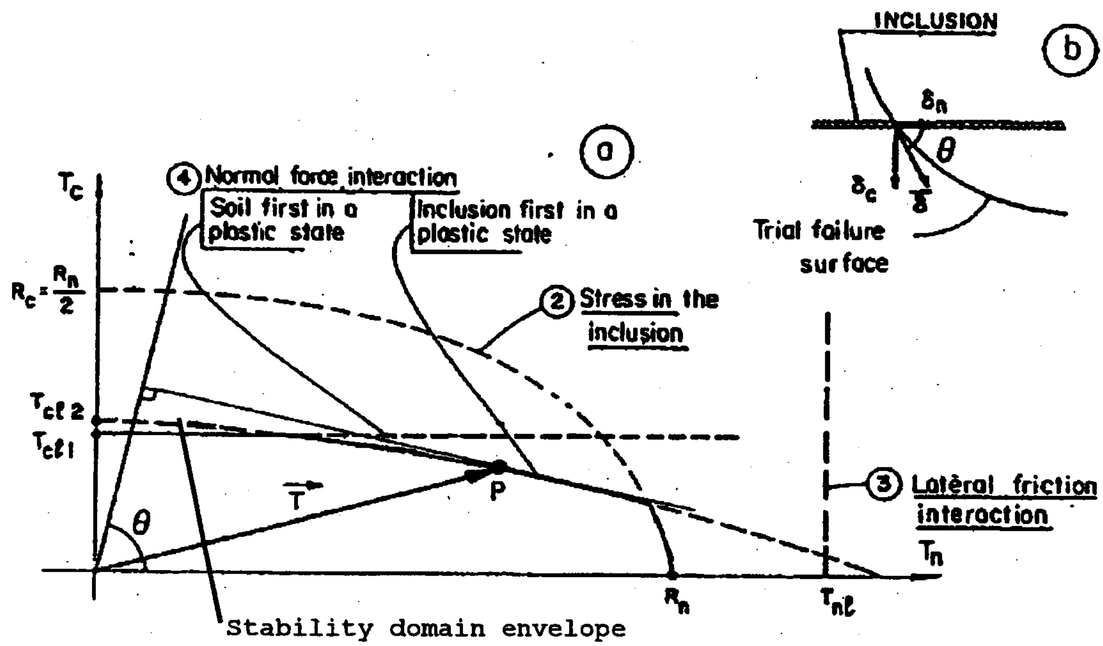


Figure 3.10 Schlosser's Multicriteria Envelope used in **Talren**.

Talren models the nails in two different ways, based on their transfer length. It assumes that they can either be modeled as an infinitely long beam, or an infinitely rigid beam. At the point of convergence, the difference between the two analyses differs by 25%.

Table 3.1 **Talren** Nail Modeling

Bending resistance of the inclusion (M_{max})	Minimum length available on one side of the failure surface	
	"Long" inclusion $L^* \geq 2 \cdot L_0$	"Short" inclusion $L^* < 2 \cdot L_0$
HIGH	$M_{max} > 0.16 \cdot p_l \cdot B \cdot L_0^2$ $T_{cl1} = p_l \cdot B \cdot L_0 / 2$	$M_{max} > p_l \cdot B \cdot L^{*} 2/27$ $T_{cl1} = p_l \cdot B \cdot L^* / 4$
LOW	$M_{max} < 0.16 \cdot p_l \cdot B \cdot L_0^2$ $T_{cl2} = 0.24 \cdot p_l \cdot B \cdot L_0 + 1.62 \cdot M_{max} / L_0$	$M_{max} < p_l \cdot B \cdot L^{*} 2/27$ $T_{cl2} = 0.10 \cdot p_l \cdot B \cdot L^* + 4.05 \cdot M_{max} / L^*$

In order to utilize the envelope to determine the limit state nail forces applied to an individual slice, the program uses Mandel's theory of maximum plastic work (Mandel, 1978). The basic principle of this theory is that at the point of intersection between the nail and the failure surface, the relative displacement between the two parts of the nail, δ, is assumed to be tangent to the failure surface (see Fig. 3.10). Point P in this figure corresponds to the point of tangency between the stability domain (as defined in Fig. 3.10) and the perpendicular to the δ direction (defined by the angle θ). T represents the combination of shear and normal forces in the nail; as can be seen in Fig. 3.10, T intersects the stability domain at point P, the limiting value of shear and normal forces in the nail.

The contribution of the nails to the stability of a given slice is handled by applying the normal and tangential reinforcing forces at the failure surface to the base of the slice and along its axis. In addition, in cases of highly heterogeneous soils it is possible to distribute the nail forces, both shear and tension, over a larger area. This is possible through the specification of a base width of diffusion for the forces L_b, and an angle of diffusion ALB, (both previously defined in Section 3.2.6) which define how the diffused area expands as it moves from the head of the nail to the slip surface. The calculation process for the overall stability is as follows.

a) Calculation of the safety factor for the unreinforced soil.
b) Calculation of the tension and shear forces for each reinforcement, based on the previously calculated safety factor.
c) Determination of the distribution of tensors associated with (b).
d) Calculation of the reinforced soil safety factor.
e) Iteration from steps (b) through (e) until convergence is obtained between the safety factors.

It is necessary to iterate until conversion because calculation of the tension and shear forces in the nails depends on the unreinforced soil safety factor. In order to derive an overall or global safety factor, **Talren** adds the component of the tension forces supplied by the nails perpendicular to the slip surface to the resisting moment, and subtracts the shear resistance supplied by the nails from the driving forces.

Output from **Talren** is in the form of plots of the wall cross-section with the slip surfaces depicted, as well as convenient displays of the material safety factors and the soil properties. Calculation output can also be in a number of different forms. The program prompts the user to define specifically which output is required; the comprehensive option includes the input parameters, as well as all worst case surfaces for each circle center and the corresponding nail forces. **Talren** supports the output of the calculation results on any number of common printers, although the printout is in landscape format. The graphical output, however, requires a plotter, post-script laser printer, or a laser-jet III or later model for proper results. The program also supports the use of two separate plotting routine programs, which are not included with the basic package. The program has a separate utility (not reachable from the main menus) that allows one to select the printer type, and provides marginally better resolution than the printscreen utility of DOS, which results in nearly illegible output of many screen figures.

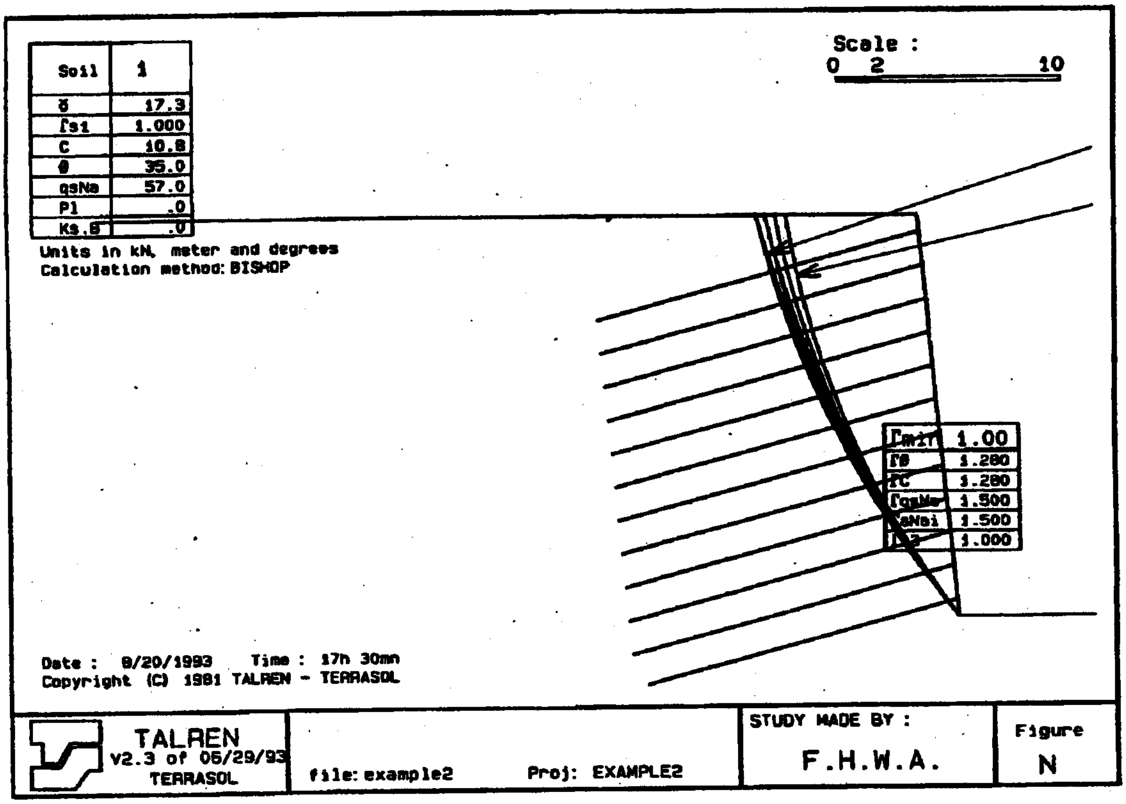


Figure 3.10 **Talren** Output.

Table 3.2 Program feature summary

	Goldnail	NailM9	Nail-Solver	Snail	Stars	Talren
Cross-section						
Can accommodate benched walls	x (1)			x		x
Multiple backslopes	x	x		x		x
Toe slopes	x			x	x	x
Wall						
Face pressure input	x			x		
Soil/water						
Number of soil layers	unlimited	unlimited	1	2	unlimited	unlimited
Irregular soil profile	x					x
Water table	x			x		x
Inclusions						
Nail bending moment considered						x
Varying nail length	x	x		x	x	x

x signifies that the program will accommodate the specific option

Notes:
(1) **Goldnail** will allow the user to enter points defining a benched wall. The program will calculate the safety factors or nail loads based on an equivalently sloped wall face. The output data defining the wall geometry will, however, remain as the user entered it.

Table 3.2 (continued)

	Goldnail	**NailM9**	**Nail-Solver**	**Snail**	**Stars**	**Talren**
Input for pullout test data	x	x		x	x	x
Can accommodate tiebacks	x			x	x	x
Loadings						
Non-areal surcharges	x		x	x	x	x
Point loads		x	x		x	x
varying surcharges				x	x	x
seismic loadings	x	x		x		x
Horizontal forces applied to wall face				x		
Failure surfaces	circle	parabola	bilinear wedge	bilinear wedge	log spiral	circle
Graphics capabilities						
On-screen display of data during input					x	
Graphical output depicting cross-section	x			x	x	x

Chapter 4

Results

4.1 Method of comparison

The analysis packages presented in Section 3 were evaluated by running fifteen examples on each program. The design examples include ten fictitious walls, three actual in-service walls, and two actual failure cases. The computed 'factor of safety' and the location of the slip surface for each case were compared to evaluate the performance of the programs.

Table 4.1 Summary of examples

Example	Brief description
Example 1	30' wall, horizontal backslope, 5.7° batter
Example 2	60' wall, horizontal backslope, 5.7° batter
Example 3	30' wall, sloped backslope, 14° batter
Example 4	20' wall, horizontal backslope, 0° batter, surcharge
Example 5	Benched 40' wall, sloped backslope, 0° batter
Example 6	60' wall, horizontal backslope, 5.7° batter, 2 soils
Example 7	40' wall, horizontal backslope, 0° batter
Example 8	40' wall, sloped backslope, 0° batter
Example 9	40' wall, sloped backslope, 10° batter

Table 4.1 (continued)

Example 10	45' wall, sloped backslope, toe slope, 0° batter
SanBernadino	25.5' wall, sloped backslope, 5.7° batter
Swift-Delta	27.5' wall, 4.8° batter, surcharge
Polyclinic	55' wall, horizontal backslope, 0° batter, 2 soils
Eparris	14' wall, sloped backslope, 20° batter
Bodenvernag-elung	20' wall, horizontal backslope, 9.5° batter, surcharge

In order to accommodate the different definitions of an overall safety factor, a standardized approach was devised to ensure that the comparison was as fair as possible. This of course does not include the inherent effect of differences present as a result of the assumed slip surfaces. There are four general safety factors which are applied to nail yield strength, bond strengths (soil/nail), soil strengths, and to overall or global stability. The procedure used in this analysis was to set the first two to 1.5, and vary the third until the fourth, or the global stability, is equal to unity.

The analysis provided by **Talren** did not include the benefit of nail shear. This was done partly to make the comparison more 'fair', and partly because of the difficulty in choosing appropriate values for the many input parameters, (see Section 3.2.6).

The additional complication of face pressure must be included in analyzing the programs, **Snail** and **Goldnail**. The larger the face pressure, the less critical the internal stability, and the closer the results of these two programs will be to the results predicted by the other programs. The procedure with **Snail** and **Goldnail** was to vary the face pressure in a given example to determine its effect, until further variation in the value produced no change in the overall safety factor. The slip surface corresponding to this final value of the safety factor, where face pressure is no longer critical, was then compared with the results of the remaining four programs.

To facilitate comparisons, a summary of program difficulties or input limitations, and additional observations are presented on an example by example basis in Section 4.2. If an example is not listed in Section 4.2, it indicates that the specific example could be successfully run by all the programs involved in the comparison. For each of the fifteen cases, three sets of plots follow the summary: a general comparison showing factors of safety and slip surface locations, and a set of two plots showing how face pressure/punching shear in **Goldnail** and **Snail** affected the location of the slip surface (note: only thirteen plots are included with the **Goldnail** and **Snail** face pressure comparisons, as face pressure was not considered to be critical in these particular failure cases). Programs that were unable to run specific examples are designated by parentheses on the comparison plot legends.

4.2 Input limitations and additional observations

Examples 1-10 and the 5 case studies:

For all of the ten examples and five case studies, trends emerged that are worth making note of before beginning any discussion on a case by case basis. The program **NailM9** predicts factors of safety that are considerably less than those predicted by the other packages. This is a result of the program's definition of a safety factor, (see Section 3.2.4). In addition, the safety factor predictions of **Goldnail** and **Snail** are almost always bounded by those of the remaining three programs (not including **NailM9**).

Example 2:

In this example one can see an artifact of **Stars'** use of a log spiral slip surface; the overhang. The program does not include a routine to reduce this overhang to a vertical section, unlike the program **Talren** (see Section 3.2.6).

Example 3:

NailM9 is unable to handle inclined soil layers or the water table and was therefore not used to run this example.

Stars will refuse to proceed with computations if it detects that the factored ϕ value for the top layer of soil is less than the backslope angle. Attempts were made to rectify this problem by introducing an infinitely small layer of high friction soil on the back-slope. This did enable the program to continue, but the program consistently determined the factors of safety to be exceedingly high, because **Stars'** chosen slip surfaces progressed infinitely into the back slope and were so deep they became horizontal at the wall toe.

Nail-Solver is unable to handle multiple soil layers, or the water table.

Differences between the output of **Snail** and **Goldnail** in Example 3 are the result of their predicted slip surfaces and their penetration under the water table. The cohesive forces acting on the two slip surfaces are similar, but with **Goldnail's** deeper slip circle, the porewater pressure has a larger effect on reducing the soil's frictional resistance.

Example 4:

NailM9 cannot handle specific sections of surcharge. It only allows input of a uniform surcharge over the entire backslope surface, and was therefore not able to run the example.

Example 5:

Goldnail cannot accommodate benched walls, so the analysis was based on an equivalent inclined wall. The nail lengths were changed to have their embedded ends in the same locations as in the actual cross-section.

An equivalent inclined wall was also used for analysis with **Nail-Solver**. However, an eleven foot wide bench at the top of the wall could not be accommodated, as **Nail-Solver** only allows for one slope angle at the crest. This problem was circumvented by using a negative surcharge on the backslope to simulate the removal of the extra soil weight. Directly behind the wall, where there is in actuality a bench, **Nail-Solver** slightly under-predicts the soil gravity load. Since the critical surface is a bilinear wedge intersecting the back of the nailed zone, however, the discrepancy makes little difference. Also, **Nail-Solver** cannot handle varying reinforcement parameters, so the nail length was an average, as was the nail diameter.

Stars also can handle only one slope angle at the wall crest, but two negative surcharges were used, one varying and one constant, to simulate the eleven foot bench, and the subsequent reduction in soil height along the back-slope.

NailM9 has a computational error that caused it to become unstable with this example. The input parameter, A, which is a multiple of the wall height, is used to represent the distance behind the crest to which you want to limit the search. By varying the A parameter from one to ten, it became clear that the program was predicting a failure surface that was located at an infinite distance behind the crest.

Example 6:

Nail-Solver cannot handle different soil layers, so average values for cohesion and unit weight were used.

NailM9 cannot handle differing pullout resistance values, so a weighted average for the two soil layers was used.

Examples 7, 8, and 9

These three examples are interesting in the fact that they demonstrate the effect of varying the wall inclination and the angle of the backslope. Example 7 is a vertical wall with a horizontal backslope and safety factors near 1.8. In Example 8 the wall remains vertical, but the backslope is inclined. The result: the slip surface changes very little, but the safety factors drop to about 1.4. With Example 9, the wall and the backslope are inclined, and the slip surface moves away from the crest, and the safety factor is raised to 1.6.

Example 7:

There is a question with the results from **Stars,** as its prediction of the failure surface is radically different than that of other programs, unless one looks at the deep seated slip surface. For this case the factor of safety is raised, and the slip surface moves away from the crest. The program has the option of computing the stability of surfaces that are not required to pass through the toe (see Section 3.2.3). The problem may be the result of the large safety factor applied to the soil strength which has rendered the soil predominantly cohesive, with little frictional strength.

Example 10:

Goldnail is unable to handle toe slopes below the wall, so the analysis was done disregarding the toe slope. Also, in order to handle the different adhesion values of the nails, an elaborate interface between the two soil types was used to correctly assess the pullout resistance of each of the nails. The strength and weight properties of the soils were unaffected.

Stars was unable to accommodate the water table involved in the problem, so the run was made without it. Also, the back slope angle problem previously mentioned again developed, as the factored ϕ angle dipped below the slope angle. This time the addition of a thin frictional layer was successful in allowing the run.

Nail-Solver was unable to handle the varying nail parameters, such as length, so an average value was used. It was also unable to accommodate the water table.

NailM9 could not handle varying pullout resistance, therefore a simple average value was used.

San Bernadino:

The following three examples were the actual in-service walls, chosen for their data availability.

All the programs except **Nail-Solver** handled the wall without problems. **Nail-Solver**, however, is unable to allow anything but uniform spacing of the nails. As a consequence, the depth to the first nail is not three feet, with regular five foot spacings below; instead, it is five feet with five foot spacings below. This difference alters the wall geometry, but with negligible effect on the results.

Swift Delta X-Sect 1:

Snail, **Goldnail**, and **Talren** all handled the wall without difficulty. The varying reinforcement parameters and surcharge provided no difficulties. The key to designing this wall was to model the bridge abutment as an additional ten feet of wall, and to add an additional two feet of live load surcharge to simulate traffic. **Stars** would not allow the extra ten feet of wall above the top of the actual wall, so additional nails with no bond strength and no yield strength were added to the top ten feet.

Nail-Solver was not applicable here, as it only allows for regular nail spacings, and would not allow for the placement of fictitious nails in the top ten feet.

NailM9 was able to analyze the wall by using an average nail length, and by analyzing the bottom nail at 15° below horizontal, instead of the actual inclination of 25°.

Seattle Polyclinic:

This wall is characterized by multi-varied nail parameters, including bond strength, nail length, yield strength, and inclination. Thus only **Goldnail, Snail, Stars,** and **Talren** can accurately represent the as-built condition without making further assumptions.

Nail-Solver, with its required regular nail spacing, added an additional nail to the bottom of the wall. It also required the use of one set of soil strength parameters. The soil strengths used were those of the larger lower layer due to the fact that the largest length of the failure surface would pass through that layer. A weighted average of the unit weights of the two layers was used.

NailM9 required the use of an average nail cross-sectional area, and the use of the pullout strength of the lower soil layer. The top nail's different length was handled through the use of the stepped nail length option, (where groups of nails are specified with a common length).

Eparris Wall:

The final two examples were the failure cases, chosen for their data availability.

All of the programs were unable to predict the actual slip surface location. This may be a result of poor soil characterization, or incorrect reinforcement parameters. **Talren** was the most notable in its prediction, as it predicted a slip surface with a grafted-on vertical section, to avoid an overhang. Repeated attempts to correct this prediction failed.

Nail-Solver was unable to handle this failure case because of its limitations on varied nail length parameters. It is unable to accommodate multiple nail lengths and bar diameters, and was therefore not used in the comparison.

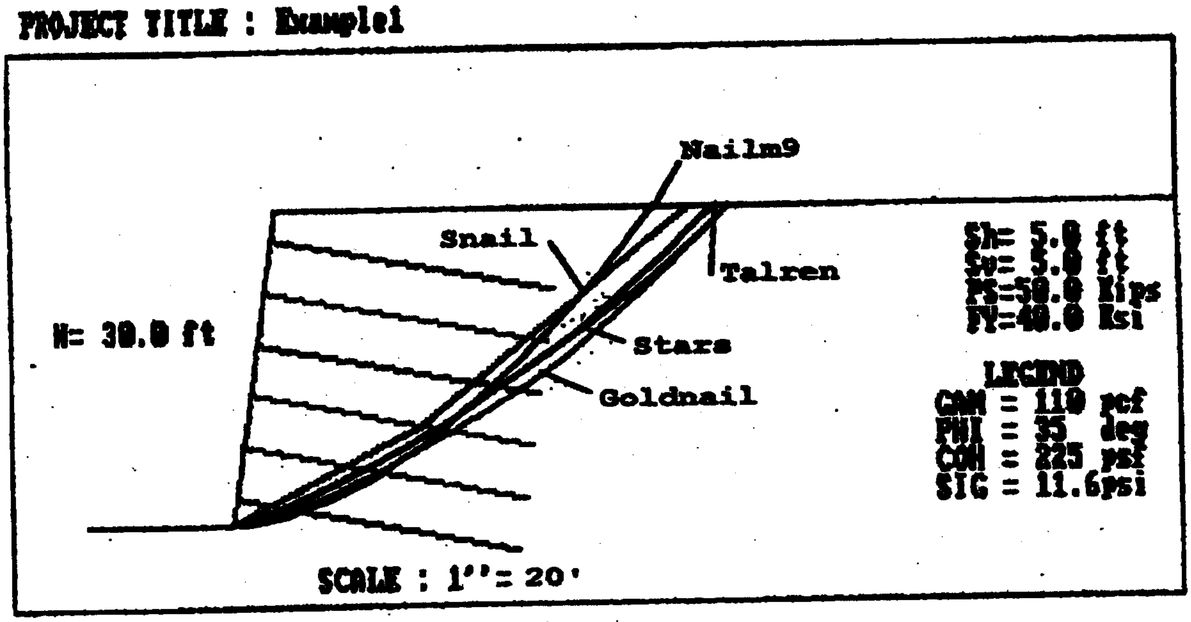
NailM9 required the use of an average nail cross-sectional area, but was able to handle the differing nail lengths.

Bodenvernagelung:

All the programs predicted the correct failure surface for this failure case. This may be the result of the excessively large surcharge dictating the slip surface exit point.

NailM9 was unable to handle the specific surcharge applied to the back-slope. As was mentioned before, it can only accommodate linear surcharges applied to the entire back-slope; thus the program was not used in the comparison.

4.3 Comparison plots and drawings



Example 1

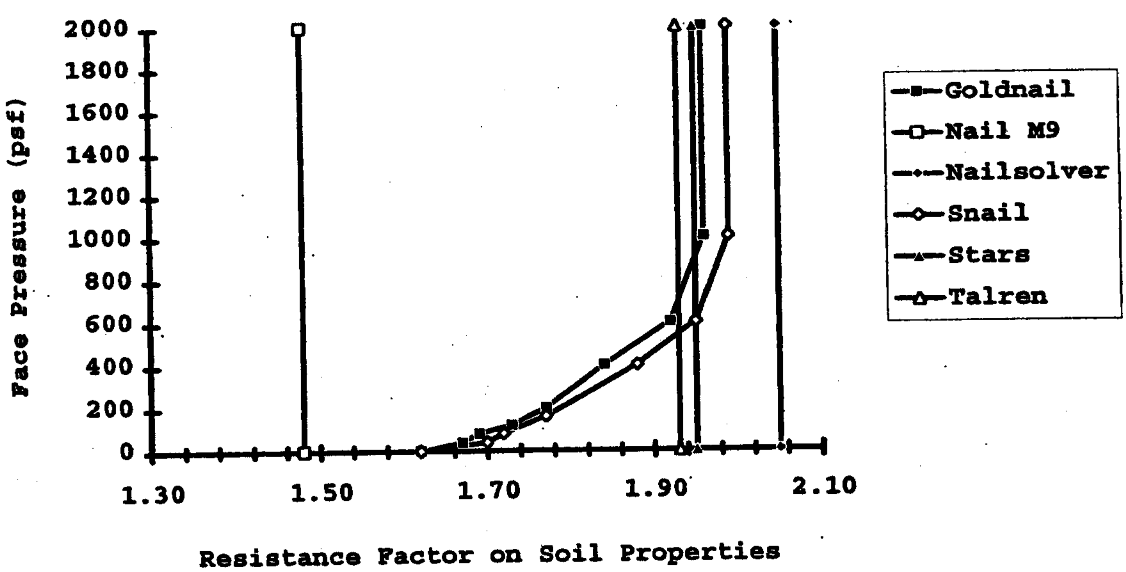
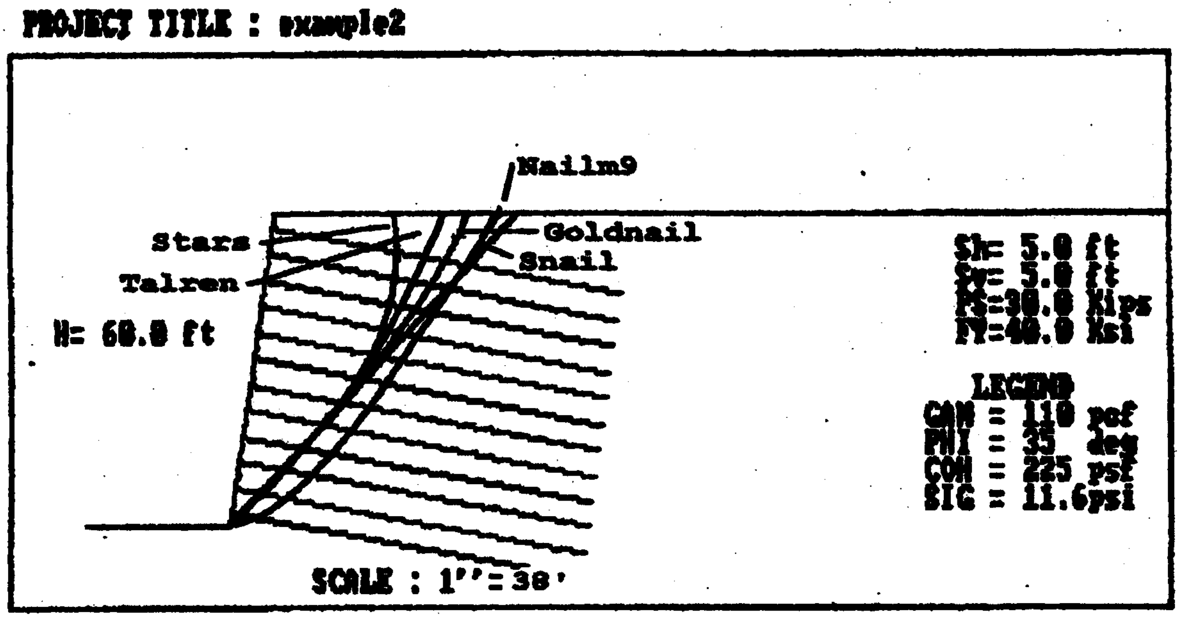


Figure 4.1 Ex. 1 comparison



Example 2

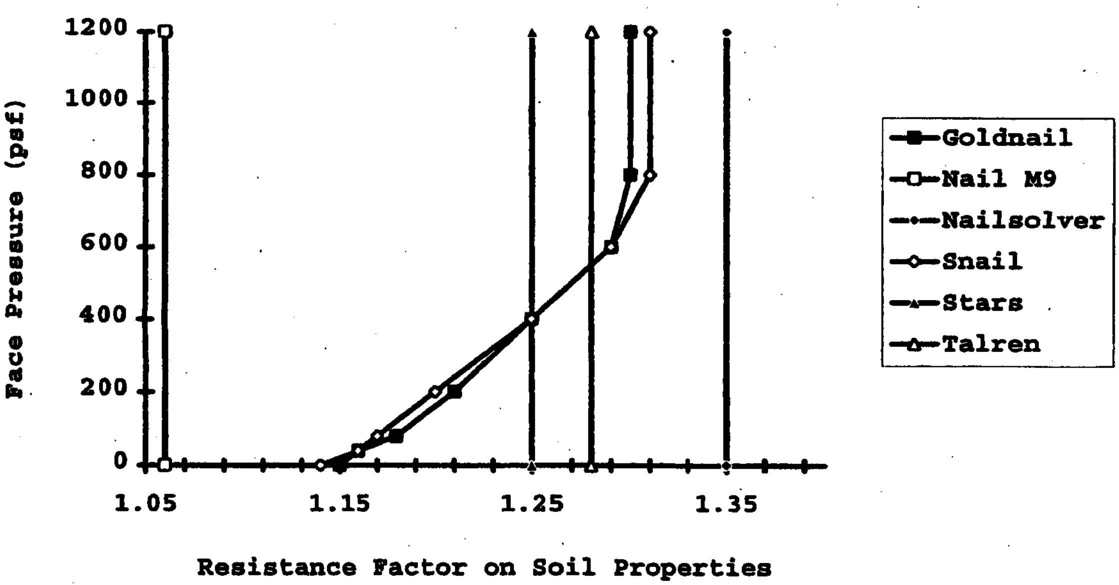
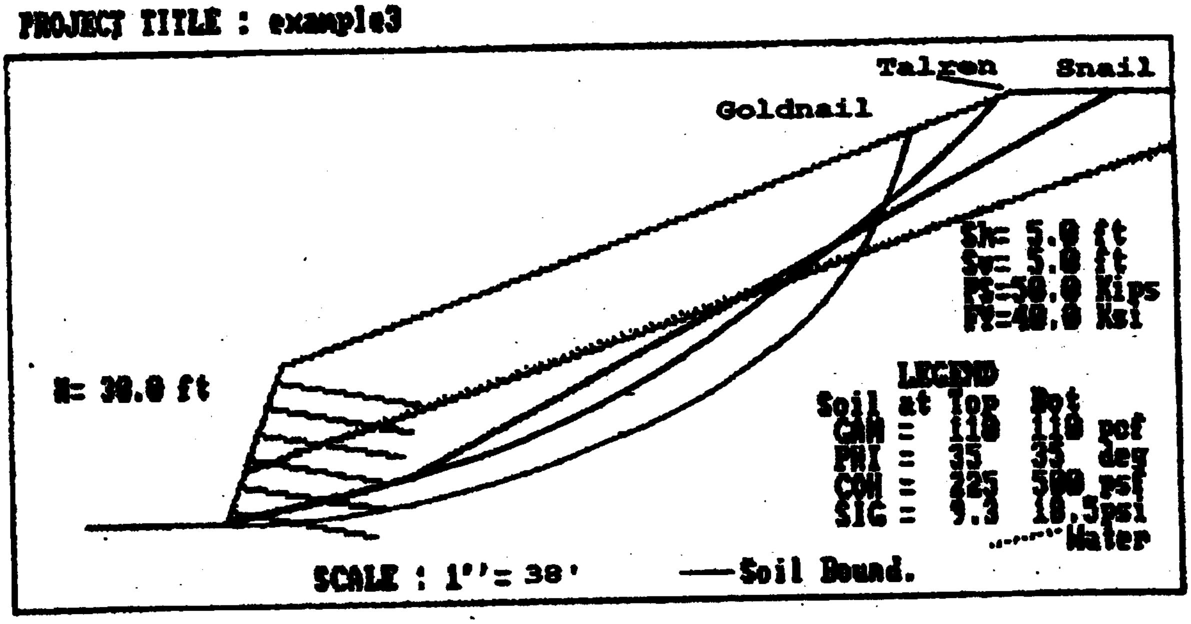


Figure 4.2 Ex. 2 comparison



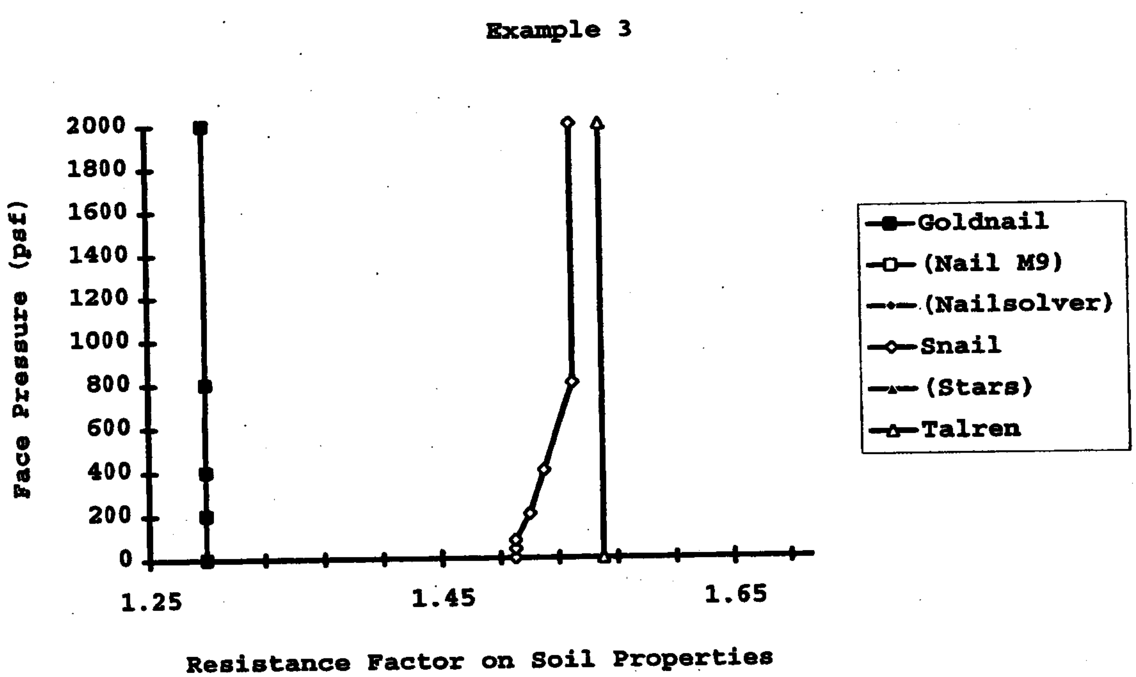
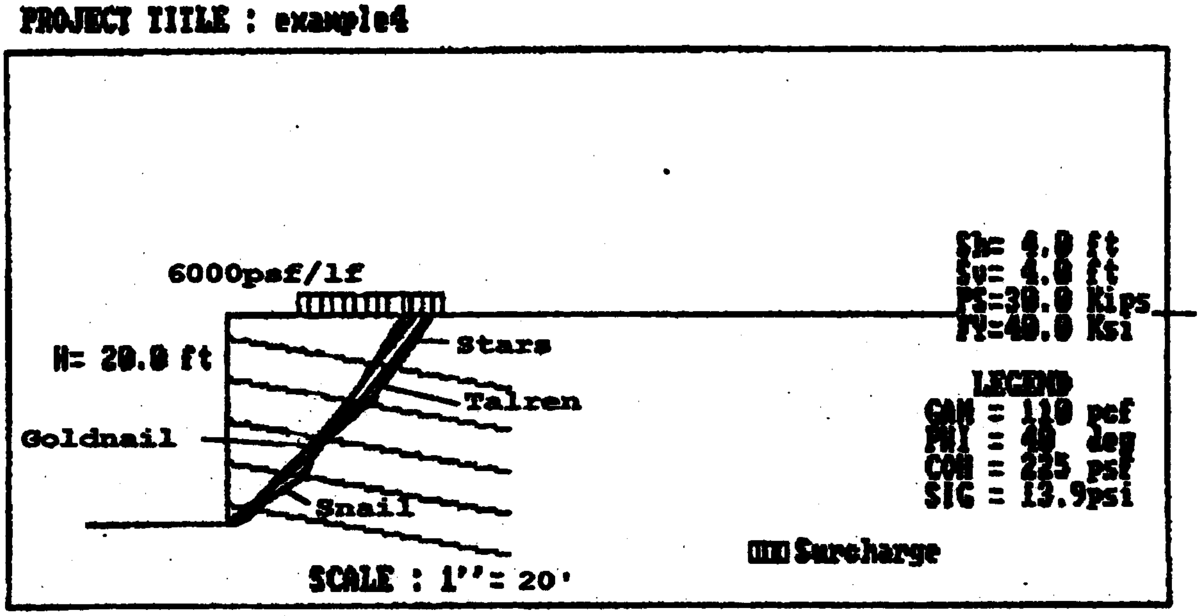


Figure 4.3 Ex.3 comparison



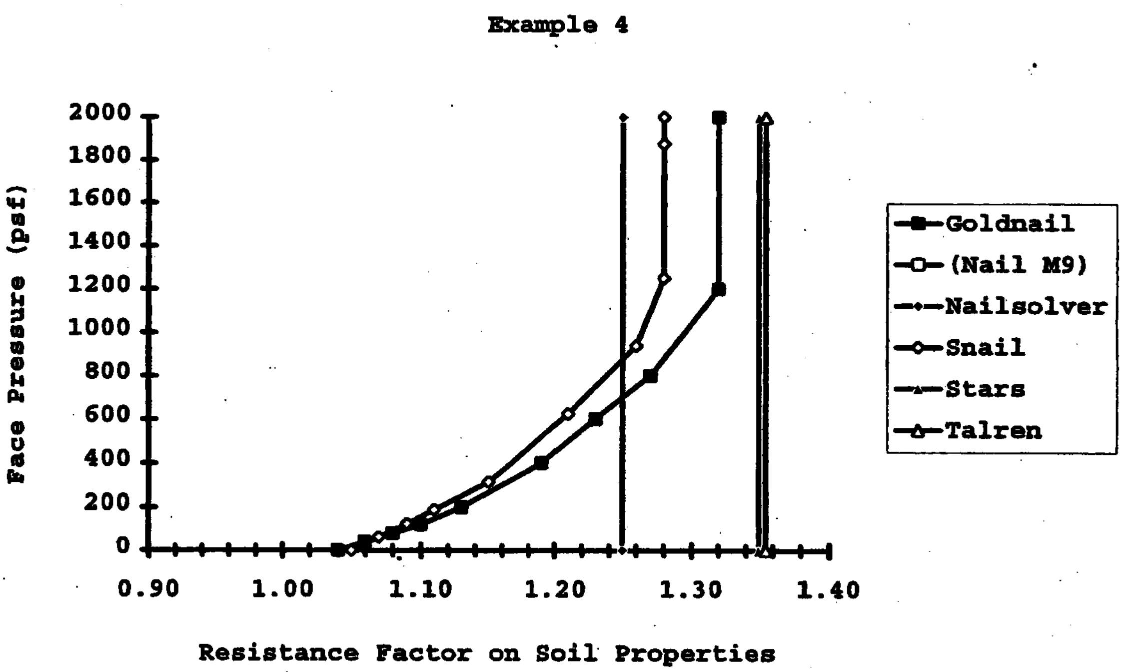
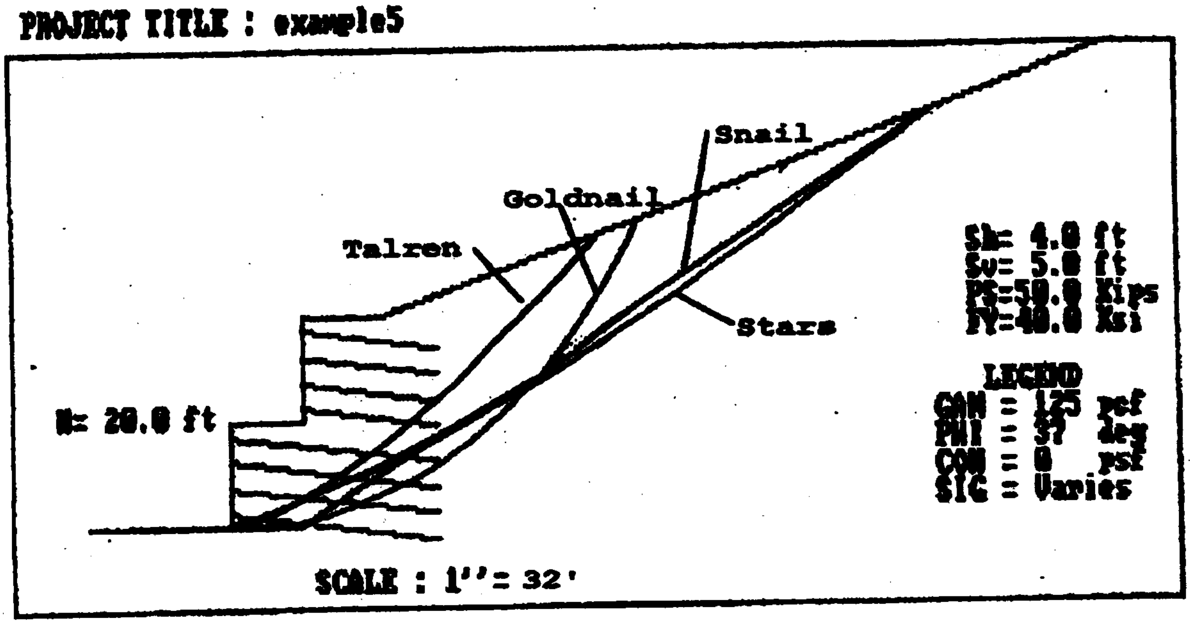


Figure 4.4 Ex. 4 comparison



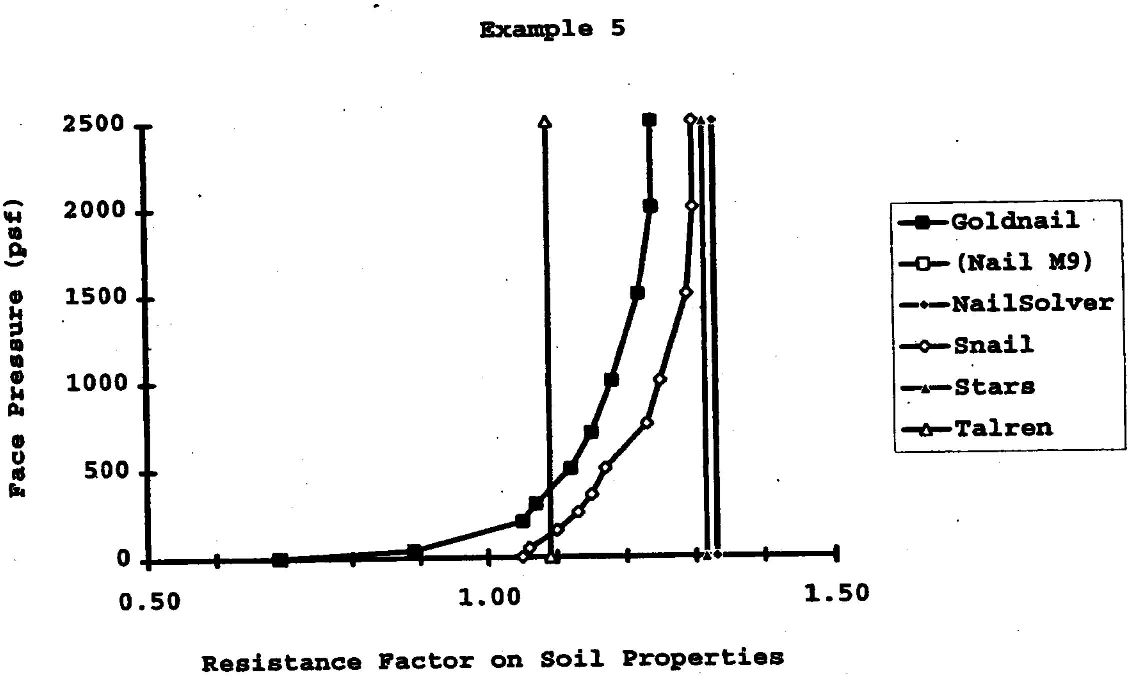
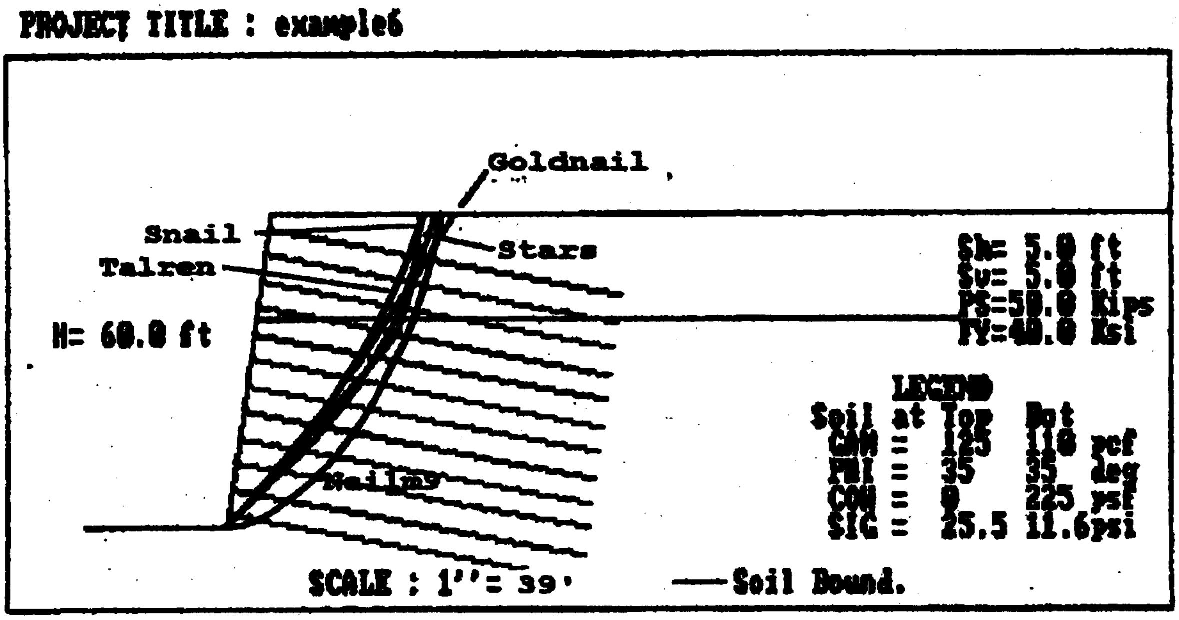


Figure 4.5 Ex. 5 comparison



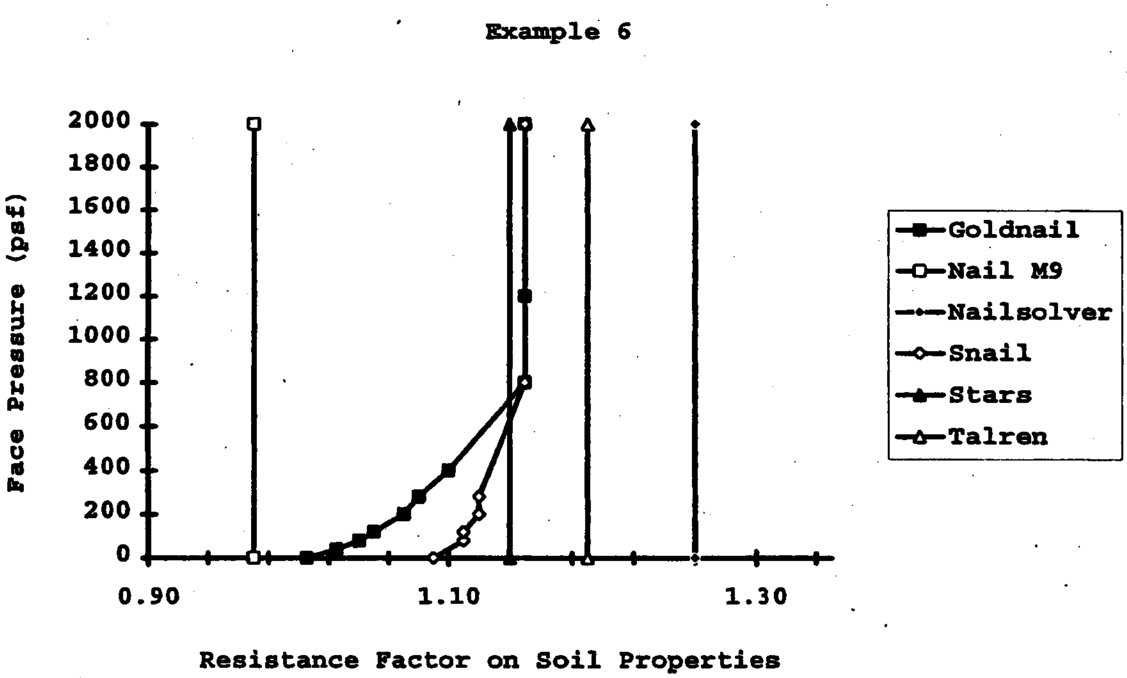


Figure 4.6 Ex. 6 comparison

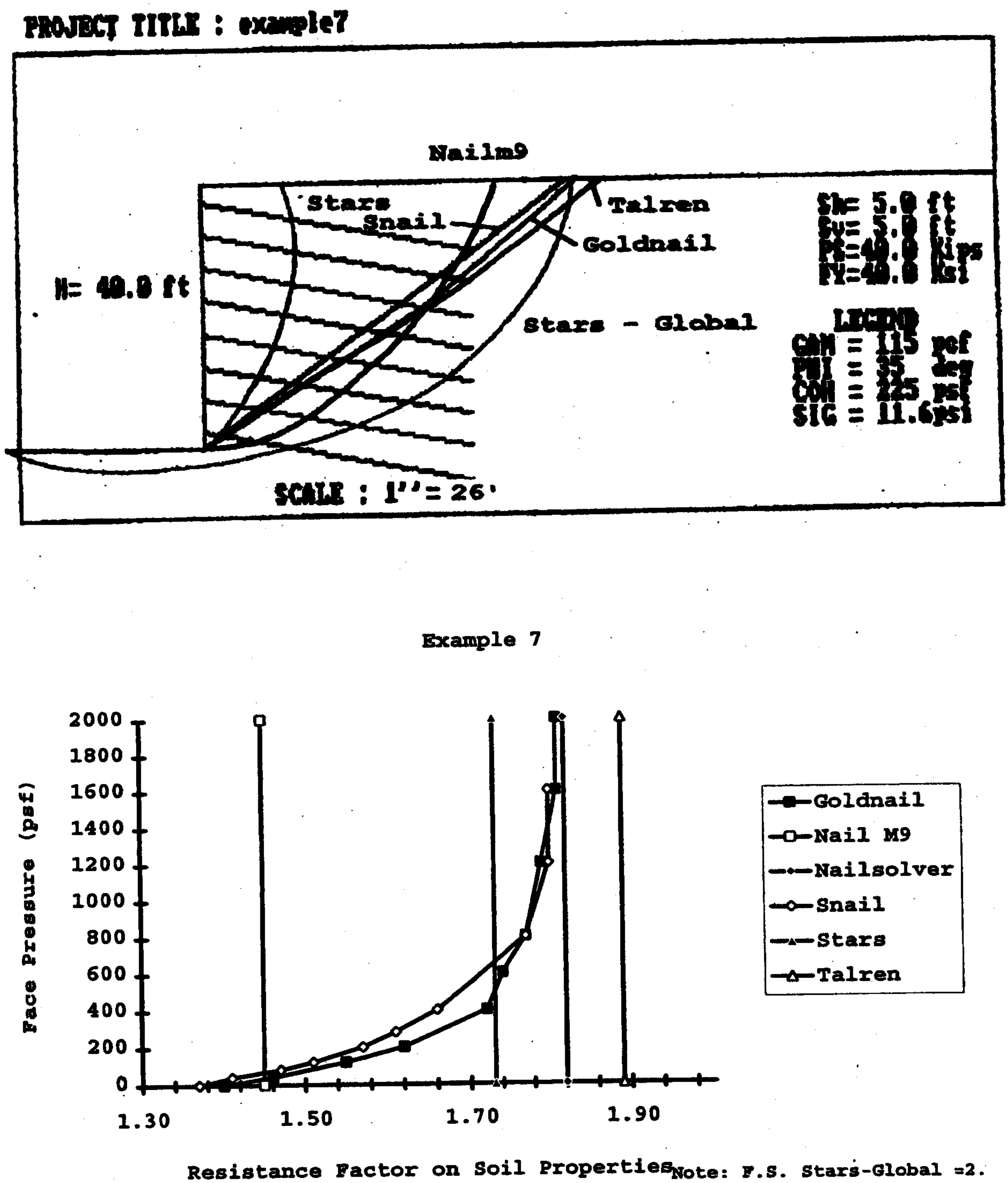
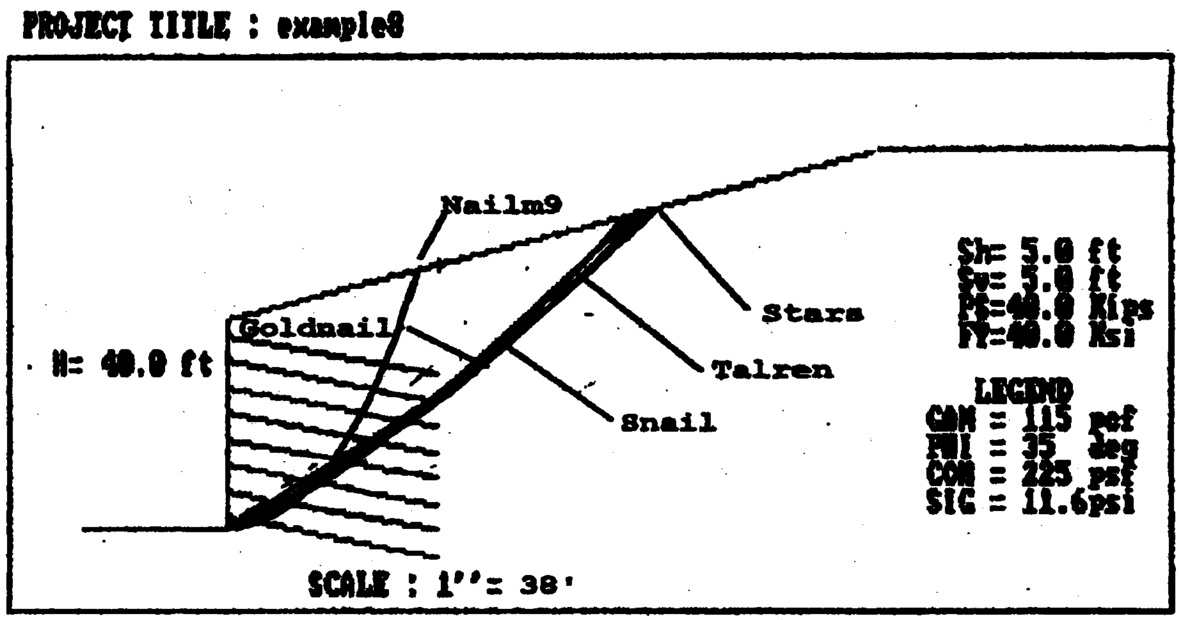


Figure 4.7 Ex. 7 comparison



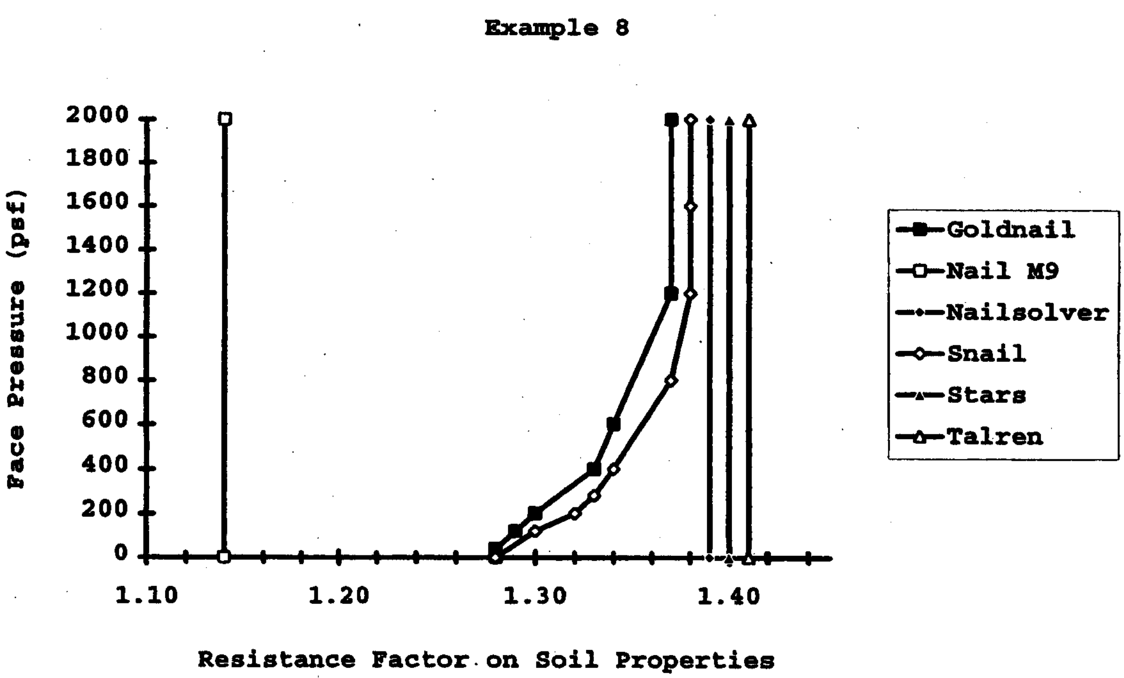


Figure 4.8 Ex. 8 comparison

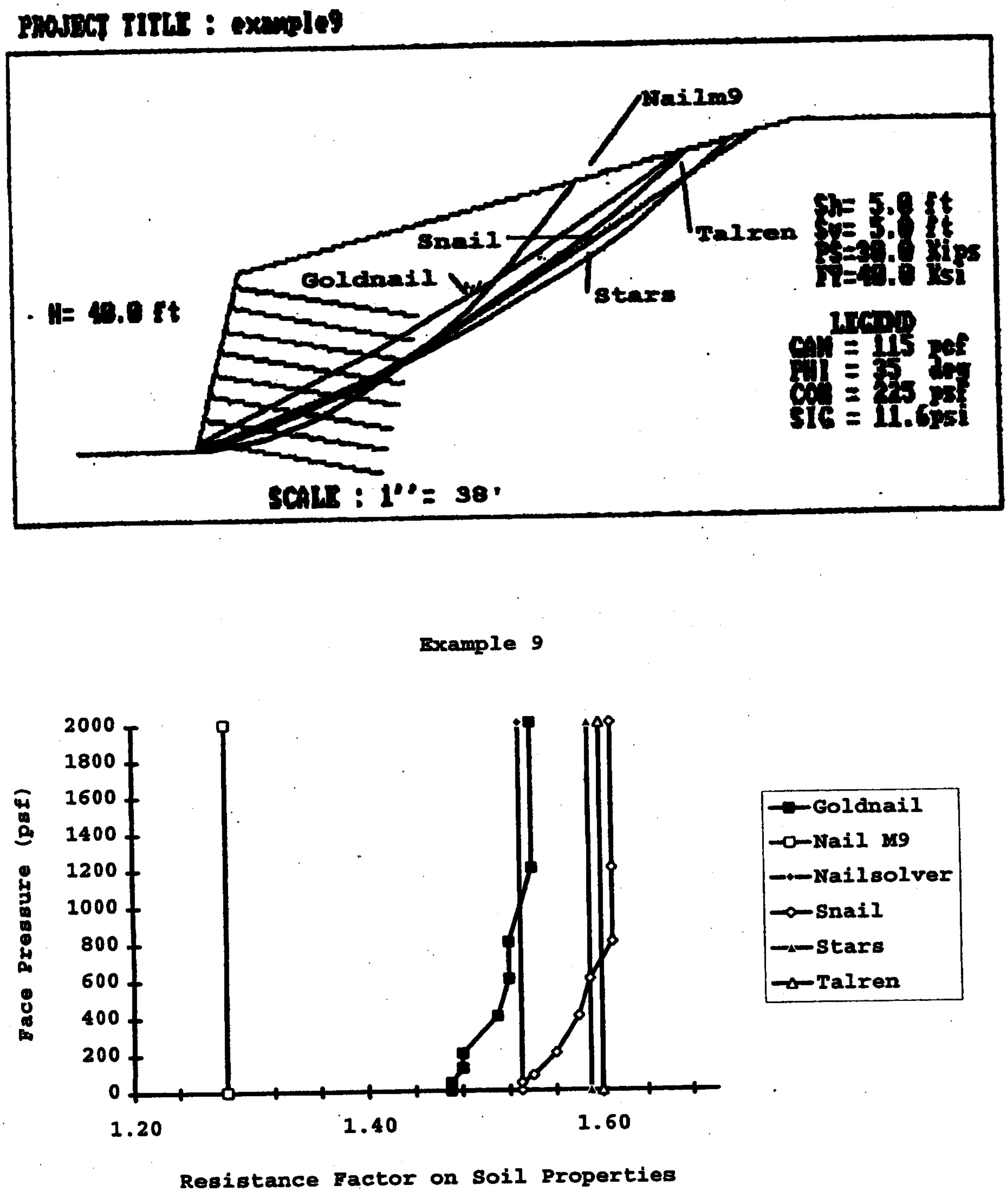


Figure 4.9 Ex. 9 comparison

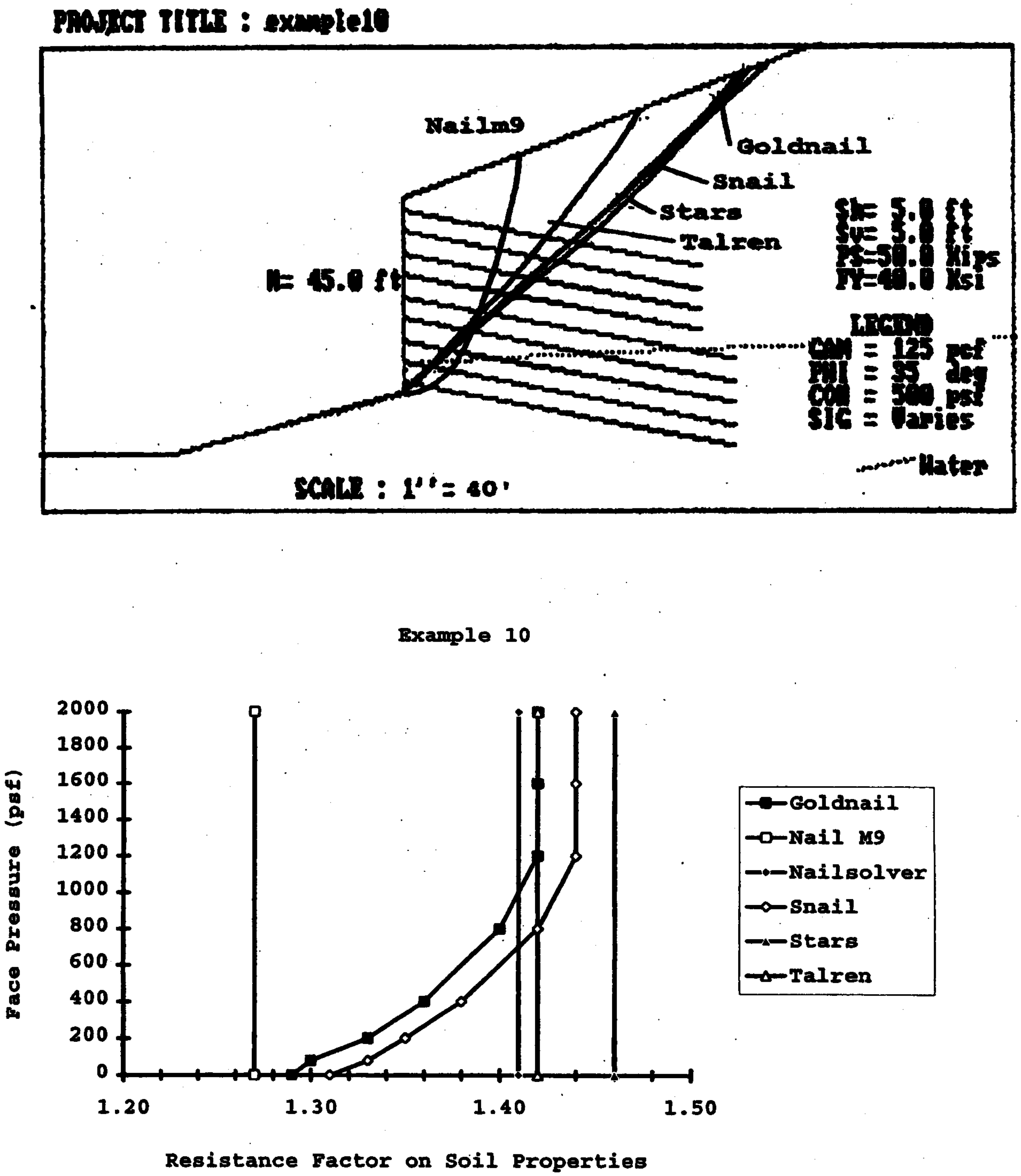
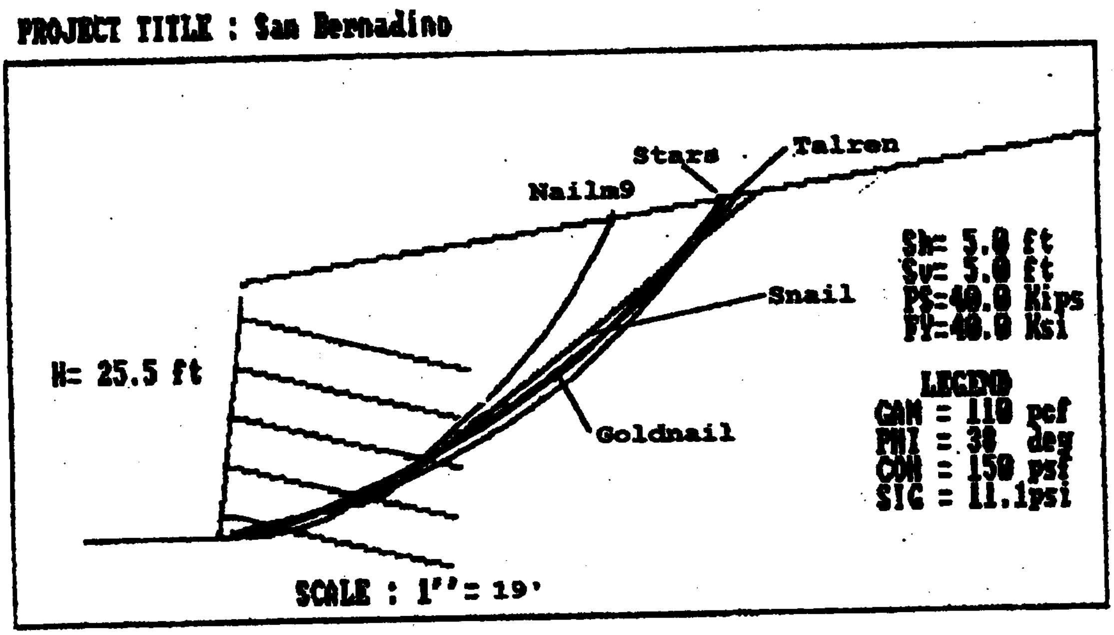


Figure 4.10 Ex. 10 comparison



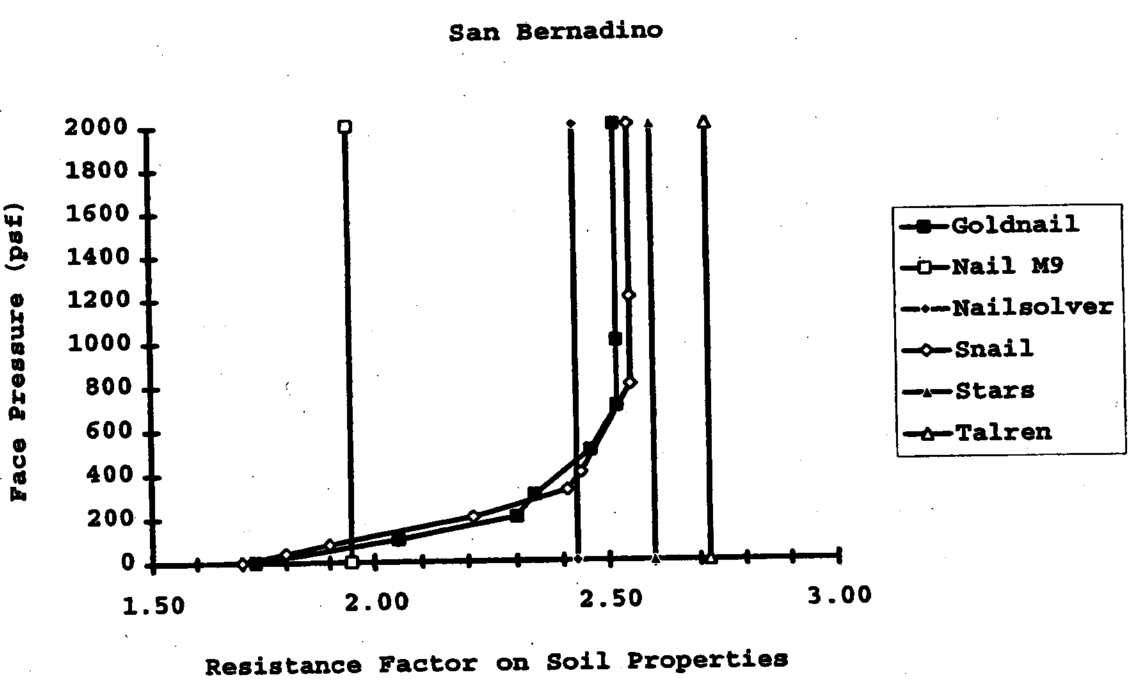
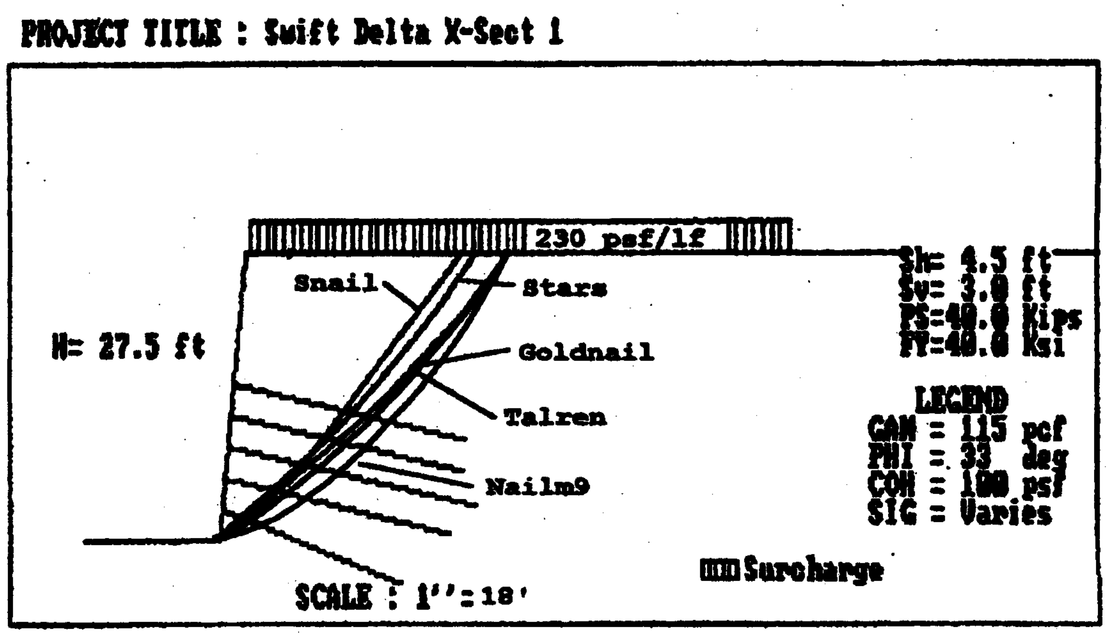


Figure 4.11 San Bernadino comparison



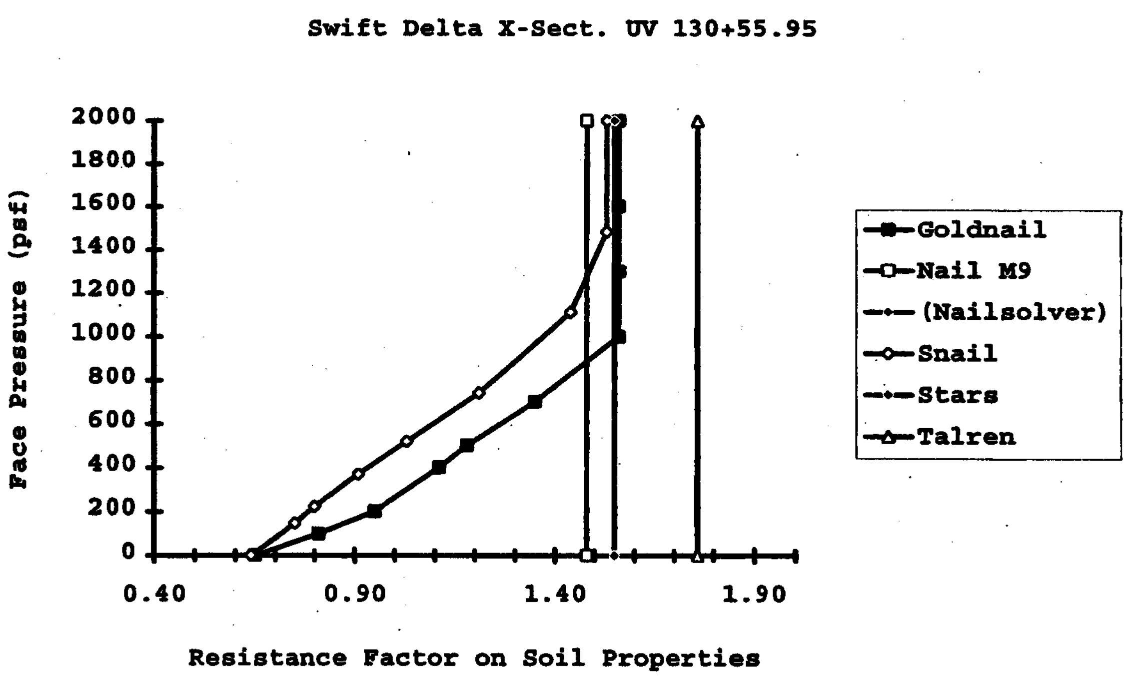
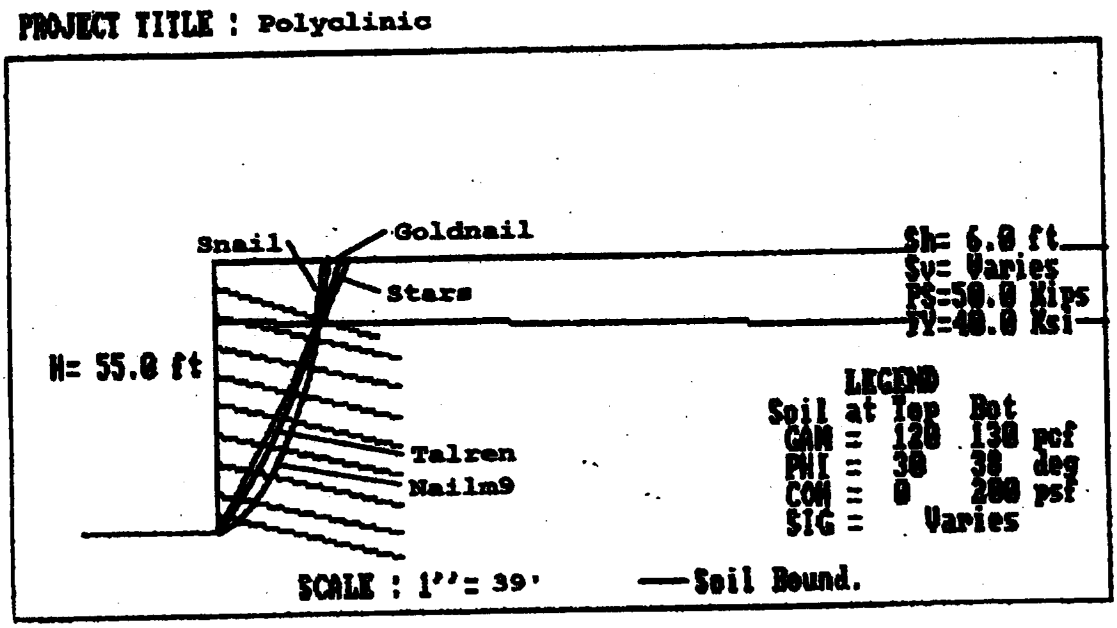


Figure 4.12 Swift Delta comparison



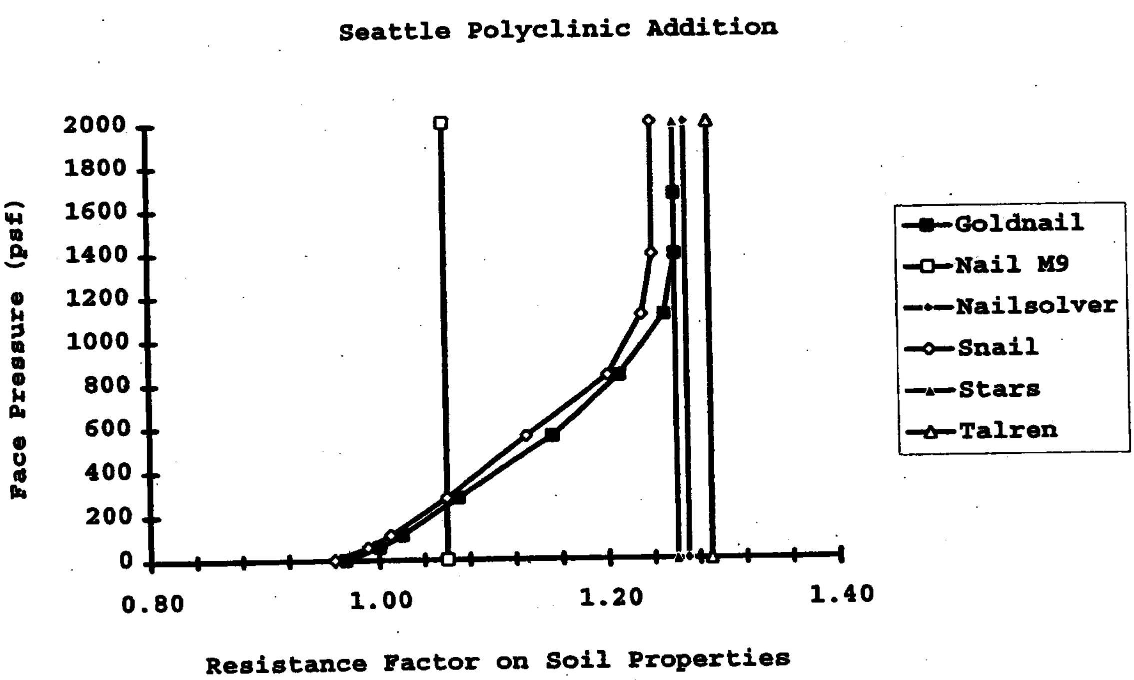
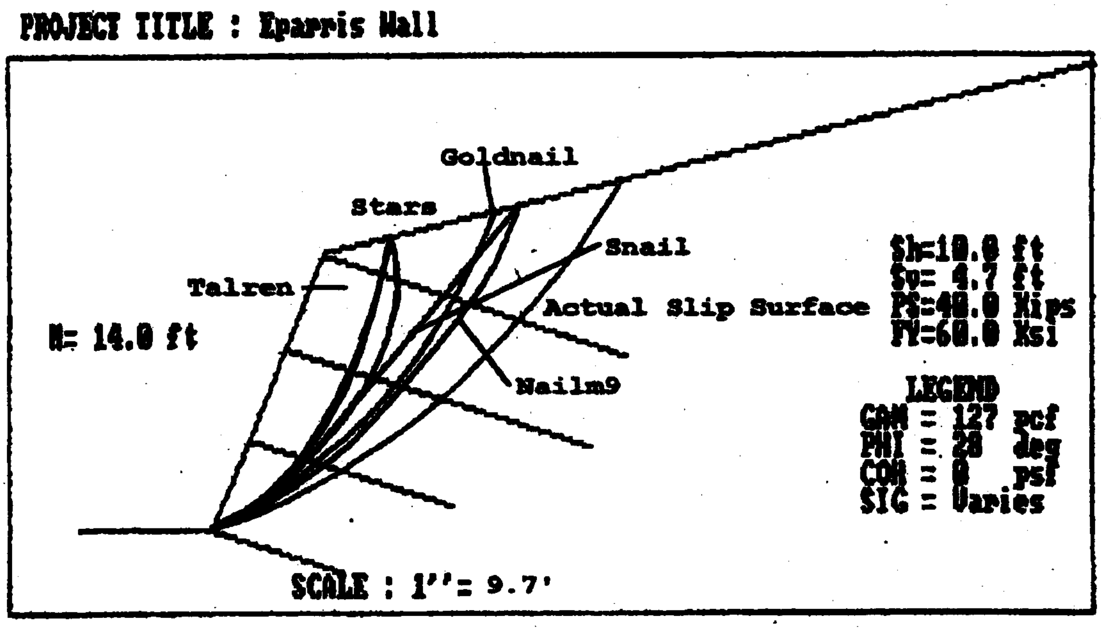


Figure 4.13 Polyclinic comparison



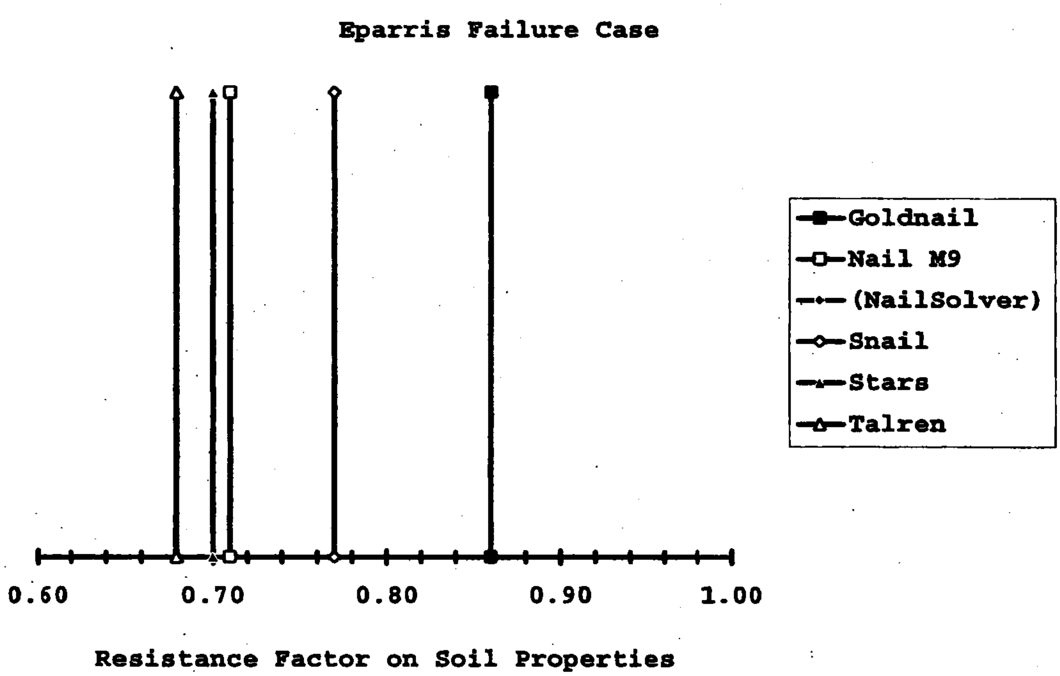
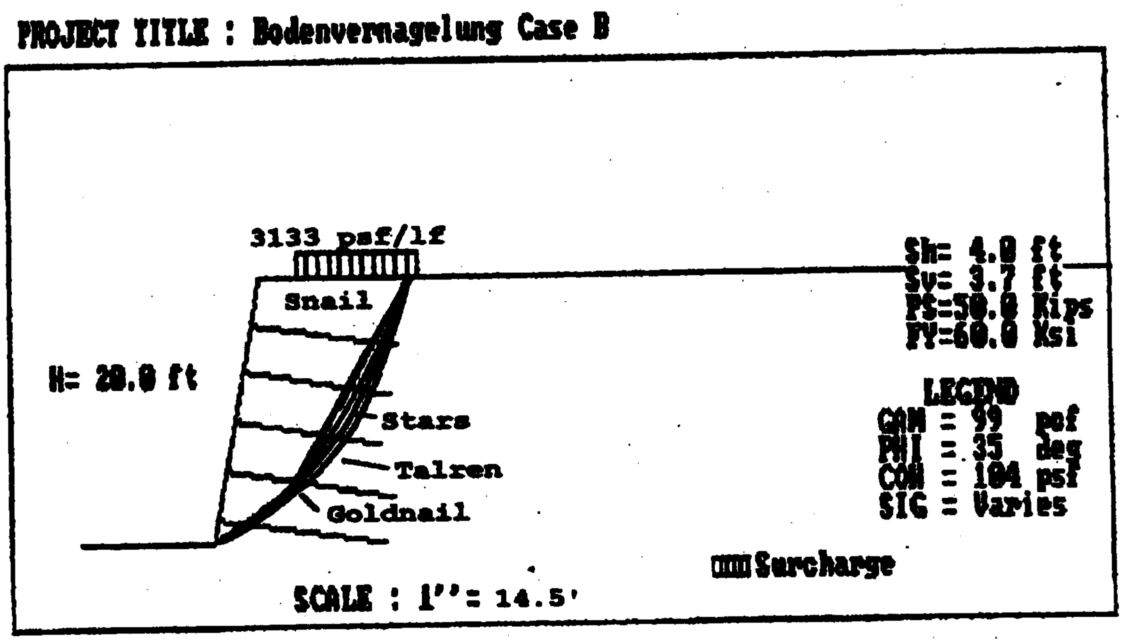


Figure 4.14 Eparris comparison



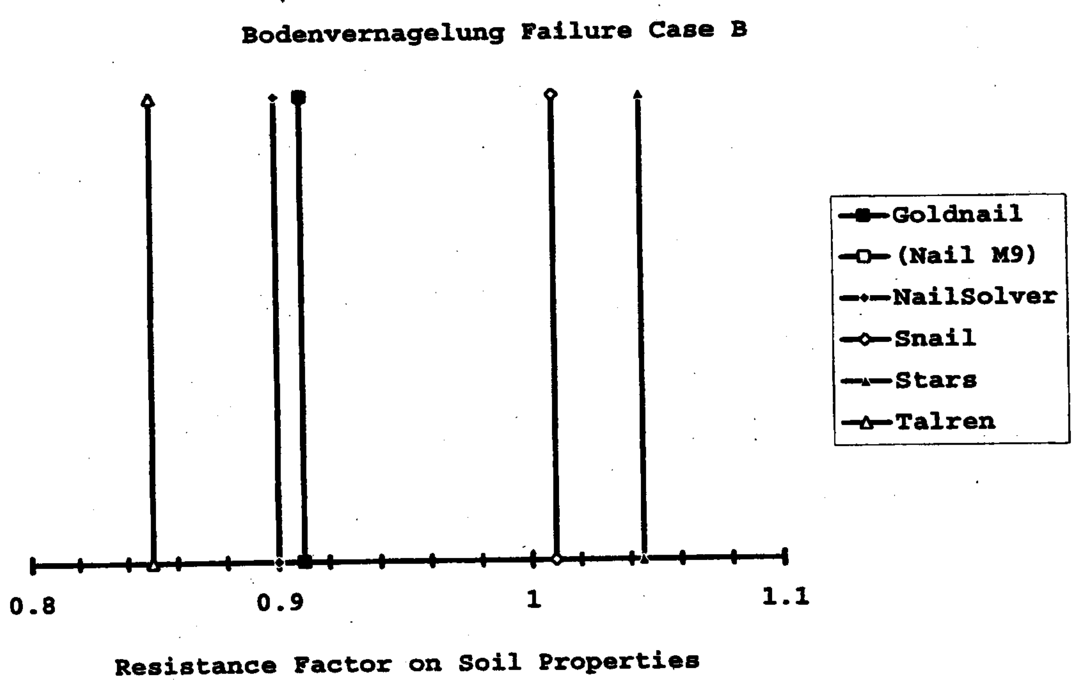
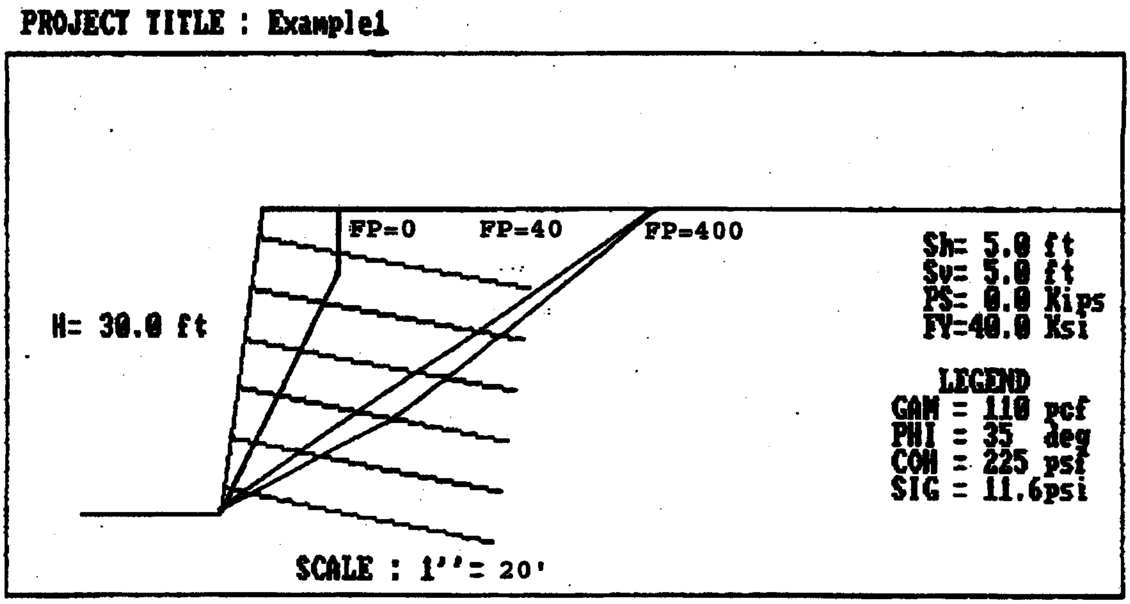


Figure 4.15 Bodenvernagelung comparison

4.4 Snail face pressure comparisons



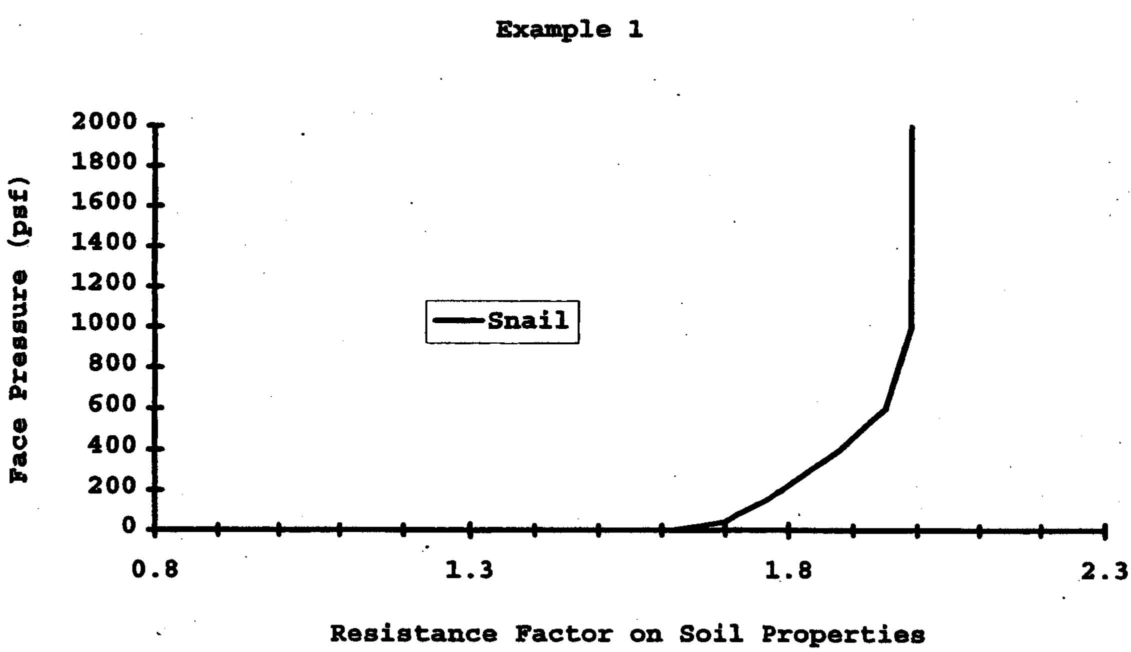
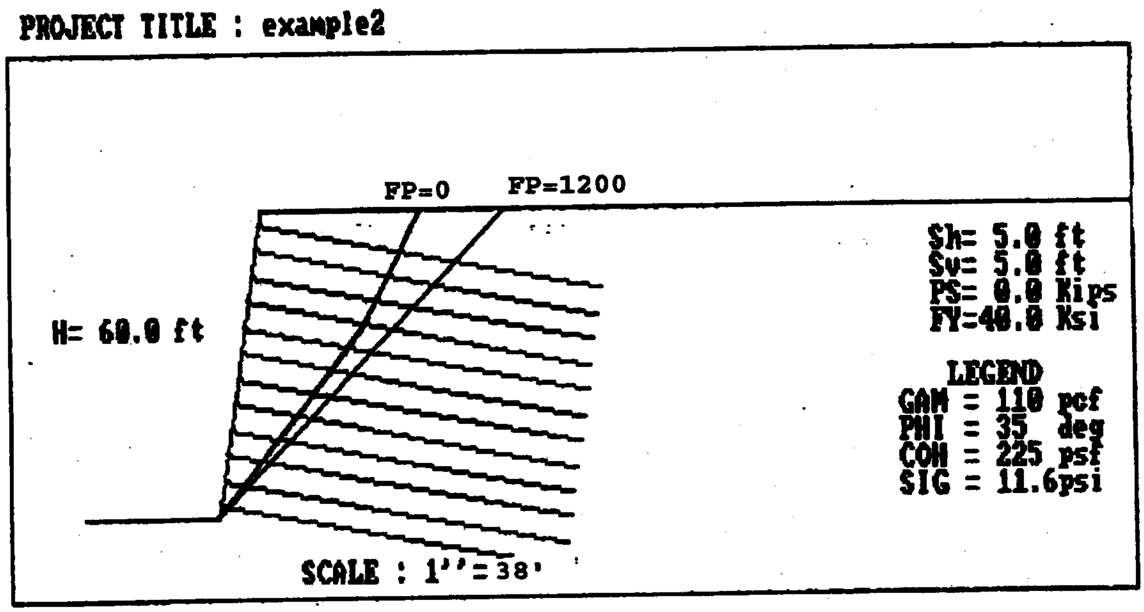


Figure 4.16 Ex. 1 **Snail** face pressure comparison



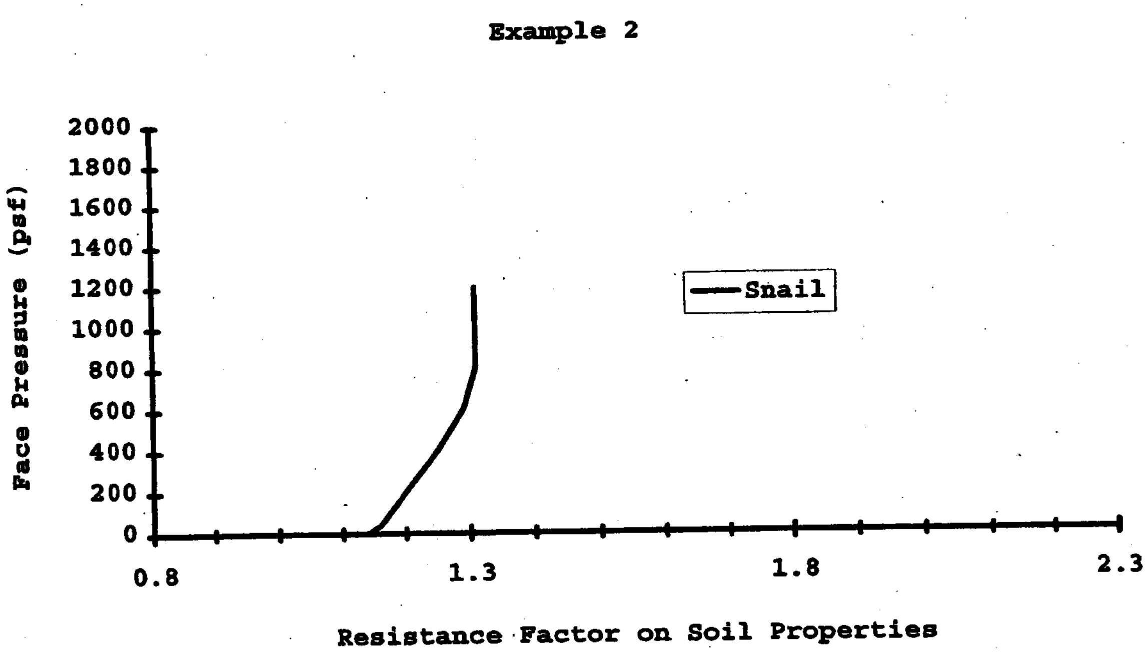
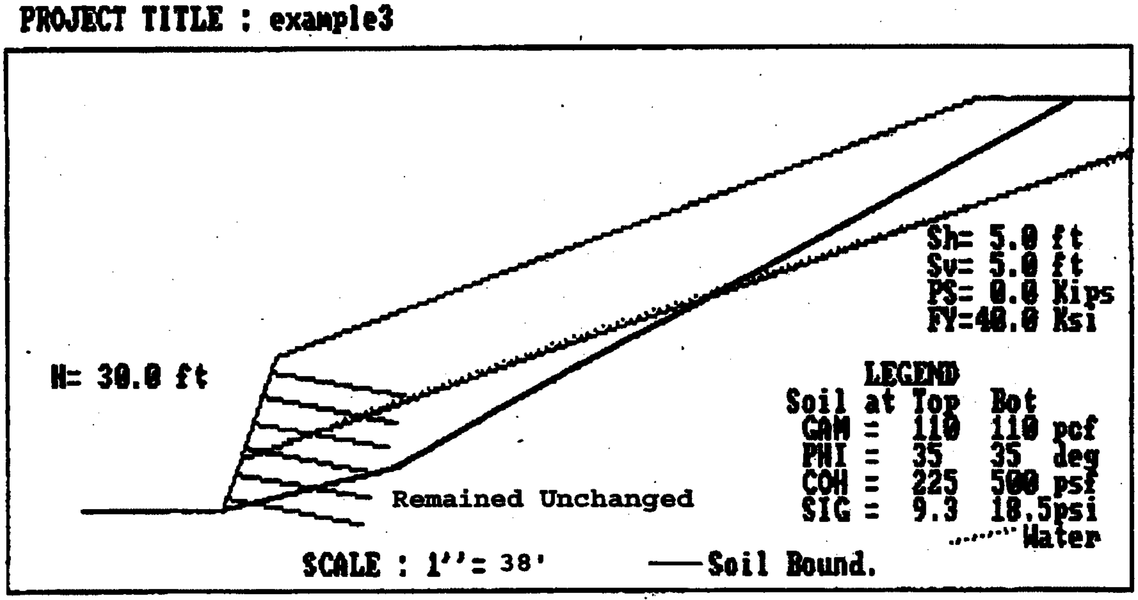
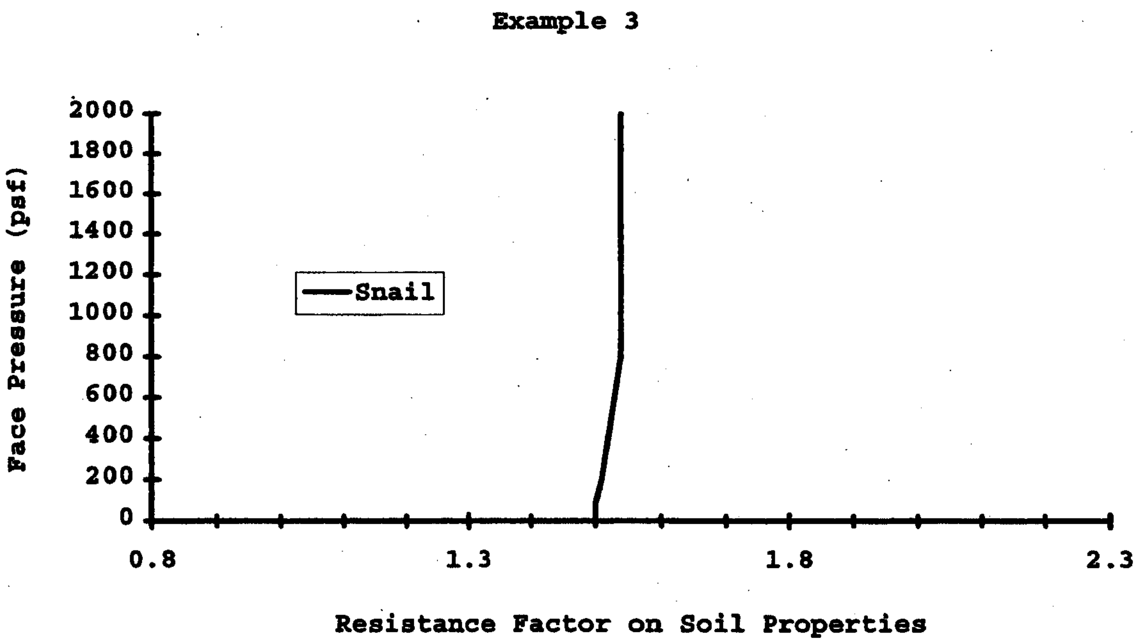


Figure 4.17 Ex. 2 **Snail** face pressure comparison





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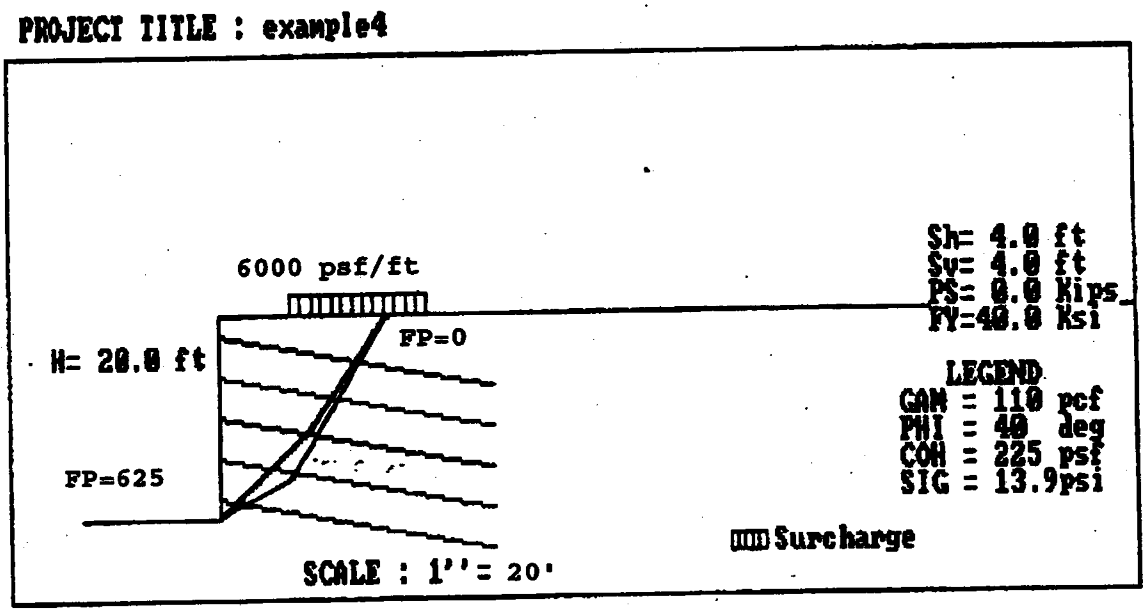

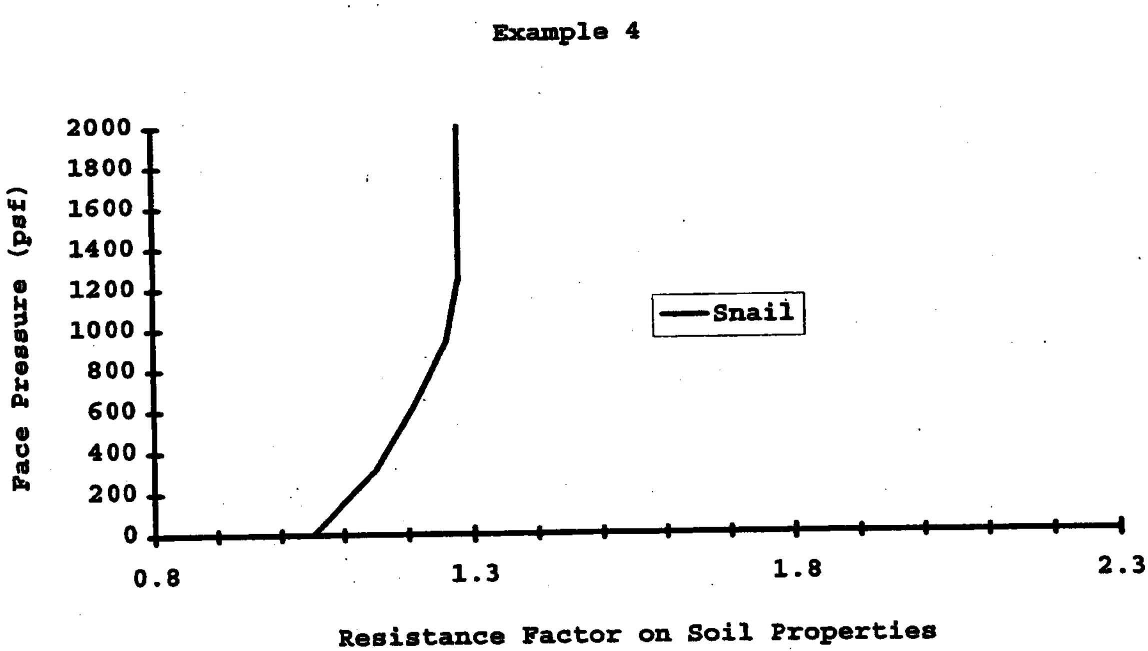

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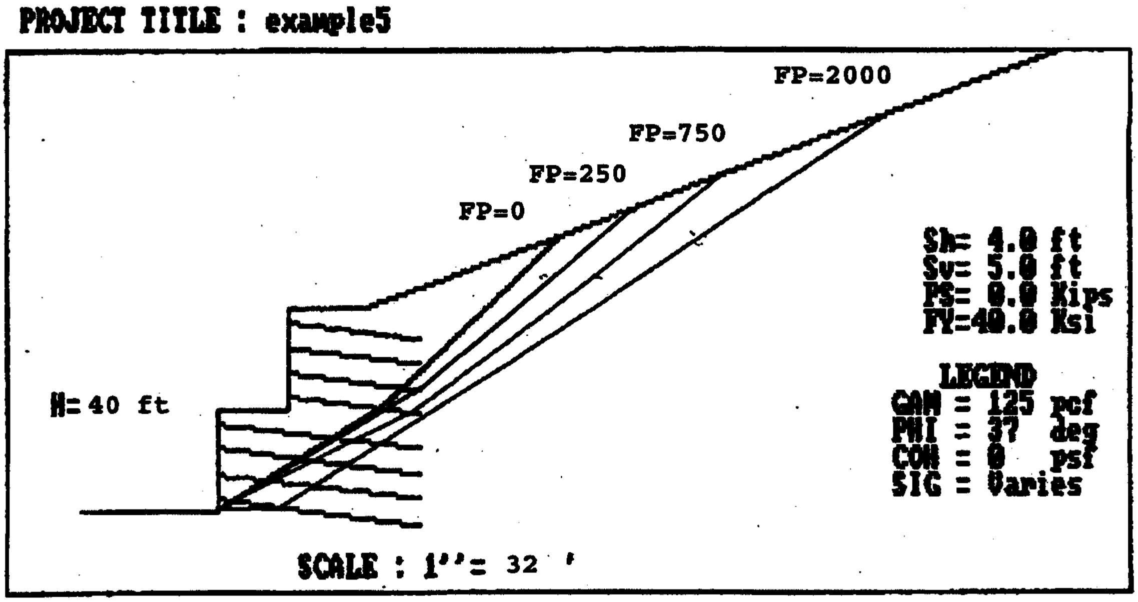

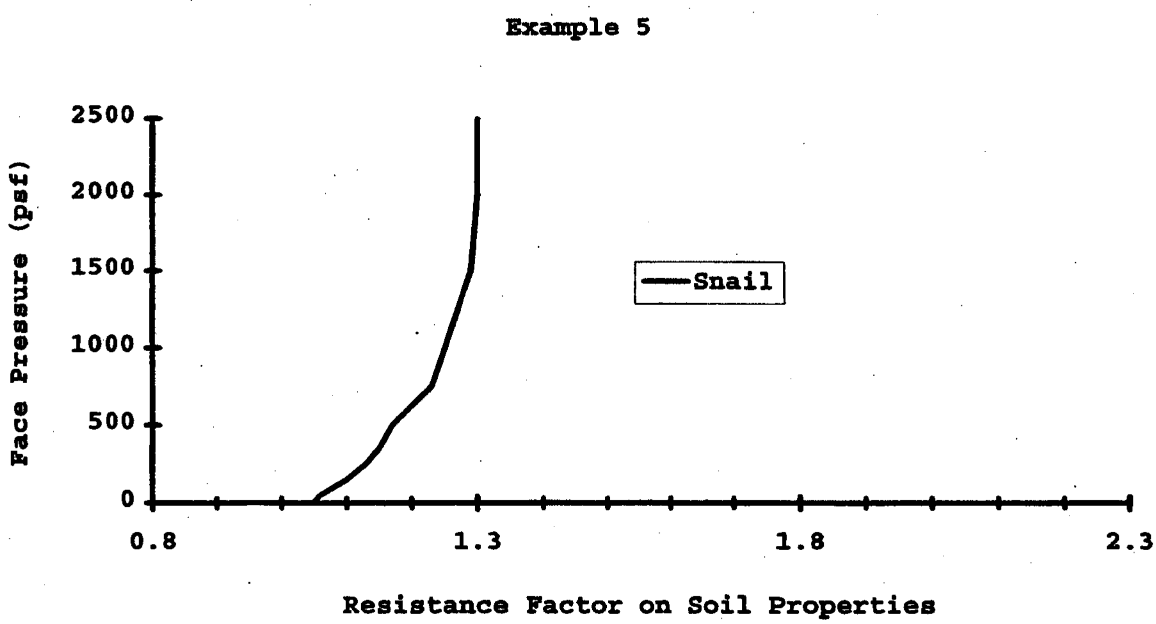

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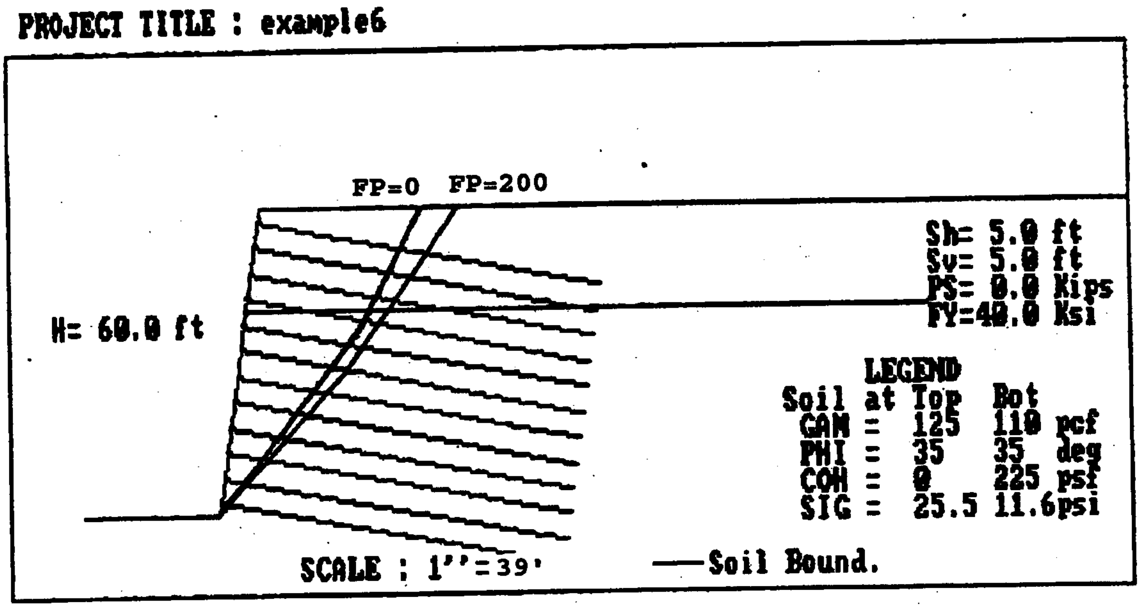

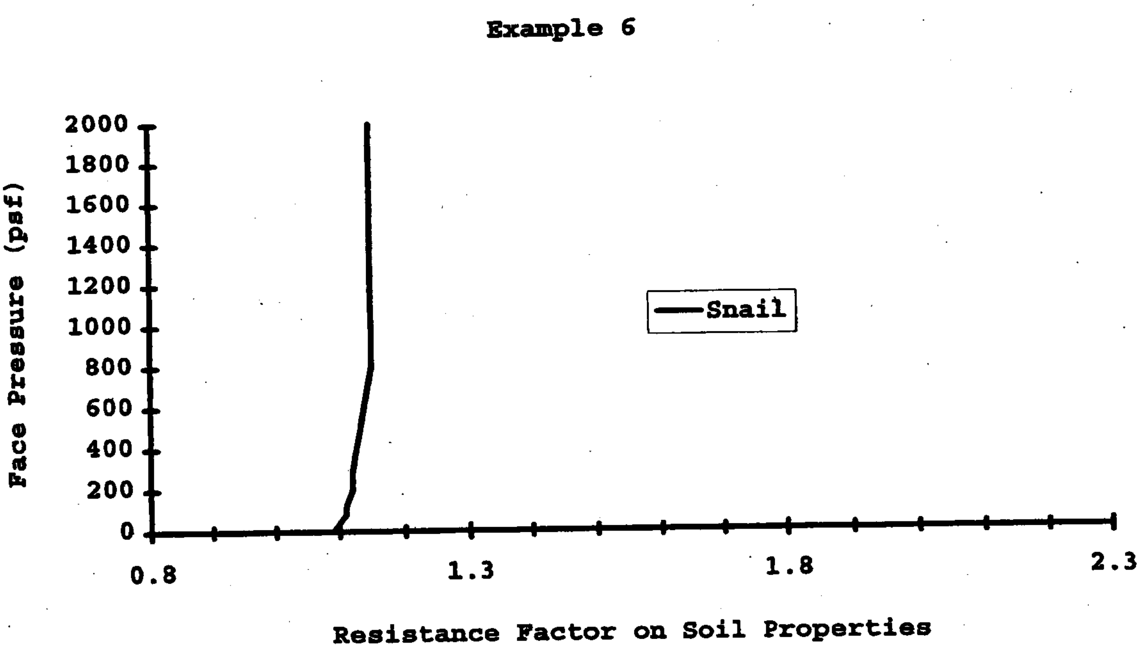

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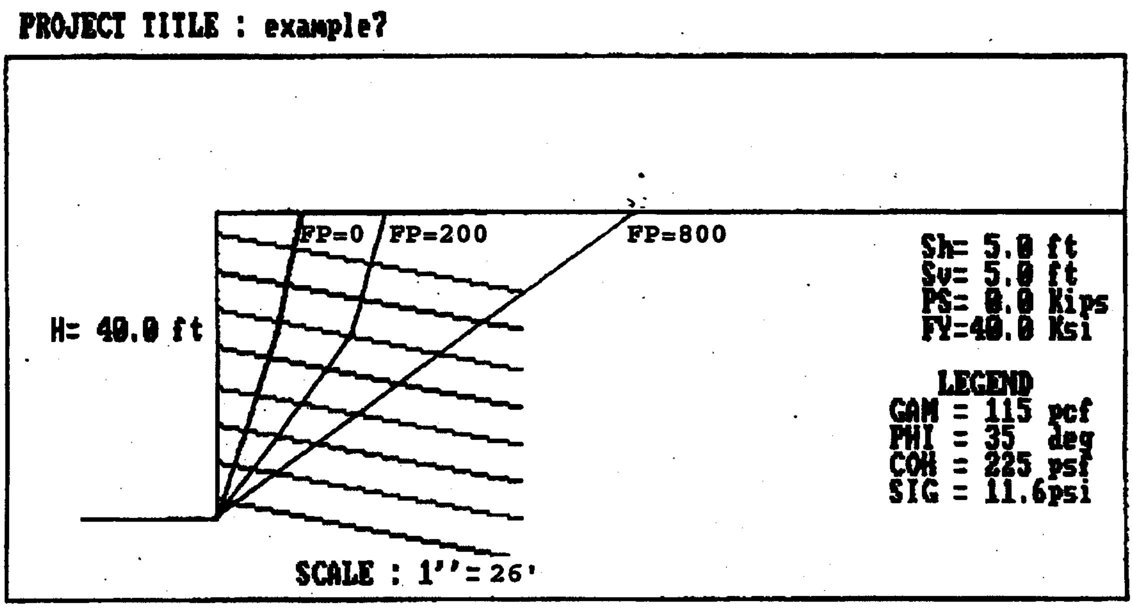


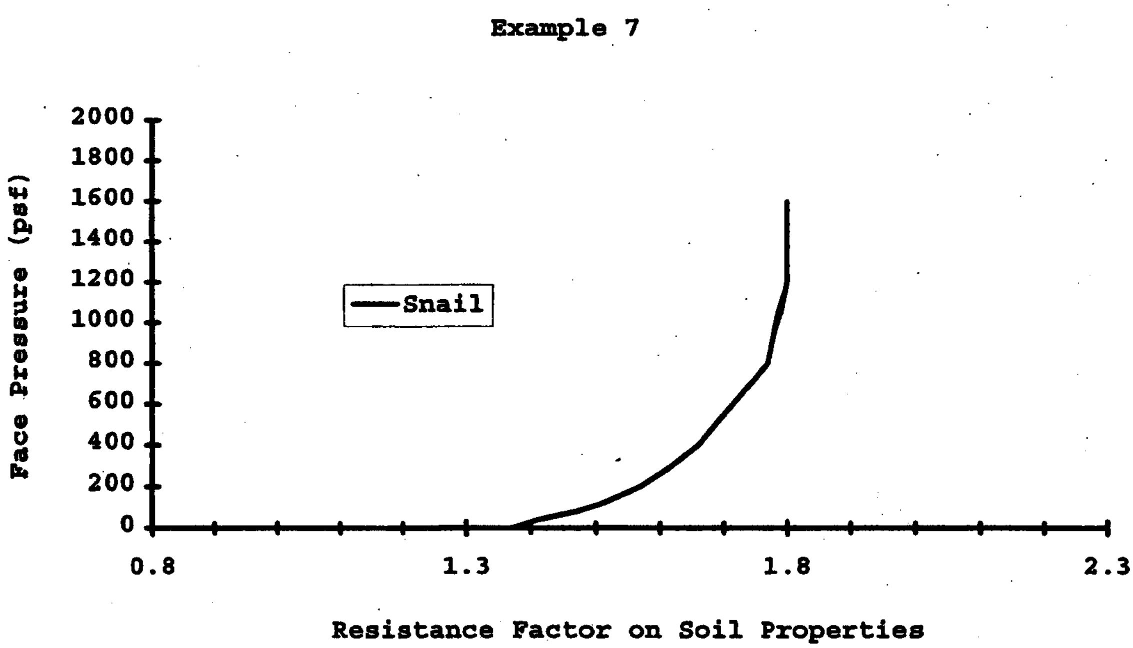
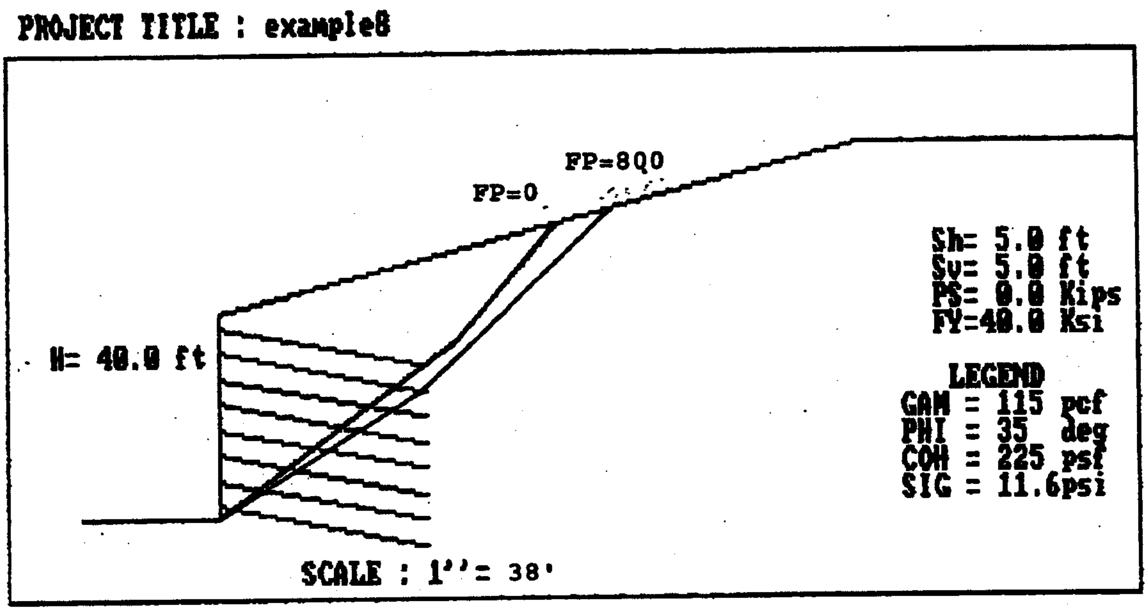
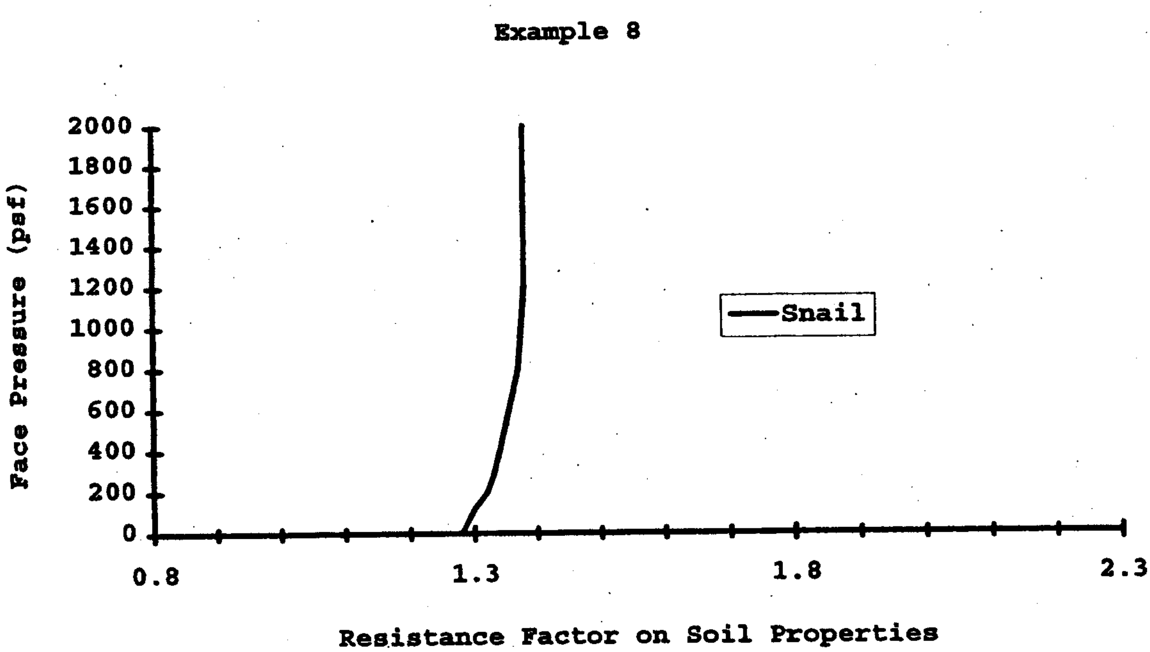


Figure 4.22 Ex. 7 **Snail** face pressure comparison





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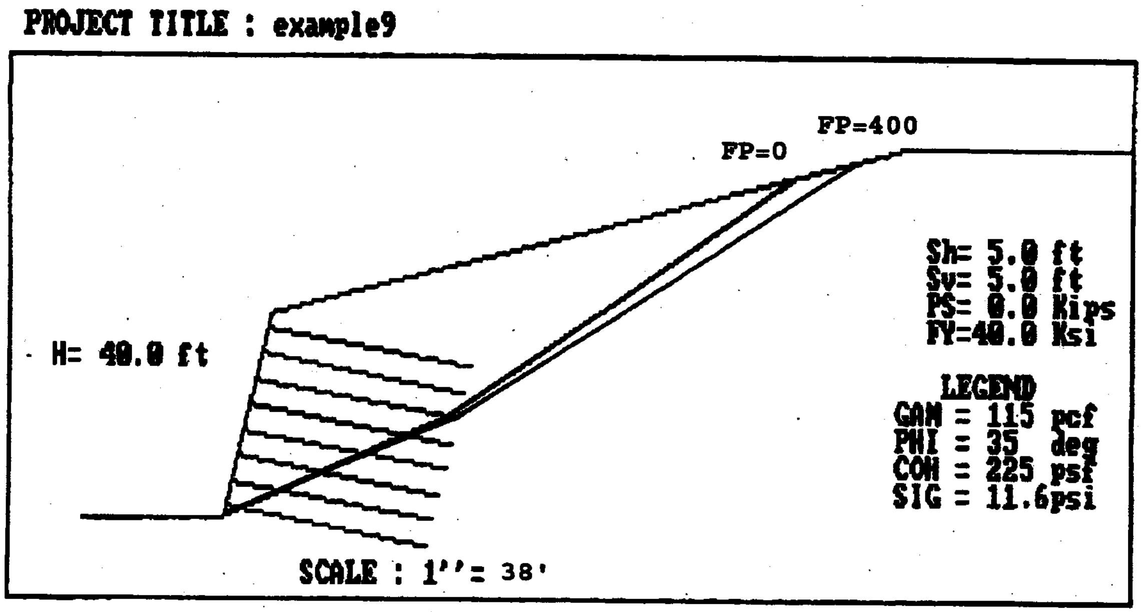

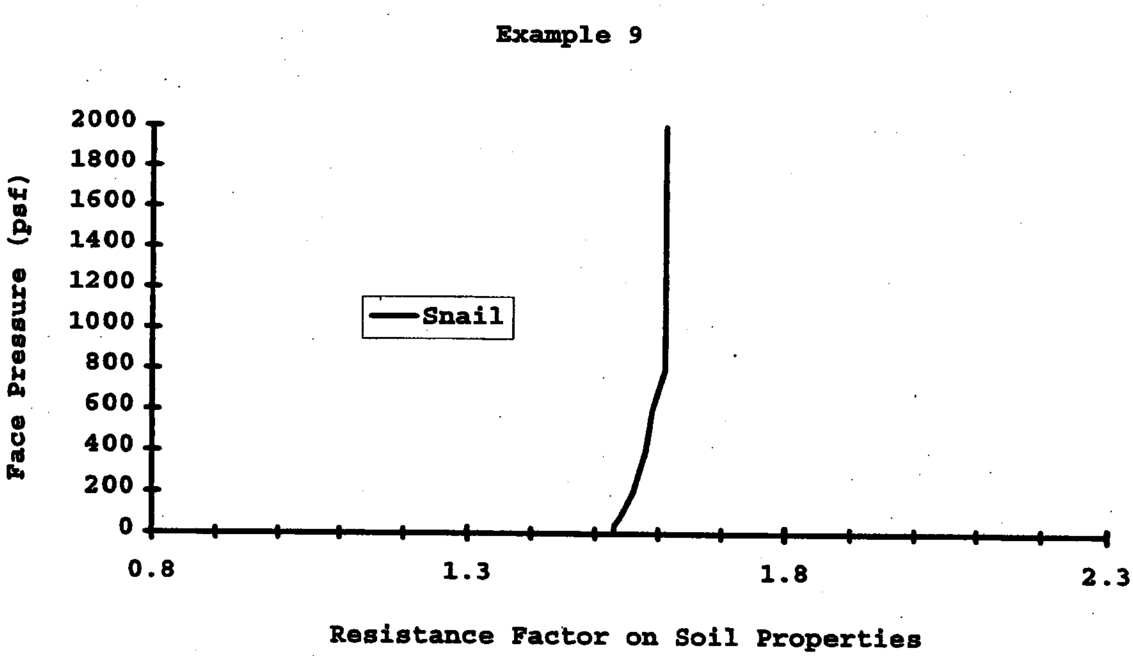

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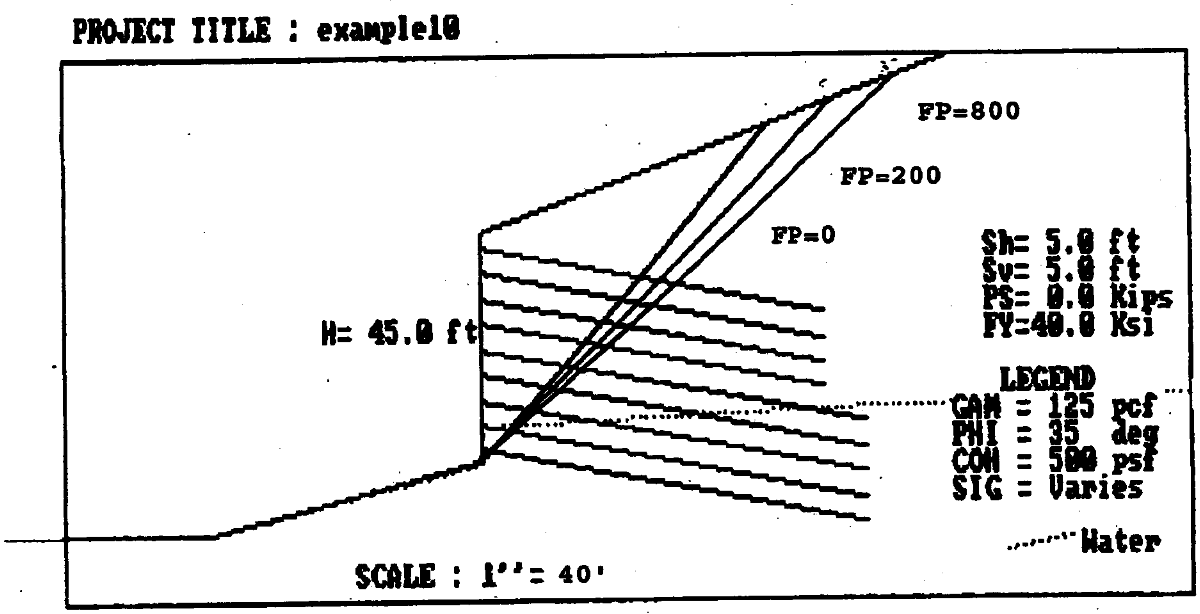


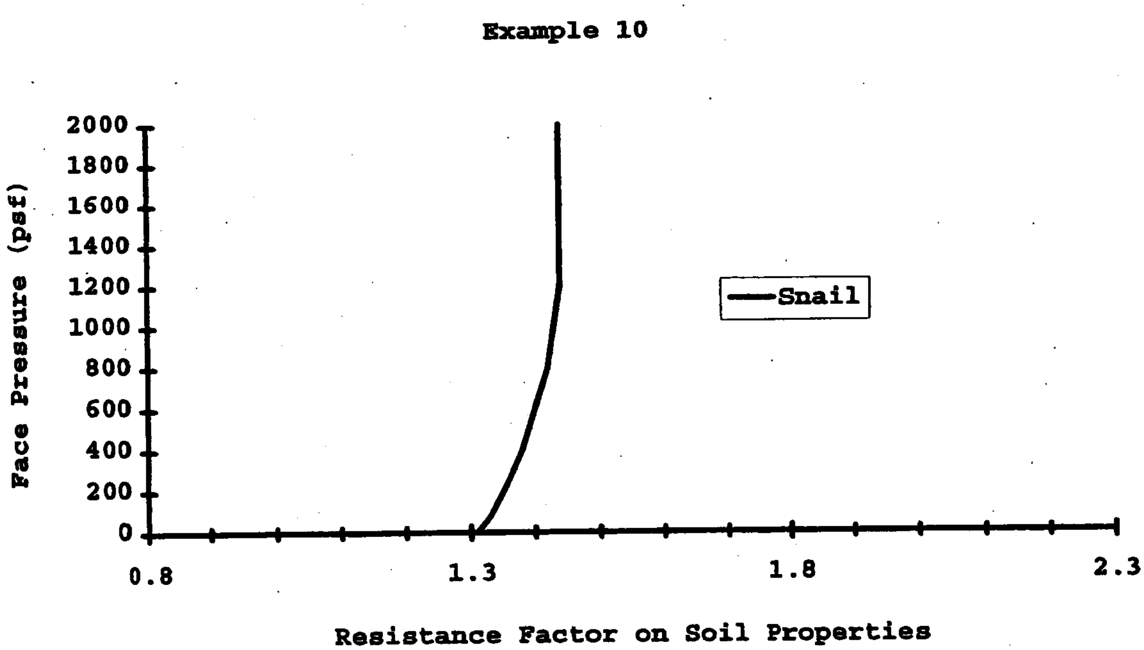
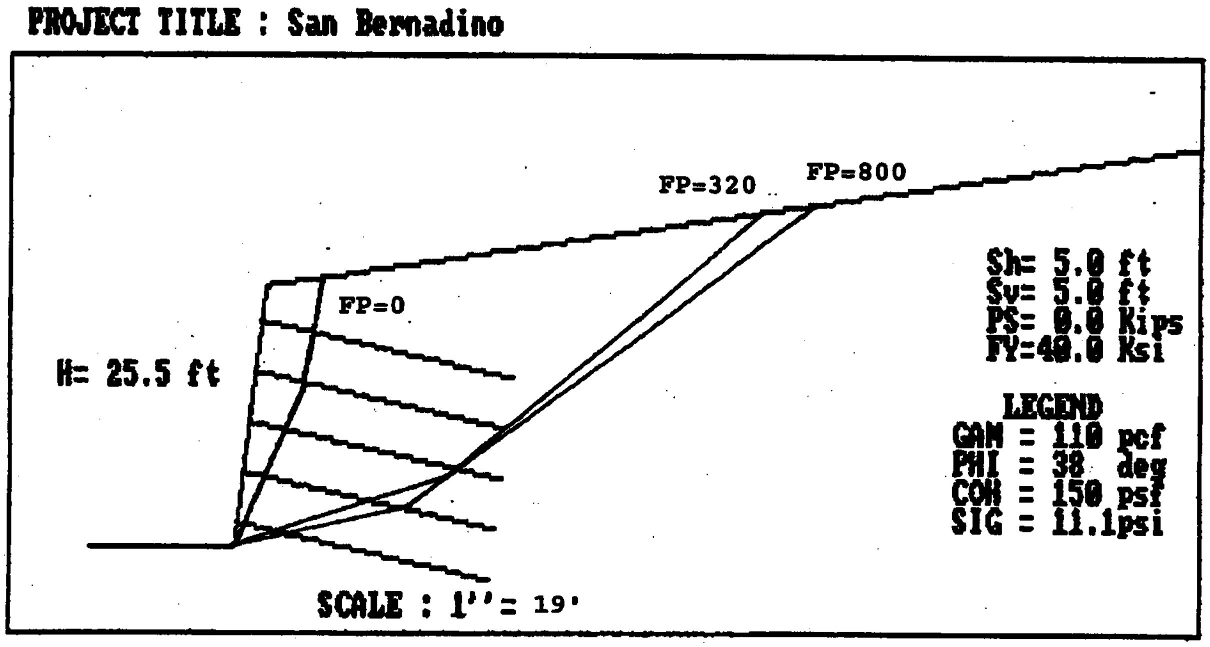


Figure 4.25 Ex. 10 **Snail** face pressure comparison



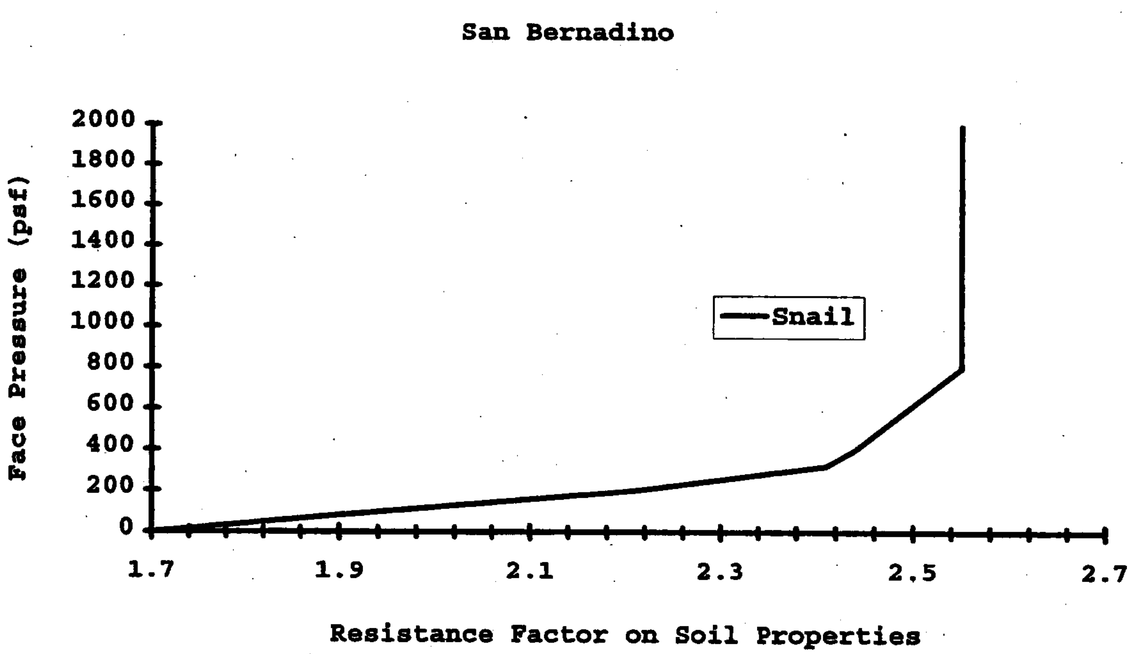
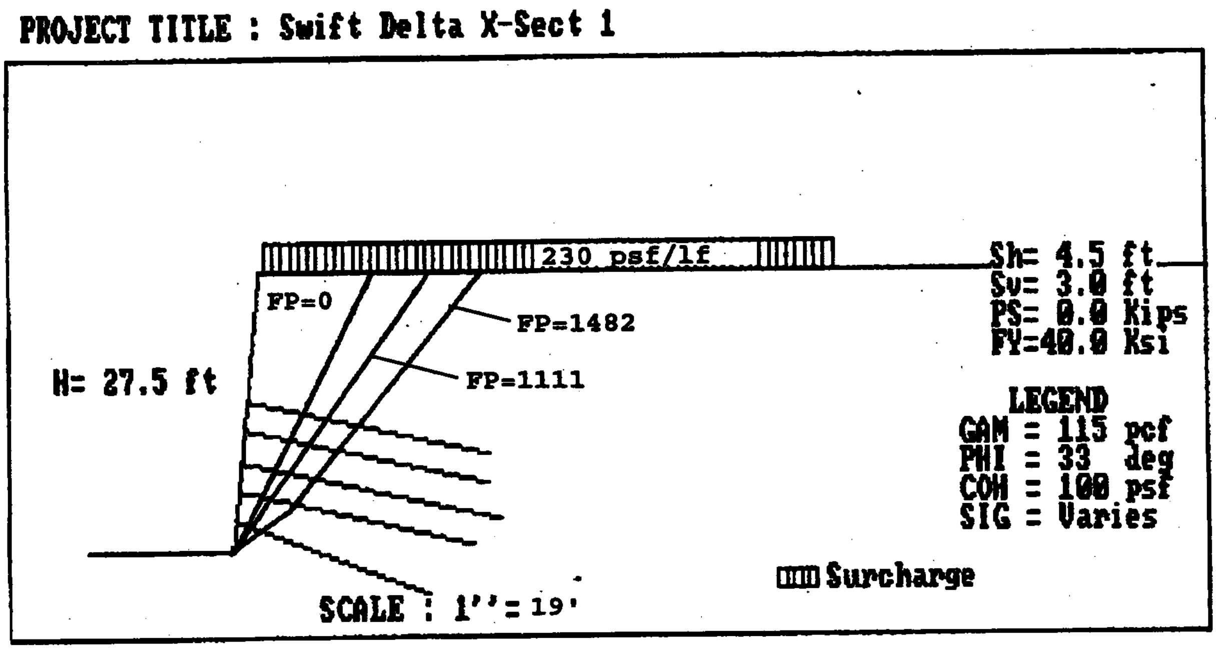


Figure 4.26 San Bernadino **Snail** face pressure comparison



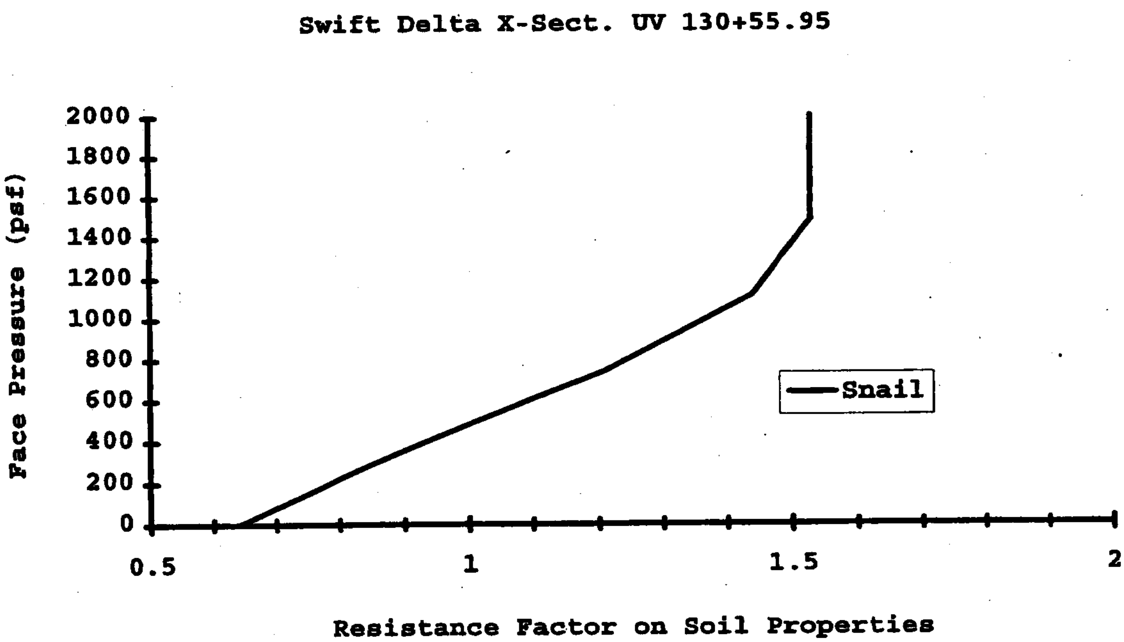
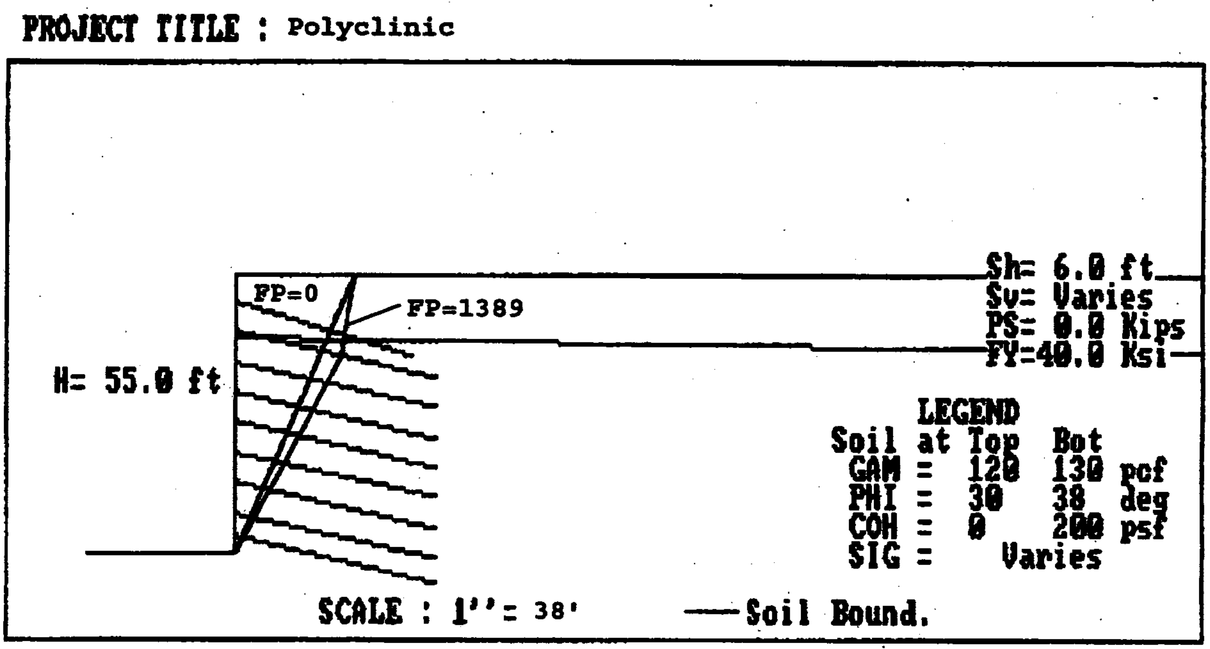


Figure 4.27 Swift Delta **Snail** face pressure comparison



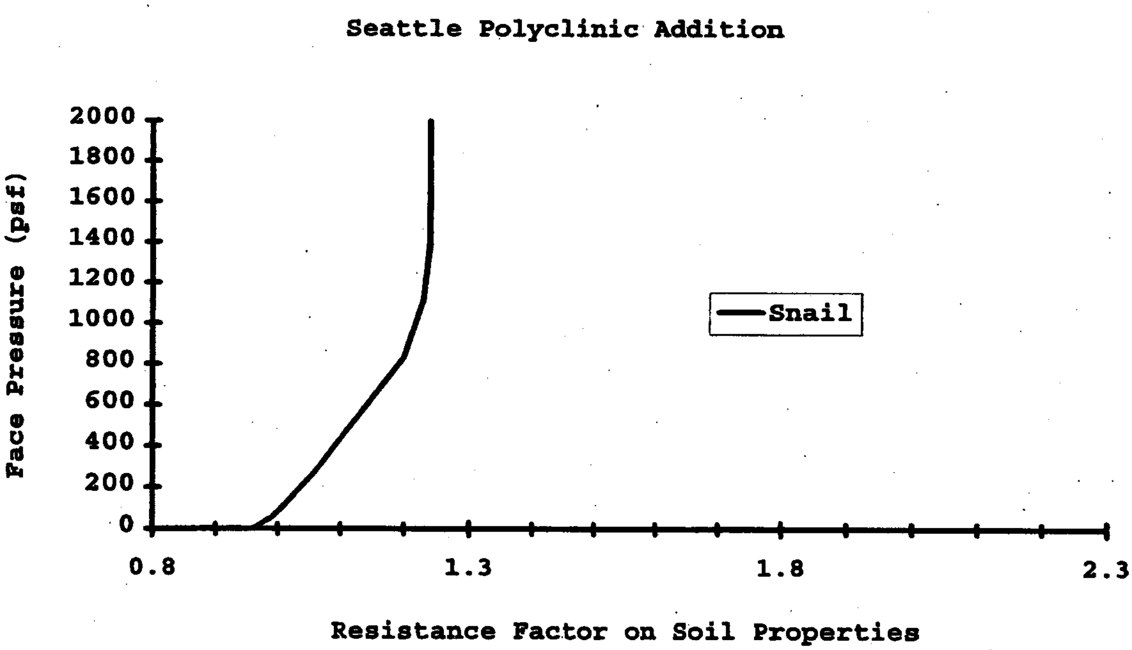
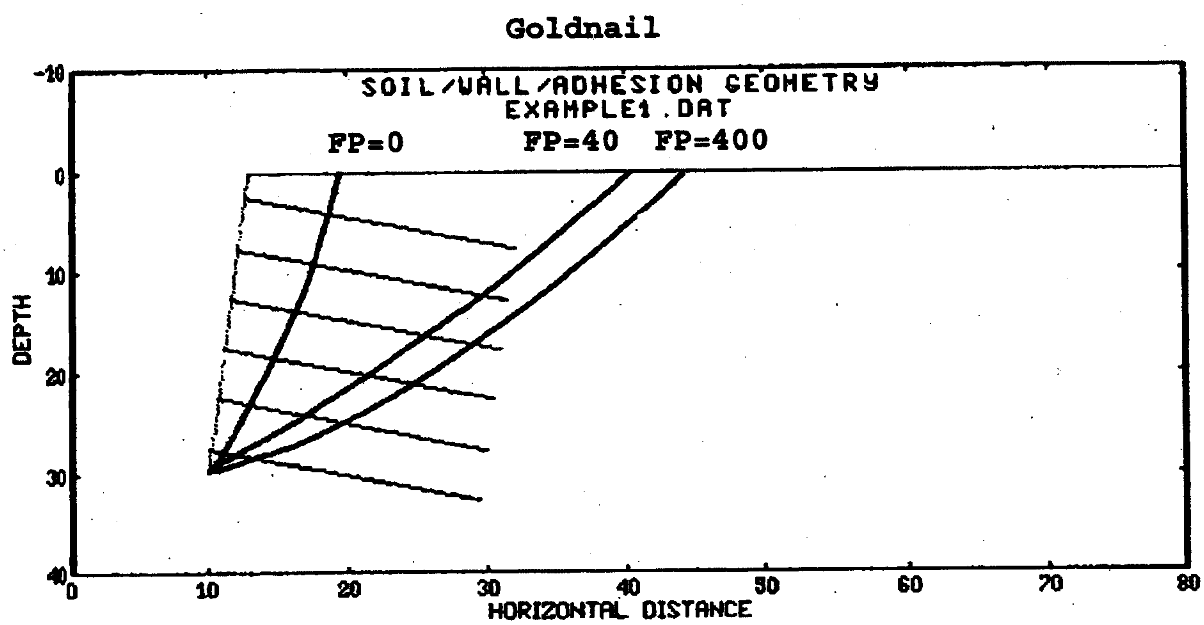


Figure 4.28 Polyclinic **Snail** face pressure comparison

4.5 Goldnail face pressure comparisons



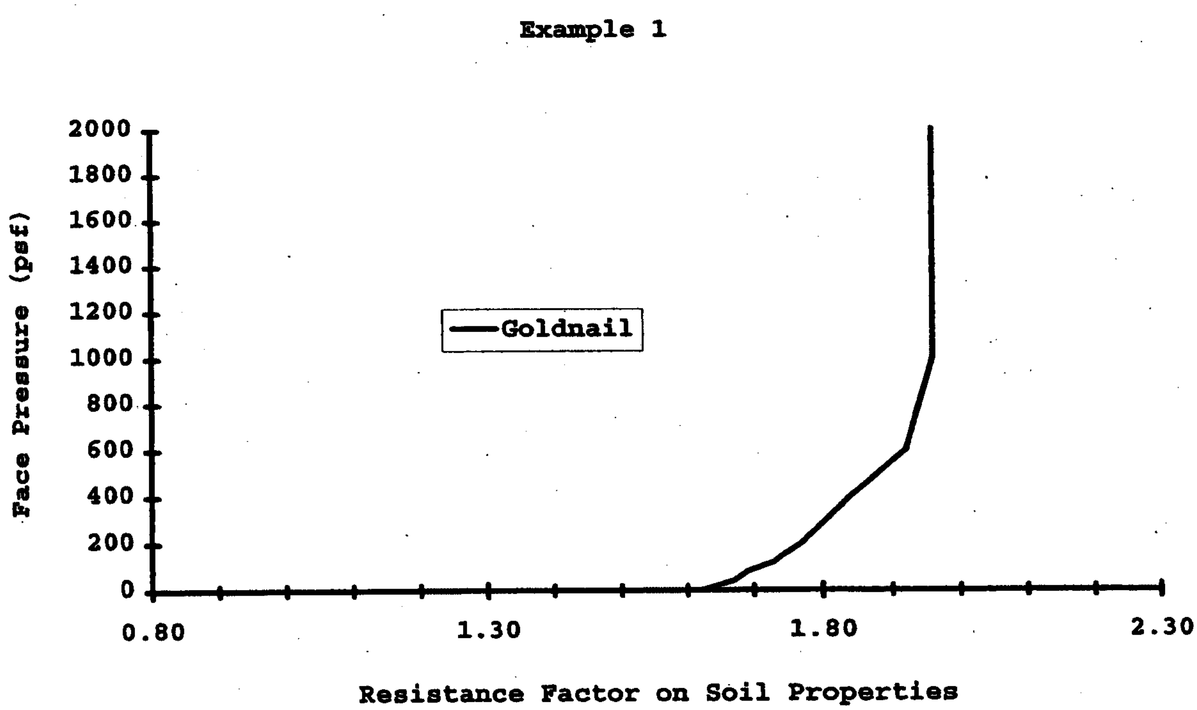
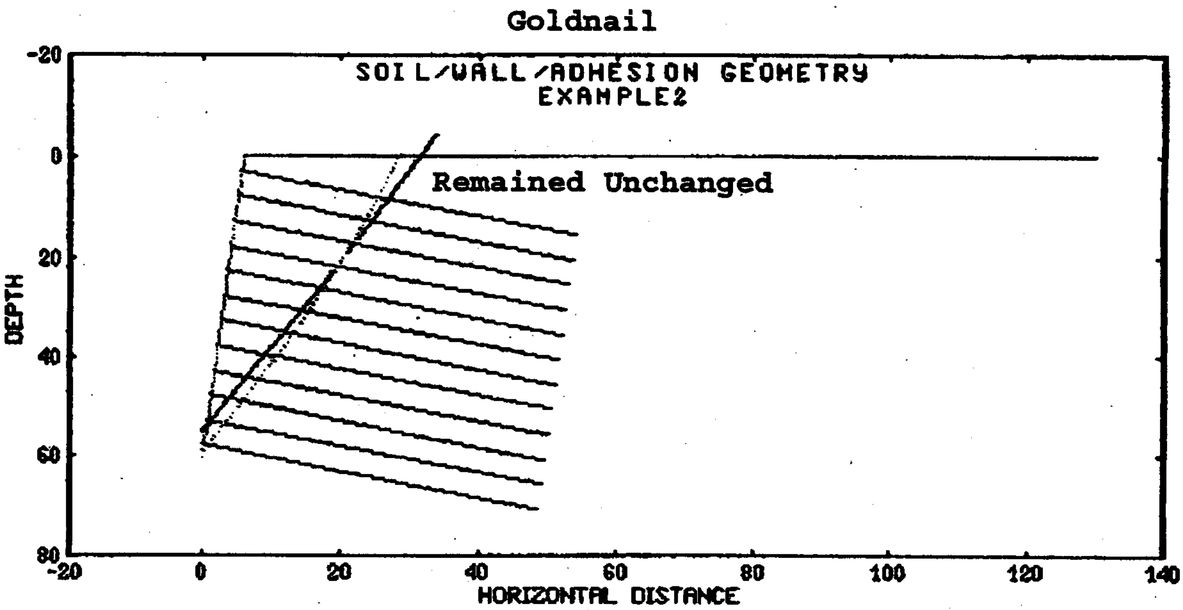


Figure 4.29 Ex. 1 **Goldnail** face pressure comparison



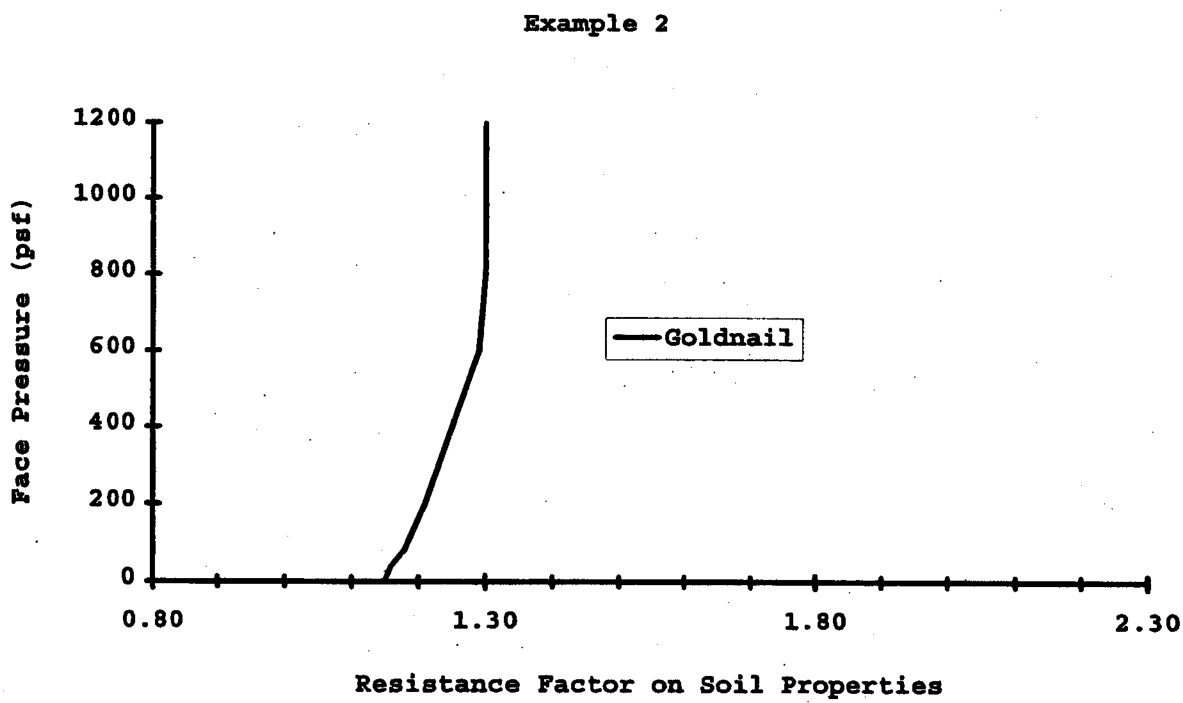
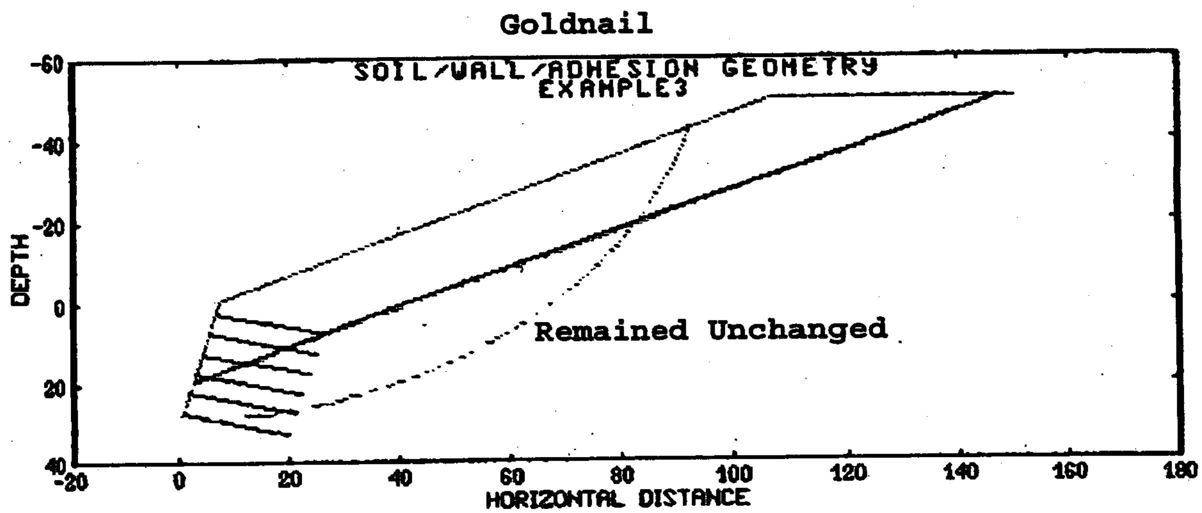


Figure 4.30 Ex. 2 **Goldnail** face pressure comparison



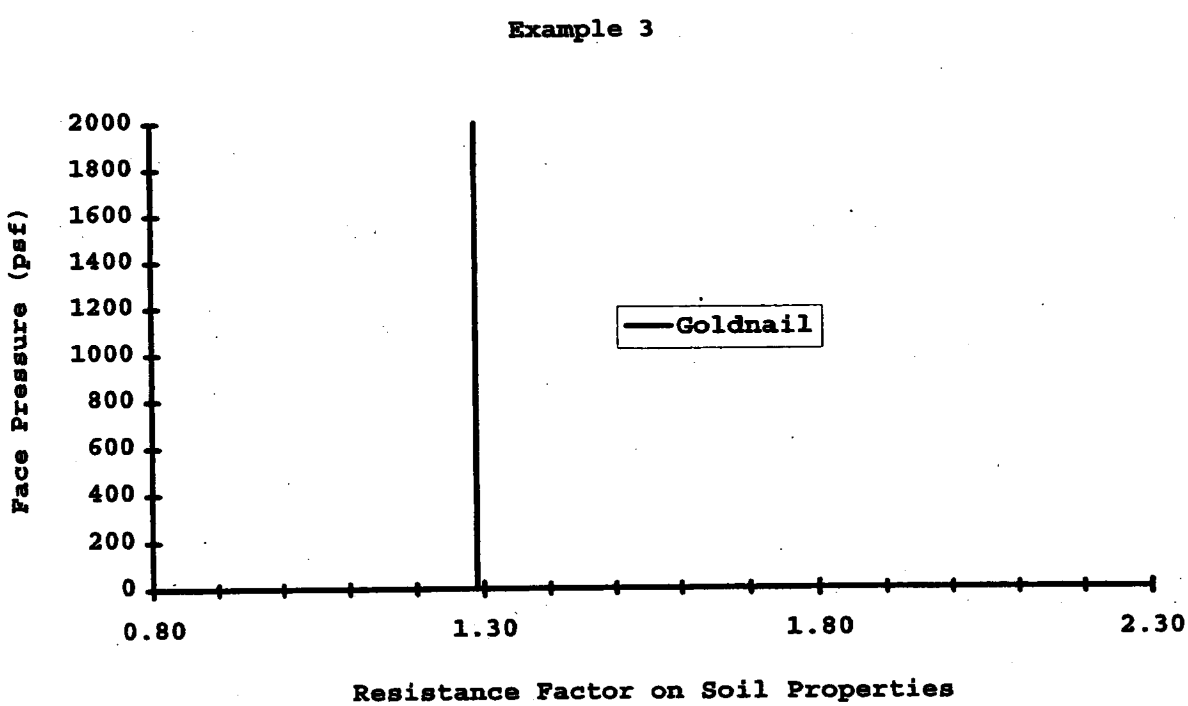
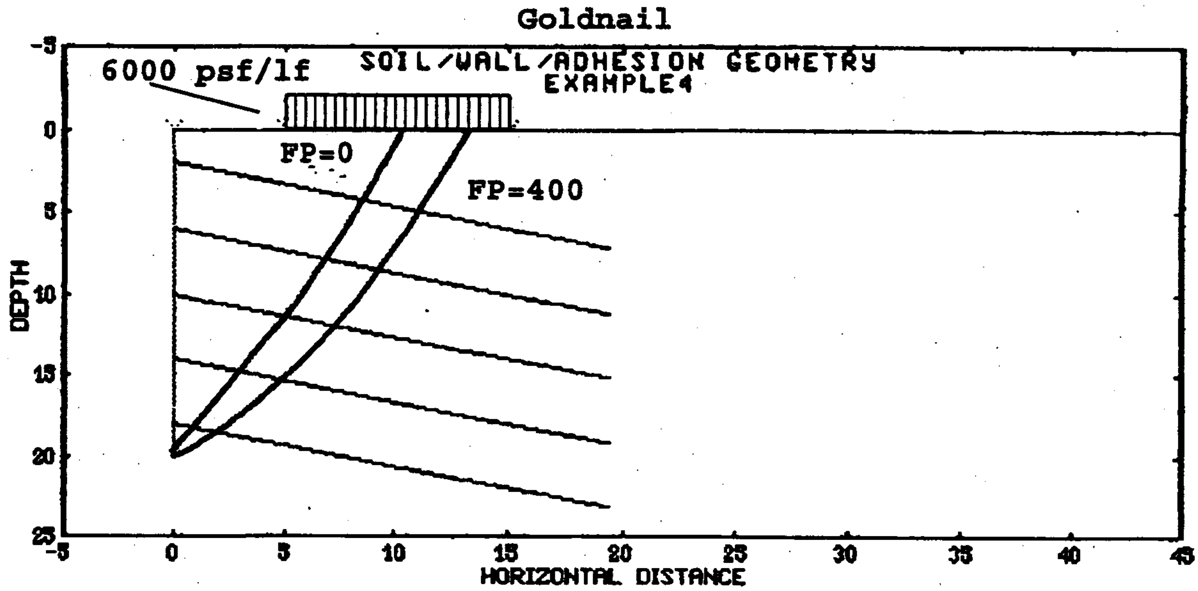


Figure 4.31 Ex. 3 **Goldnail** face pressure comparison



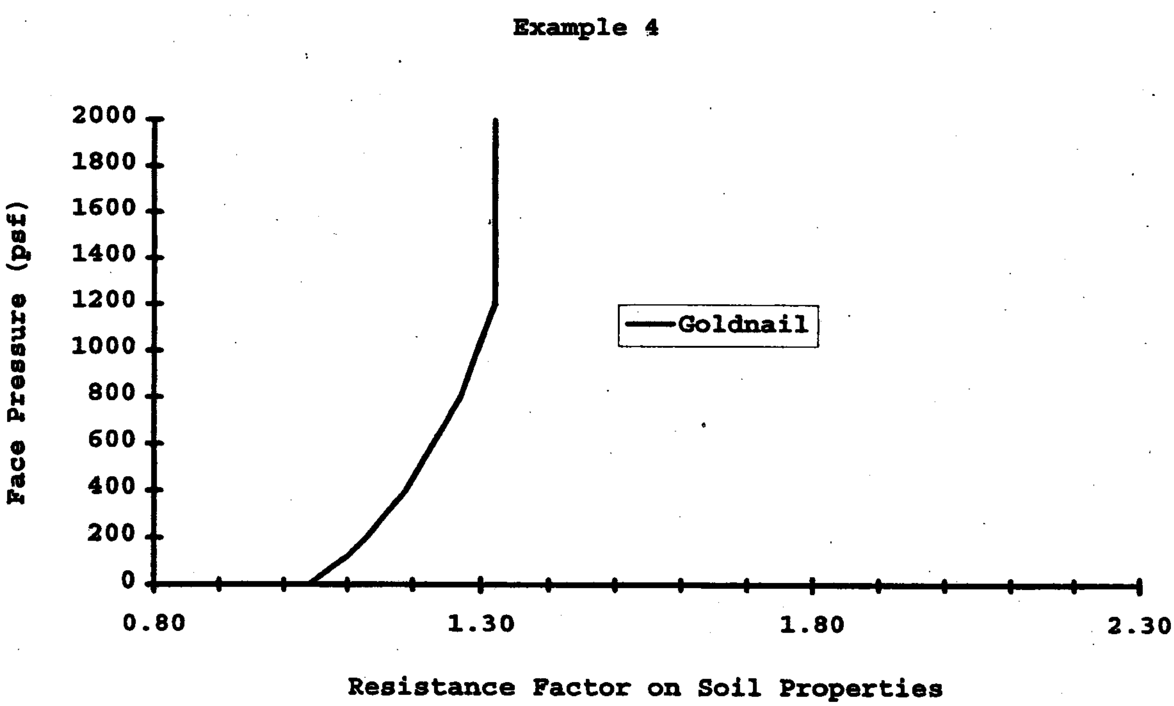
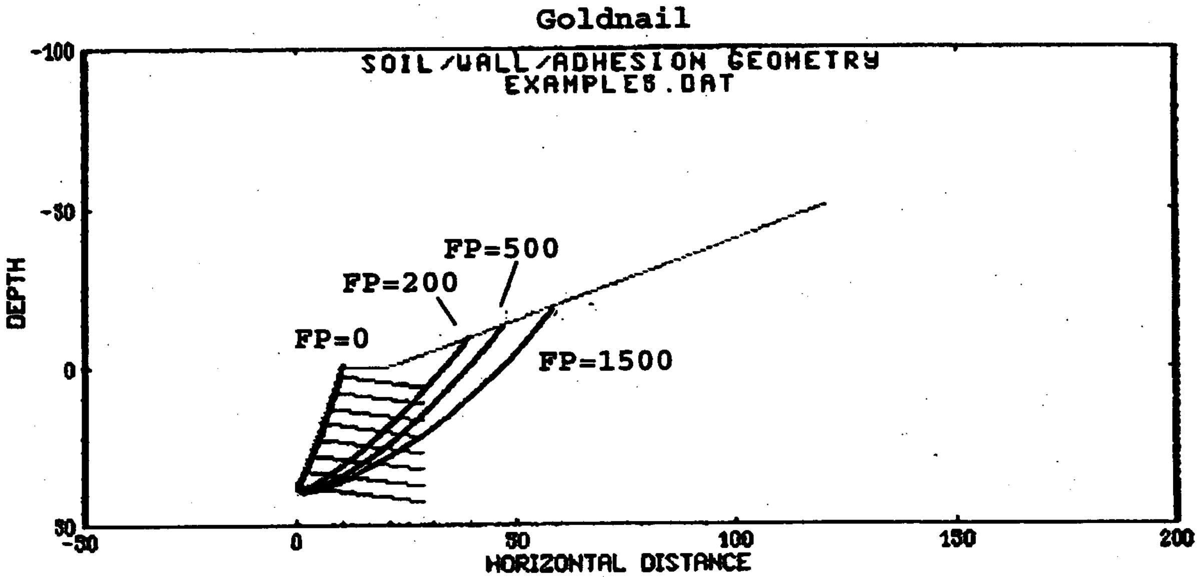


Figure 4.32 Ex. 4 **Goldnail** face pressure comparison



Example 5

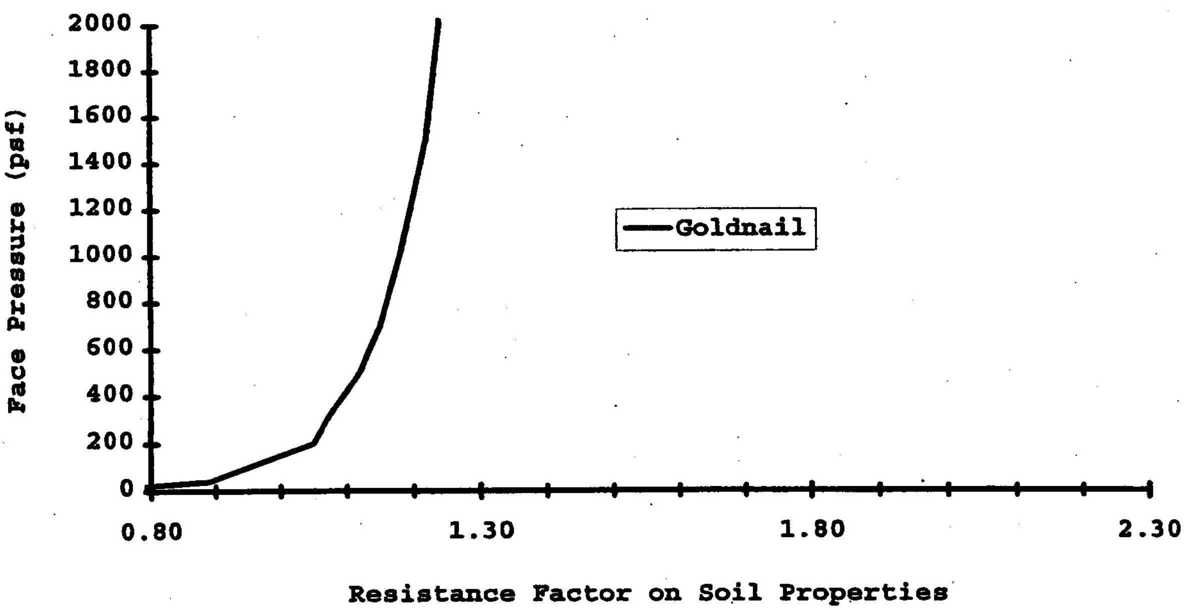
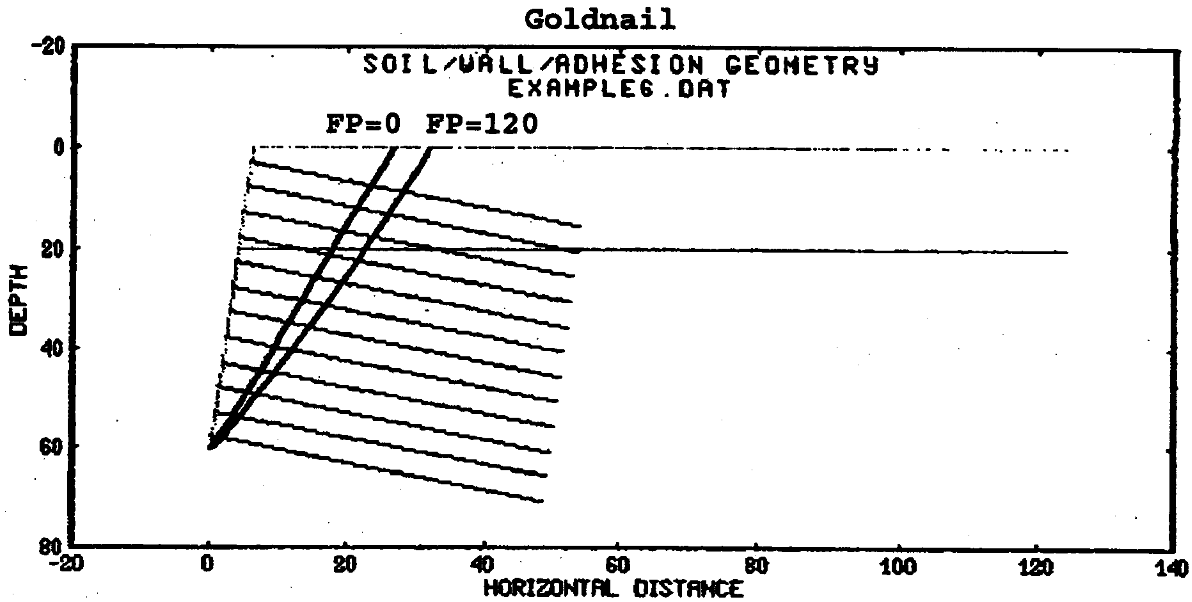


Figure 4.33 Ex. 5 **Goldnail** face pressure comparison



Example 6

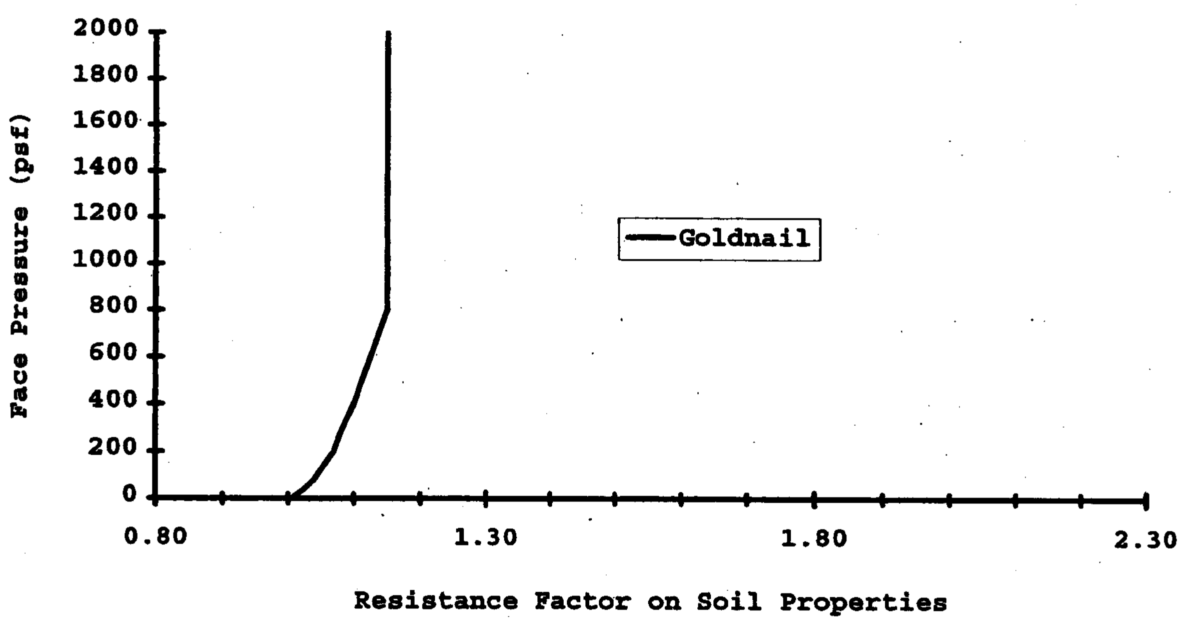
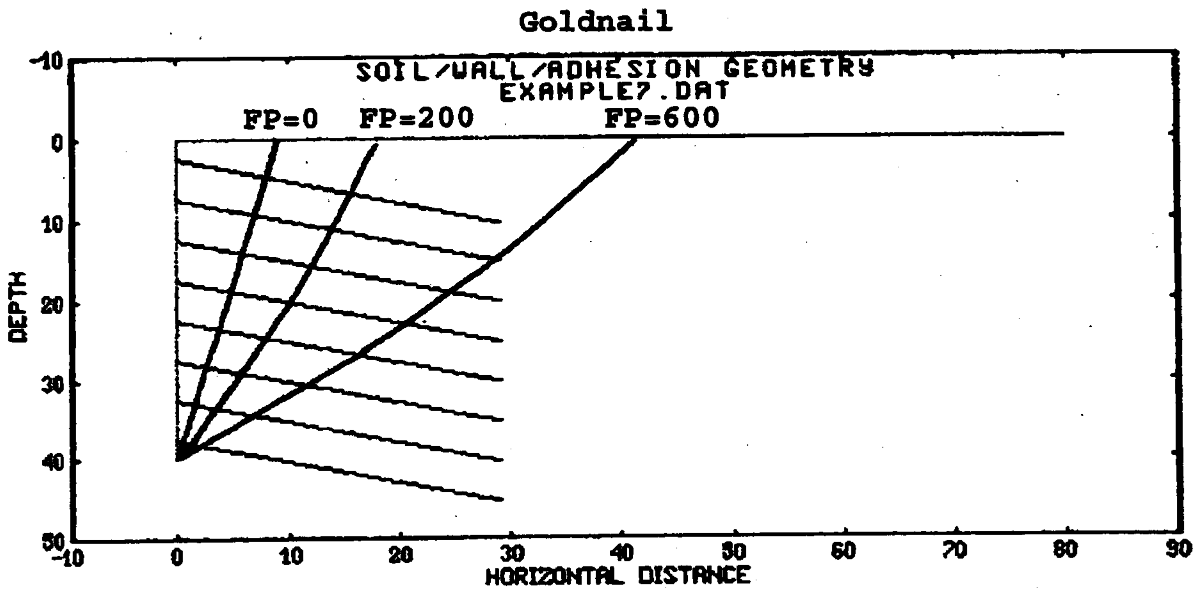


Figure 4.34 Ex. 6 **Goldnail** face pressure comparison



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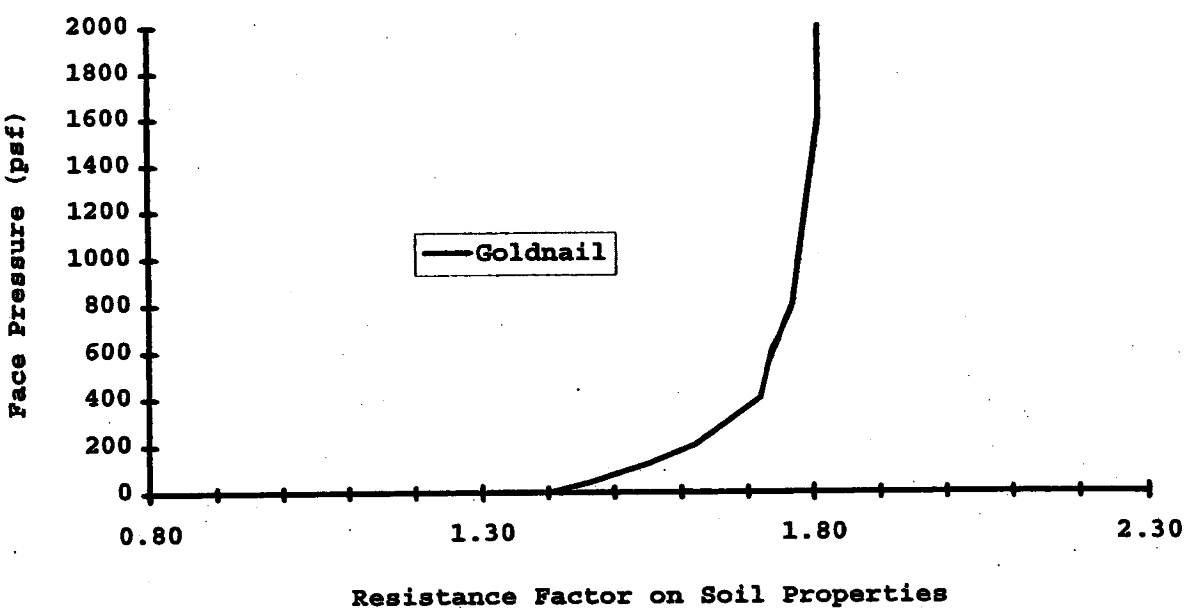
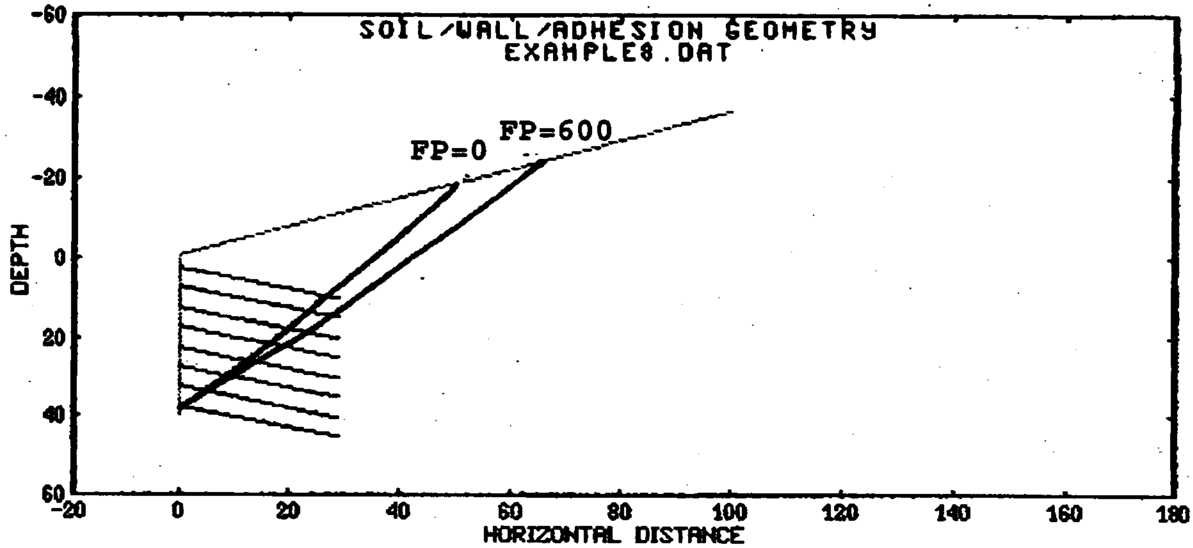


Figure 4.35 Ex. 7 **Goldnail** face pressure comparison

Goldnail



Example 8

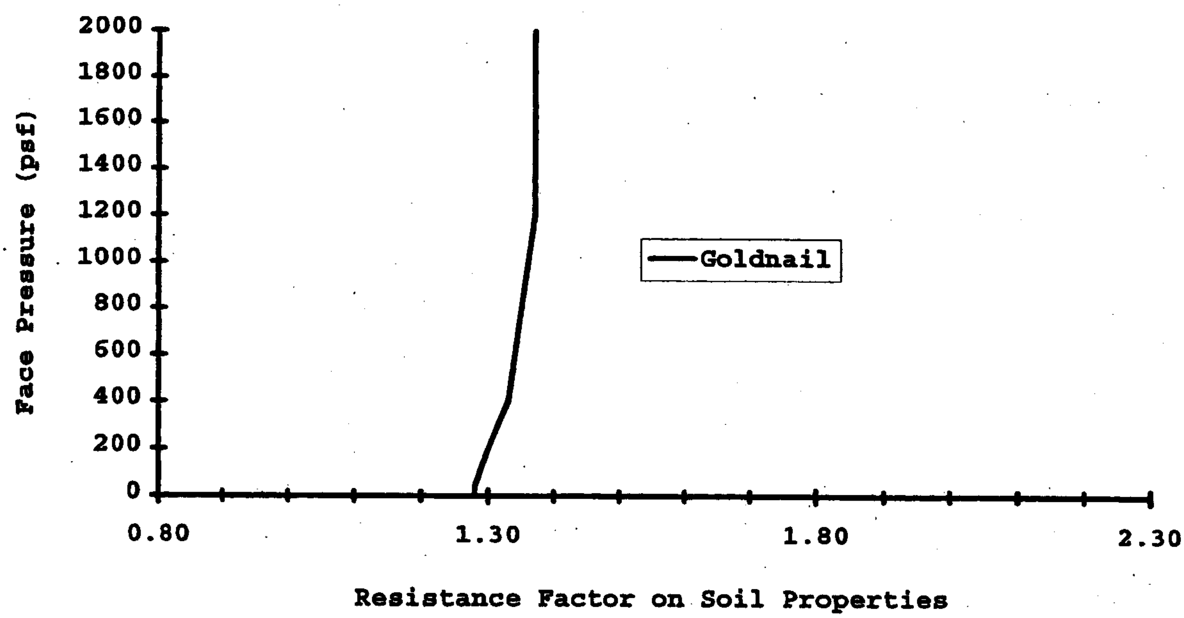
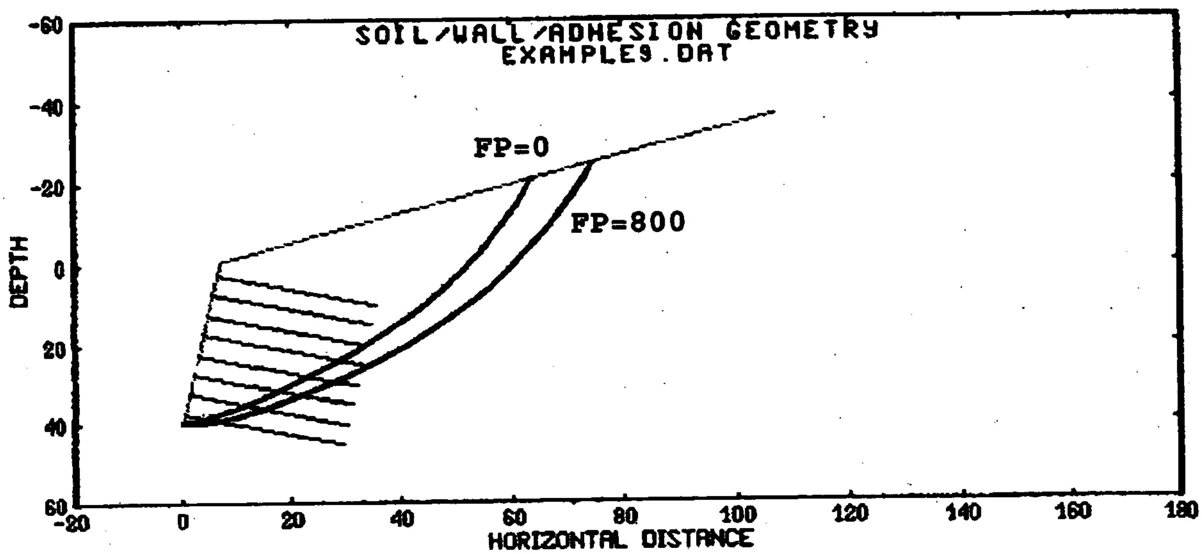


Figure 4.36 Ex. 8 **Goldnail** face pressure comparison

Goldnail



Example 9

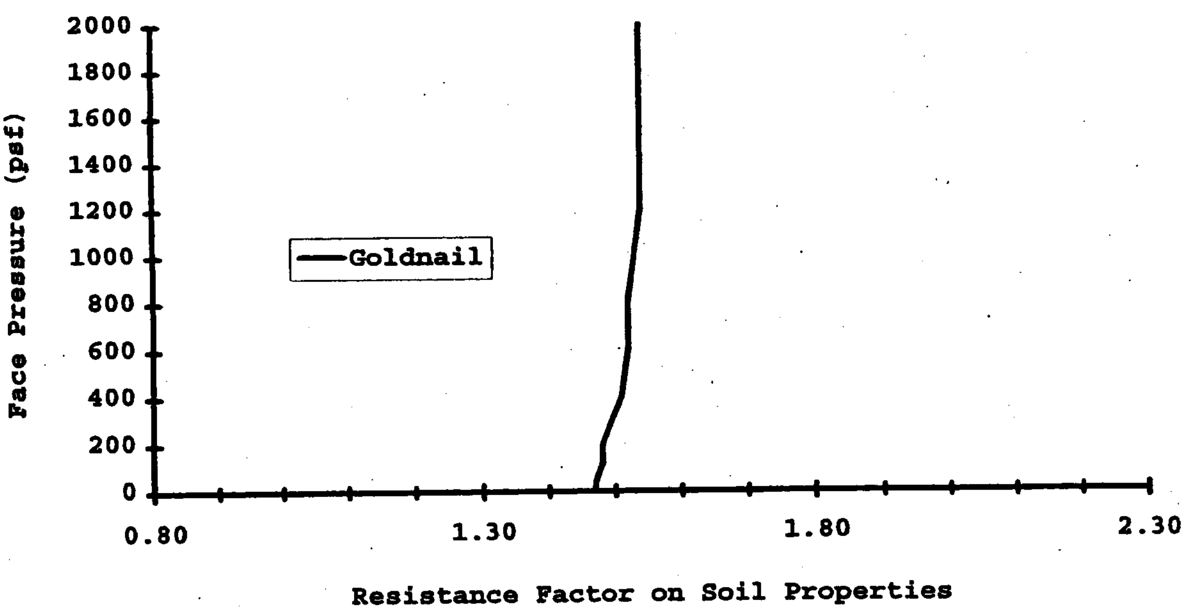
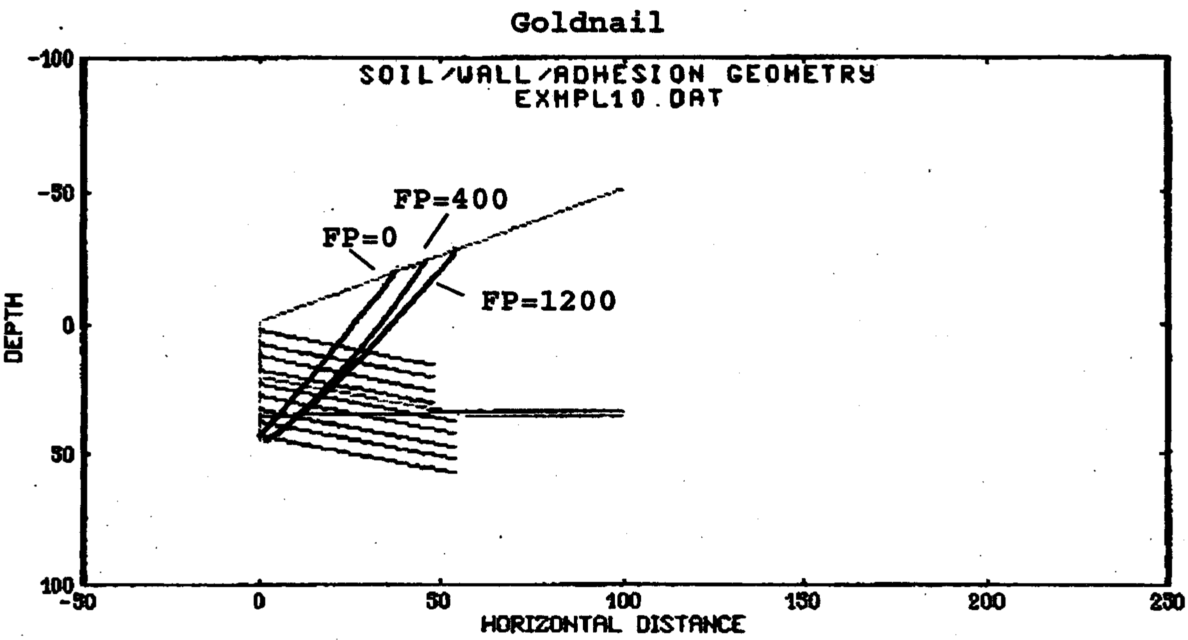


Figure 4.37 Ex. 9 **Goldnail** face pressure comparison



Example 10

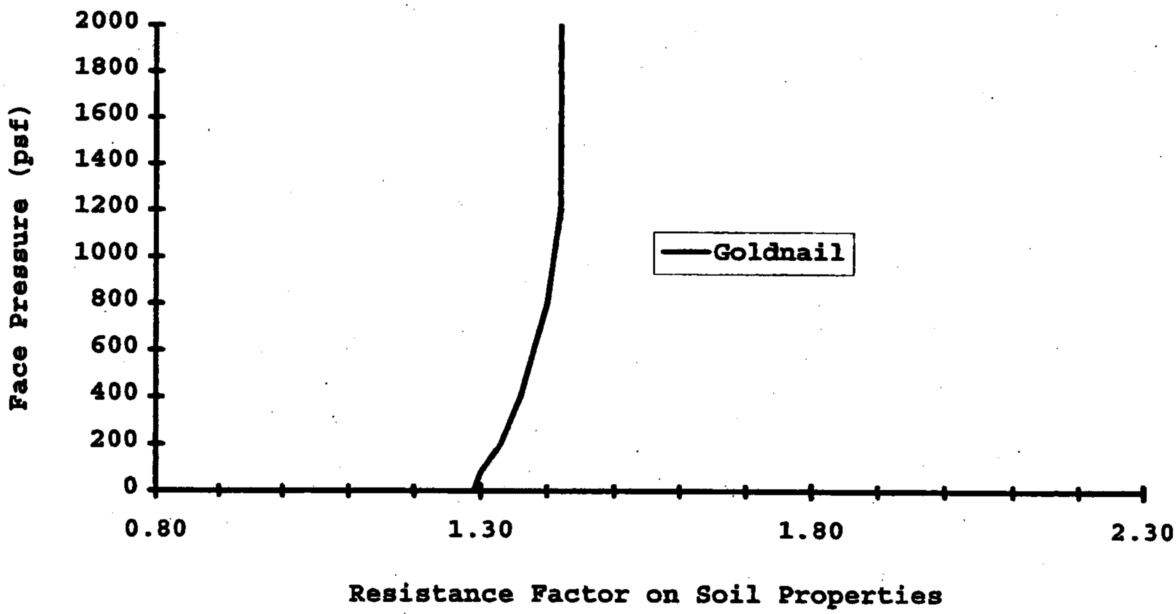
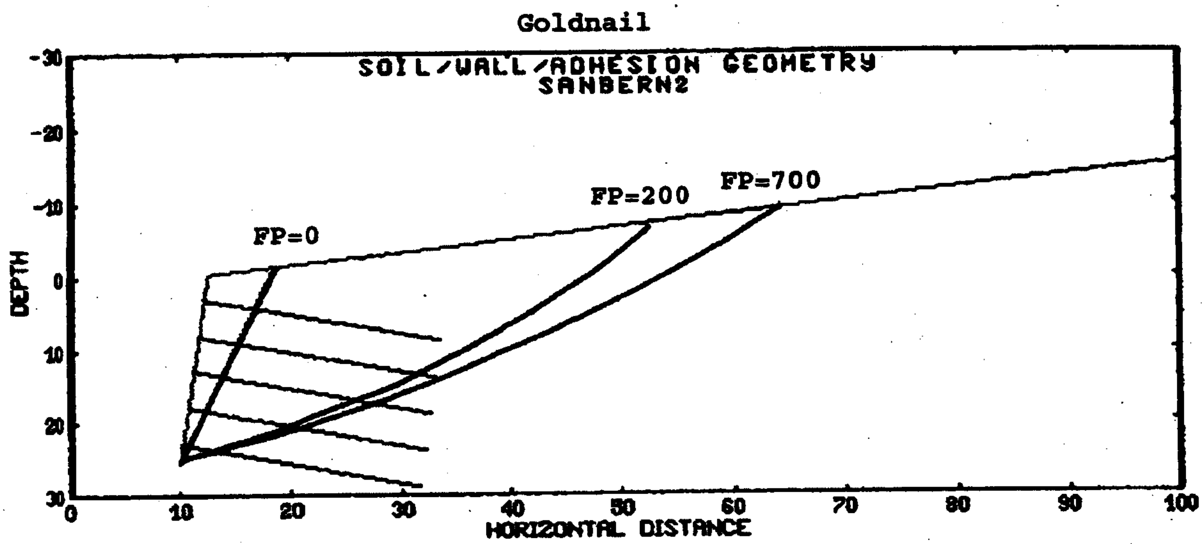


Figure 4.38 Ex. 10 **Goldnail** face pressure comparison



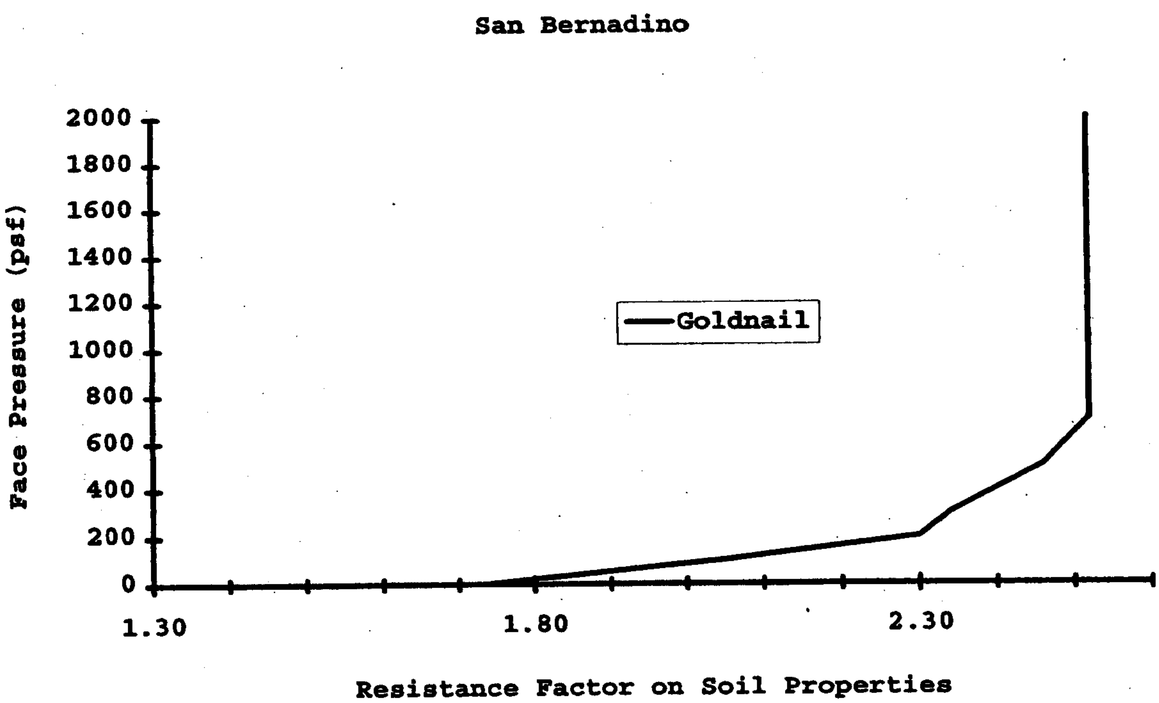
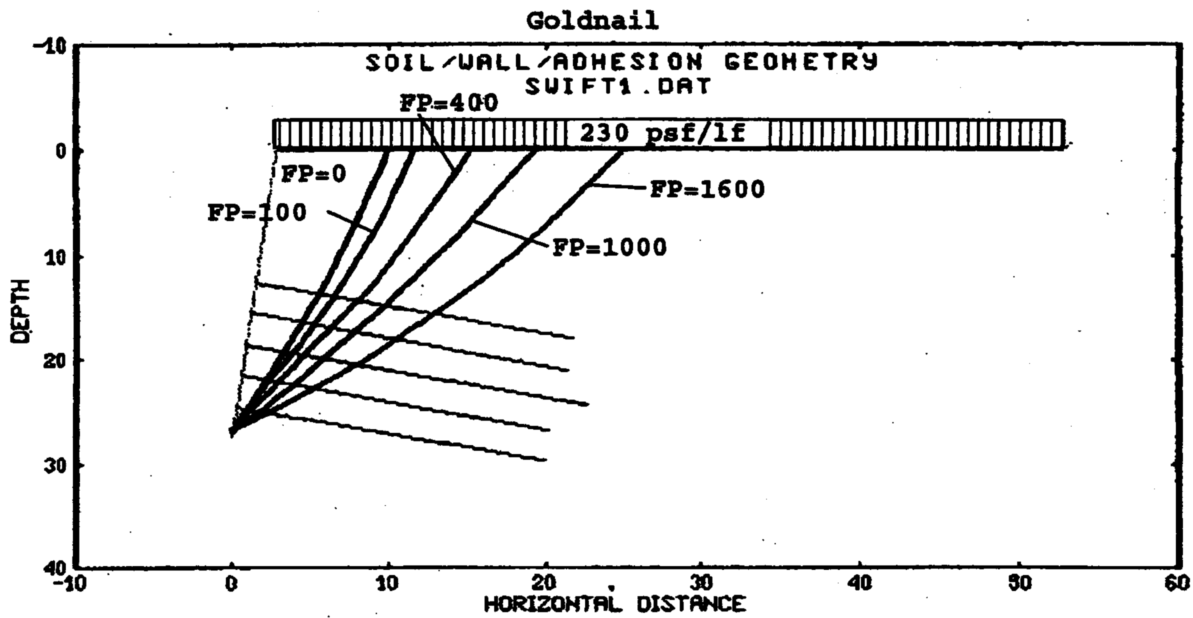


Figure 4.39 San Bernadino **Goldnail** face pressure comparison



Swift Creek X-Sect. UV 130+55.95

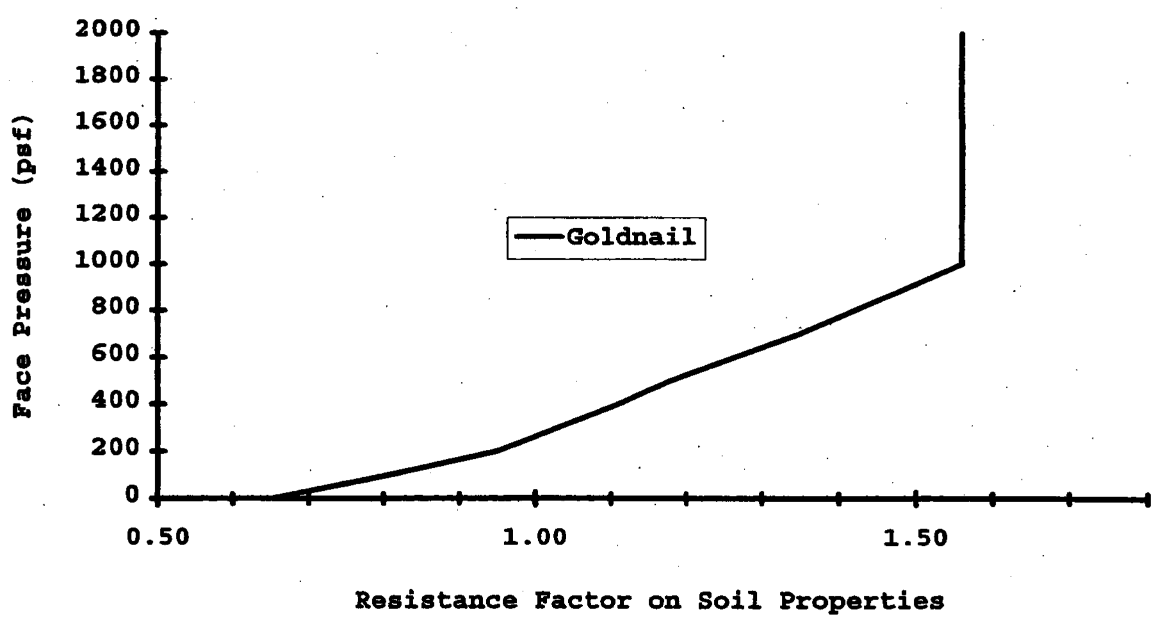
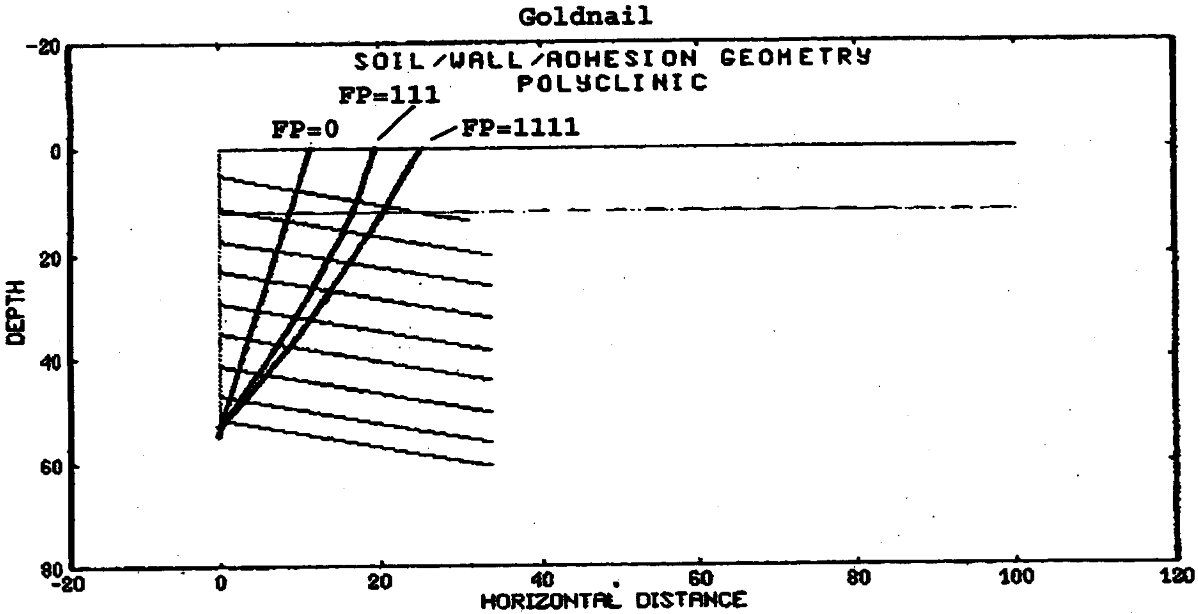


Figure 4.40 Swift Delta Goldnail face pressure comparison



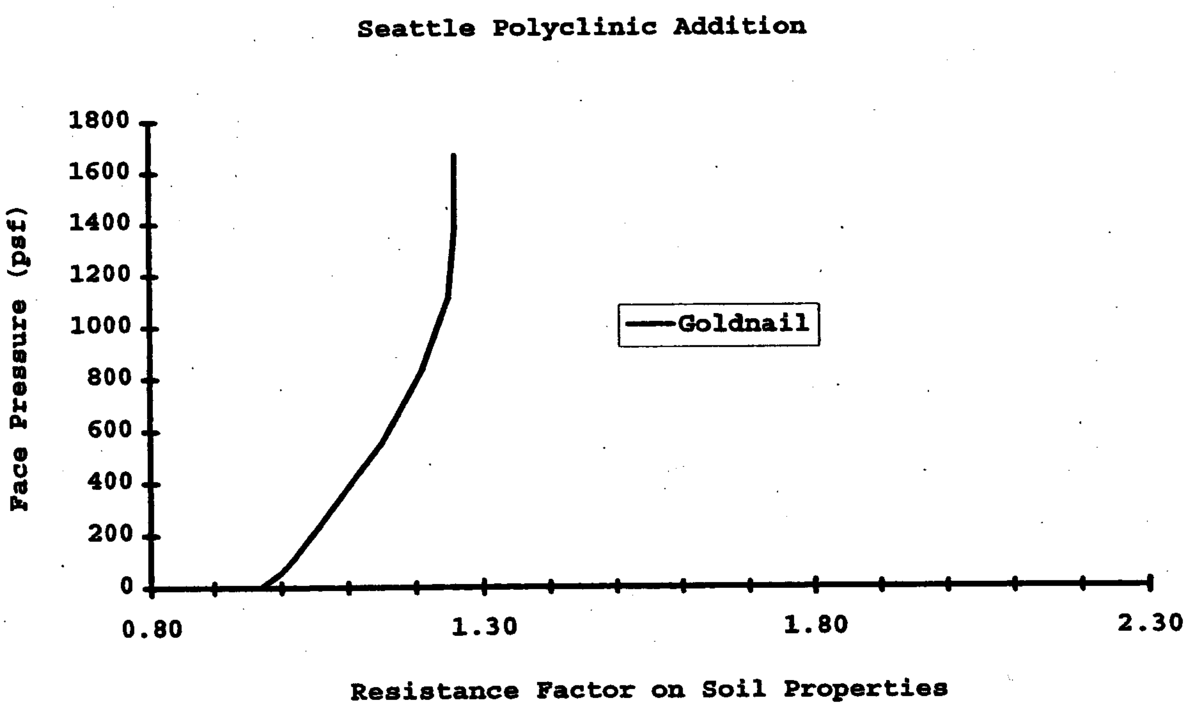


Figure 4.41 Polyclinic **Goldnail** face pressure comparison

Chapter 5

Summary of results and conclusions

5.1 Summary of results and conclusions

Notwithstanding its tremendous potential, soil-nailing has been slow to gain acceptance and wide-spread use. The average designer faces a lack of consensus within the engineering community regarding the proper soil-nailing design methodology. Numerous models of soil/nail interaction, nail contribution to stability, and overall system behavior have been proposed. The purposes of the present evaluation were to assess the performance of the analysis packages as affected by the varying underlying assumptions, as well as to assess the relative ease of use associated with each of the programs.

The evaluation was formally accomplished by performing a number of example analyses. The ten hypothetical cases and five case studies chosen in this comparison were meant only to represent common design scenarios, and not to reveal any discrepancies between program output. Some of the examples were adapted from the FHWA initial design method comparison (FHWA, 1991). Three of the hypothetical cases were presented in Juran, et al., (1990a). Appendix A contains further description and references for the five case studies used in this evaluation.

A number of trends became quite evident; the most obvious is that the safety factors predicted by **NailM9** were consistently lower than those predicted by the other five programs. **NailM9** defines the global stability as the ratio of the component of resisting forces along the direction of the driving forces, divided by the total driving force (see Section 3.2.4).

As for other discernible trends, the safety factors predicted by **Snail** and **Goldnail** were bounded by those of the three other programs (not including **NailM9**) in ten of the fifteen cases. For the remaining cases, **Snail** and **Goldnail's** results were practically identical to those of the other three programs.

Overall, the largest difference between the predicted safety factors was 0.7, which occurred for the San Bernadino wall. This value is an outlier, however, with the average difference being about 0.35. If **NailM9's** prediction is discounted due to its different definition of the safety factor (discussed above), the result is an average spread between the remaining five programs of about 0.1, with the smallest difference being 0.04.

The predicted locations of the slip surfaces were almost identical for all of the fifteen examples and case studies, with one notable exception, Eparris. With this failure case, the programs predicted slip surfaces more shallow than that of the actual failure surface.

Assumptions related to face pressure are important to design, and it is a desirable feature to be included in a soil-nailing analysis package. It is noteworthy that the **Snail** and **Goldnail** analyses for the Polyclinic wall predict an unstable wall in the absence of face pressure. The remaining four programs used to analyze the wall do not consider the wall's structural contribution to stability.

Major conclusions

Program assumptions, which may include slip surface type and nail modeling, make very little difference to:

- predicted safety factors
- predicted slip surface location

From the point of view of the program user, the ease of interaction with the programs varied considerably with regard to:

- input flexibility
- ease of data entry

As a final note, if one were to provide a somewhat subjective rating or evaluation of specific program features, then the preferred features of each would be as follows:

- Flexibility of input - **Talren.**
- On-screen display of data during data entry - **Stars.**
- Input of a face pressure parameter- **Goldnail** and **Snail.**
- Toe search capability - **Snail, Talren, and Stars.**
- Output quality - **Talren** (with the correct printer, see Section 3.2.6)
- Ease of existing data modification - **Stars, Snail,** and **Nail-Solver.**
- Calculation methods - **Snail, Goldnail,** and **Talren.**

5.2 Future research

Limit equilibrium design methods are valuable to designers for they allow a quick calculation of stability that is most often conservative. Further research on soil-nailing design needs to address the issue of predicting working nail loads from instrumented walls with strain gage data. Limit equilibrium methods are not well suited to the prediction of nail loads, with their concept of a single well defined failure surface. With regard to utilizing the knowledge gained from this evaluation, it would be prudent to develop an analysis package that utilizes the key features of each of the programs, as they were presented in Section 5.1. Further research on the topic of soil-nailing must also include the development of a finite element package to predict wall deformations and nail loads. The program should be flexible enough to allow time sequence display of deformations, corresponding to individual excavation lifts.

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Appendix A

Input parameters for the fifteen examples

Example 1 (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
225	35	110	6	.875	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2500	30	5	5	20	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
17.36	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	84.3	0	160	57

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
3927	36079	Varies	.67

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm^2	m.		
414	9	1	2.26

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.6	0	2500	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
57	0	0	1.5	160	0	1	0

Example 2 (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
225	35	110	6	.875	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2500	60	5	5	50	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
17.36	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	84.3	0	160	57

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
3927	36079	Varies	.83

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm^2	m.		
414	18	1	.8

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.6	0	2500	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
57	0	0	1.5	160	0	1	0

Example 3 Upper Soil (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
225	35	110	6	.875	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2000	30	5	5	20	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
13.89	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
	Not	Applicable		

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
3142	36079	Varies	.67

Nail-Solver			
Ult. Nail Stress	H Max.	fb	Kl
N/mm^2	m.		
	Not	Applicable	

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
	Not	Applicable	

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
46	0	0	1.5	160	0	1	0

Example 3 Lower Soil (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
500	35	110	6	.875		60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
4000	30	5	5	20	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
27.78	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
	Not	Applicable		

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
6283	36079	Varies	.67

Nail-Solver			
Ult. Nail Stress	H Max.	fb	Kl
N/mm^2	m.		
	Not	Applicable	

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
	Not	Applicable	

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
92	0	0	1.5	160	0	1	0

Example 4 (Note: Values Shown Are Ultimates)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
225	40	110	6	.875	2	60
Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
3000	20	4	4	20	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
20.83	Varies

Stars				
$\beta 1$	$\beta 2$	$\beta 3$	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	90	0	160	69

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
4712	36079	Varies	1

Nail-Solver			
Ult. Nail Stress	H Max.	fb	Kl
N/mm^2	m.		
414	9	1	2.22

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
	Not	Applicable	

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
69	0	0	1.2	160	0	1	0

Example 5 Top 4 Nails (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
0	37	125	3.5	1	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2456	40	4	5	19	30000	10

Snail	
Bond Stress	Punching Shear
psi.	kips.
17.05	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
27	76	0	210	33

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
2250	47124	Varies	.6

Nail-Solver					
Ult. Nail Stress	H Max.	Nail Length	Bar Diam.	fb	Kl
N/mm²	m.	m.	mm.		
414	27	7.2	28.8	1	.8

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in²	ft.	psf.	
	Not	Applicable	

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
33	0	0	1.5	210	0	1	0

Example 5 Bottom 4 Nails (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
0	37	125	3.5	1.27		60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2456	40	4	5	29	30000	10

Snail	
Bond Stress	Punching Shear
psi.	kips.
17.05	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
27	76	0	338	33

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
2250	76006	Varies	.6

Nail-Solver					
Ult. Nail Stress	H Max.	Nail Length	Bar Diam.	fb	K1
N/mm^2	m.	m.	mm.		
414	27	7.2	28.8	1	.8

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
	Not	Applicable	

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
33	0	0	1.5	338	0	1	0

Example 6 Upper Soil (Note: Values Shown Are Ultimates)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
0	35	125	6	.875	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
5500	60	5	5	50	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
38.2	Varies

Stars				
$\beta 1$	$\beta 2$	$\beta 3$	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	84.3	0	160	126

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
8639.3	36079	Varies	.83

Nail-Solver						
Ult. Nail Stress	C	ϕ	γ	H Max.	fb	Kl
N/mm^2	kNs/m^2	Degrees	kNs/m^3	m.		
414	8.97	35	18.1	18	1	.73

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.6	0	3000	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
126	0	0	1.5	160	0	1	0

Example 6 Lower Soil (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
225	35	110	6	.875		60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclinati on
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2500	60	5	5	50	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
17.36	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	84.3	0	160	57

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
3927	36079	Varies	.83

Nail-Solver						
Ult. Nail Stress	C	φ	γ	H Max.	fb	K1
N/mm^2	kNs/m^2	Degrees	kNs/m^3	m.		
414	8.97	35	18.1	18	1	.73

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.6	0	3000	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
57	0	0	1.5	160	0	1	0

Example 7 (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
225	35	115	8	1	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2500	40	5	5	30	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
17.36	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	90	0	210	76

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
5236	47124	Varies	.75

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm^2	m.		
414	12	1	3.32

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.79	0	2500	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
76	0	0	1.5	210	0	1	0

Example 8 (Note: Values Shown Are Ultimates)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
225	35	115	8	1	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclinati on
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2500	40	5	5	30	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
17.36	Varies

Stars				
$\beta 1$	$\beta 2$	$\beta 3$	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
20	90	0	210	76

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
5236	47124	Varies	.75

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm^2	m.		
414	22	1	.8

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.79	0	2500	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
76	0	0	1.5	210	0	1	0

Example 9 (Note: Values Shown Are Ultimates)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
225	35	115	8	1	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2500	40	5	5	30	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
17.36	Varies

Stars				
$\beta 1$	$\beta 2$	$\beta 3$	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
20	80	0	210	76

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
5236	47124	Varies	.75

Nail-Solver			
Ult. Nail Stress	H Max.	fb	Kl
N/mm^2	m.		
414	22	1	1.11

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.79	0	2500	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
76	0	0	1.5	210	0	1	0

Example 10 Top 4 Nails (Note: Values Shown Are Ultimates)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
500	35	125	8	1	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclinati on
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
1728	45	5	5	50	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
12	Varies

Stars				
$\beta 1$	$\beta 2$	$\beta 3$	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
27	90	20	210	53

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
3620	47124	Varies	1.3

Nail-Solver				
Ult. Nail Stress	H Max.	fb	Nail Length	K1
N/mm^2	m.		m.	
414	28.5	1	15.9	.53

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.79	0	1950	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
53	0	0	1.5	210	0	1	0

Example 10 Lower 5 Nails (Note: Values Shown Are Ultimates)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
500	35	125	8	1		60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2161	45	5	5	56	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
15	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
27	90	20	210	66

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
4525	47124	Varies	1.3

Nail-Solver				
Ult. Nail Stress	H Max.	fb	Nail Length	Kl
N/mm²	m.		m.	
414	28.5	1	15.9	.53

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in²	ft.	psf.	
.79	0	1950	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
66	0	0	1.5	210	0	1	0

San Bernadino (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
150	38	110	8	1	3	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
2387	25.5	5	5	22	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
16.6	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
10	84.3	0	210	73

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
5000	47124	Varies	.86

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm^2	m.		
414	12	1	3.2

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.79	0	2387	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
73	0	0	1.5	210	0	1	0

(Juran & Elias, 1990a)

Swift Delta UV130+55.95 (Note: Values Shown Are Ultimates)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
100	33	115	7	1	2.5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
1000	27.5	4.5	3	21	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
6.95	Varies

Stars				
$\beta 1$	$\beta 2$	$\beta 3$	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	85.2	0	210	27

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
1833	47124	Varies	.8

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm^2	m.		
	Not	Applicable	

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.79	0	1000	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
27	0	0	.9	210	0	1	0

(Sakr, 1991)

Polyclinic Upper Soil (Note: Values Shown Are Ultimates)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
0	30	120	8	1	5	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclinati on
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
1432	55	6	6	32	30000	20

Snail	
Bond Stress	Punching Shear
psi.	kips.
9.95	Varies

Stars				
$\beta1$	$\beta2$	$\beta3$	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	90	0	210	44

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
3000	47124	Varies	.6

Nail-Solver							
Ult. Nail Stress	C	ϕ	γ	H Max.	fb	Nail Length	Kl
N/mm^2	kNs/m^2	Degrees	kNs/m^3	m.		m.	
414	9.6	38	20	16.5	1	10.5	1.01

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
1.06	0	3820	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
44	0	0	1.8	210	0	1	0

(Thompson & Miller, 1990)

Polyclinic Lower Soil (Note: Values Shown Are Ultimates)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
200	38	130	8	1.27		60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
3820	55	6	6	35	30000	15

Snail	
Bond Stress	Punching Shear
psi.	kips.
26.53	Varies

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	90	0	338	117

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
8000	76006	Varies	.6

Nail-Solver							
Ult. Nail Stress	C	φ	γ	H Max.	fb	Nail Length	Kl
N/mm^2	kNs/m^2	Degrees	kNs/m^3	m.		m.	
414	9.6	38	20	16.5	1	10.5	1.01

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
1.06	0	3820	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
117	0	0	1.8	338	0	1	0

(Thompson & Miller, 1990)

Eparris Top and Bottom Nail (Note: Values Shown Are Design)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
0	28	127	4	.79	0	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclinati on
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
982	14	10	4.67	10/15	30000	20

Snail	
Bond Stress	Punching Shear
psi.	kips.
6.82	40

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
15	70	0	131	15

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
1028	29410	2000	.83

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm^2	m.		
	Not	Applicable	

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
.49	0	982	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
15	0	0	1.4	131	0	1	0

(Bruce & Jewell, 1987) as in (Schlosser, 1985)

Eparris Middle 2 Nails (Note: Values Shown Are Design)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
0	28	127	4	1.26		60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclinati on
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
982	14	10	4.67	10/15	30000	20

Snail	
Bond Stress	Punching Shear
psi.	kips.
6.82	40

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
15	70	0	333	15

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
1028	74814	2000	.83

Nail-Solver			
Ult. Nail Stress	H Max.	fb	Kl
N/mm^2	m.		
	Not	Applicable	

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
1.25	0	982	2

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
15	0	0	1.4	333	0	1	0

(Bruce & Jewell, 1987) as in (Schlosser, 1985)

Bodenvernagelung Top 3 Nails (Note: Values Shown Are Design)

C	φ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
104	35	99	4	.875	3.33	60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclination
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
1963	20	4	3.7	10	30000	10

Snail	
Bond Stress	Punching Shear
psi.	kips.
13.63	50

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	80.5	0	160	30

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
2056	36079	2000	.5

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm^2	m.		
	Not	Applicable	

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in^2	ft.	psf.	
	Not	Applicable	

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
30	0	0	1.11	160	0	1	0

(Stocker et al., 1979)

Bodenvernagelung Low. 2 Nails(Note: Values Shown Are Design)

C	ϕ	γ	Grout Diam.	Bar Diam.	Depth to 1st Nail	Steel Yield Stress
psf.	Degrees	pcf.	in.	in.	ft.	ksi.
104	35	99	4	.875		60

Bond Stress	Wall Height	Horiz. Nail Spac.	Vert. Nail Spac.	Length of Nail	E of Nail	Nail Inclinati on
psf.	ft.	ft.	ft.	ft.	ksi.	Degrees
1963	20	4	3.7	11.6	30000	10

Snail	
Bond Stress	Punching Shear
psi.	kips.
13.63	50

Stars				
β1	β2	β3	Traction	Friction
Degrees	Degrees	Degrees	kN	kN/m
0	80.5	0	160	30

Goldnail			
Adhesion	Max. Nail Force	Face Pressure	Nail Length Factor
lbs/ft.	lbs.	psf.	
2056	36079	2000	.5

Nail-Solver			
Ult. Nail Stress	H Max.	fb	K1
N/mm²	m.		
	Not	Applicable	

NailM9			
Nail X-Sect. Area	Unbonded Length	Average Pullout	A
in²	ft.	psf.	
	Not	Applicable	

Talren							
QS	PL	KSB	LB	TR	ALB	IND	RCIS
kN/m	kPa		m	kN	Deg.		kN
30	0	0	1.11	160	0	1	0

(Stocker et al., 1979)