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The ABCs of Soil Nailing: an Integrated Tutorial and Knowledge-based Approach to Teaching Design*

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Soil nailing is an earth stabilization method that combines in-situ reinforcements and a flexible facing to support existing natural slopes and hillside cuts or excavations. Since its inception in the early 1970's soil nailing has proven to be a successful and reliable shoring approach when proper design guidelines and construction methods are applied. Given the highly empirical nature of available design approaches, a fundamental understanding of the behavior of soil-nailed walls is critical to a safe and satisfactory outcome. In this respect case studies of successes and failures and established codes of practice are very important teaching and training resources. This paper describes an integrated approach for teaching engineering design. The approach was developed for the case of soil-nailed walls but could be applied in other similar engineering design contexts. The approach comprises a computer-based tutorial combined with an automated knowledge base developed to assist in formulating design decisions. The students are introduced to the basic principles through an interactive tutorial module and guided through the design process by the automated tool which is based on the CLOUTERRE and FHWA Guidelines.

INTRODUCTION

THE RELIANCE on computer-centered teaching in engineering design courses is not as pervasive as the now-regular use in basic didactic education. That is particularly true in the field of geotechnical engineering, where most design methodologies are rooted in empirical approaches. Our earlier attempts at the American University of Beirut have concentrated on developing and using a *Soil and Site Improvement Guide* which has proven to be a very useful and effective teaching tool [1]. We have since explored the possibility of expanding such tools and educational methods into more specialized and complex geotechnical applications. In this respect, computer-aided approaches for teaching design offer a number of advantages that traditional engineering references do not:

- interaction between material and learner;
- integration of text, image and sound to convey the information in a user friendly environment;
- allowing the student to learn and have access to the basics at their own pace; etc.

Building on the encouraging response to the *Soil and Site Improvement Guide* by faculty and students the *ABCs of Soil Nailing* was designed and developed to enhance the experience of teaching and learning the engineering design of complex earth support systems.

The support of natural slopes and engineered excavated cuts by soil nailing has proven to be a successful and economical technique for more than fifteen years. However, much remains to be done to address unanswered questions which may be traced to a lack of understanding of the complex interactions within the system [2]. *The ABCs of Soil Nailing* introduced herein aims to provide a tool which would enhance the learning process leading to a thorough understanding of soil nailing fundamentals for students typically in their senior year or early in their graduate studies. In addition to working as an interactive tutorial, the tool itself integrates the available codes of practice into an automated design knowledge base.

This paper presents the process of development and design which resulted in the *ABCs of Soil Nailing*. An example application is included along with the results of student feedback ranging across a number of classes and backgrounds. In essence, the process begins with an interactive tutorial framework which introduces the user to the basics of slope stabilization using soil nailing as well as related fundamental design concepts and parameters. This phase is followed by an additional level which allows the user to automatically obtain a preliminary design using code requirements and guidelines based on the existing state of

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practice and recommendations [3, 4]. The outcomes of this second stage are presented in a format compatible with the specialized analysis software *SNAILZ* (DOS and Windows versions), provided as freeware by *CALTrans* [5].

OBJECTIVES AND SCOPE

The main objective of the work presented herein was to develop a computer-based learning and preliminary design tool for slope and excavation support using soil nailing. The challenge/value of such a task is compounded by the lack of straightforward unique and programmable equations for the design of soil-nailed walls [2]. While some geotechnical engineering problems are typically addressed through the careful application of *empirical equations* (e.g. design of shallow foundations), soil nailing stabilization requires the application of *empirical guidelines.* Furthermore, many of these guidelines, while 'theoretically' correct, have failed in practice or have contradicted other recommendations [2]. Major questions concerning the general behavior mechanisms, failure modes, durability aspects, facing design and seismic behavior were left unanswered and have led to the initiation of a soil nailing joint investigation project between US and French researchers in the early 1990s. The cooperative project was called *CLOUTERRE*, which is French for 'soil nail' [6].

For the work presented herein, we have chosen to follow the *CLOUTERRE* recommendations [3]. Where necessary we have complemented the information with the more recent FHWA guidelines for soil nail walls [4]. The tutorial part of the guide will address the task of learning about the soil nailing 'technique' (such as its applications and methods of installation) as well as design guidelines. The design-aid module, which was developed using Visual Basic 6.0 [7], allows the user to complete a preliminary soil nailing design and dimensioning quickly and efficiently. It permits the user to suggest adequate nail reinforcement (length, diameter, etc.) based on given soil and wall characteristics. The design could then be confirmed/completed and optimized through a final and more rigorous analysis using a specialized software, *SNAILZ* by *CALTrans* (California department of transportation) [5].

THE ABCS OF SOIL NAILING: INTERACTIVE TUTORIAL

Soil nailing has gained acceptance and popularity as an economical, time-saving method of earth retention [8]. This section introduces the tutorial part of *The ABCs of Soil Nailing* which presents the theory and techniques involved in soil nailing.

The tutorial is available both as a web page (that can be viewed with any Internet browser) or as a Microsoft PowerPoint presentation. The welcome page gives direct access to the 'Main Menu' from which the user can follow one of the below listed links:

- Quick Learning
- Design
- Web Links/Education
- Picture Gallery
- Tutorial Map

In what follows, a brief description of each module is presented.

Quick Learning

The Quick Learning page (Fig. 1) is a focal point; it is the starting line of the soil nailing

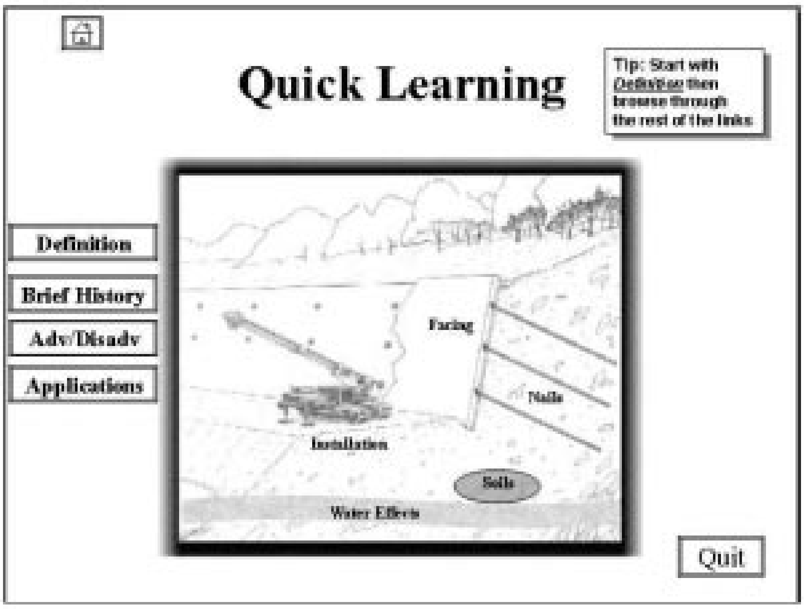

Fig. 1. The Quick Learning focal page.

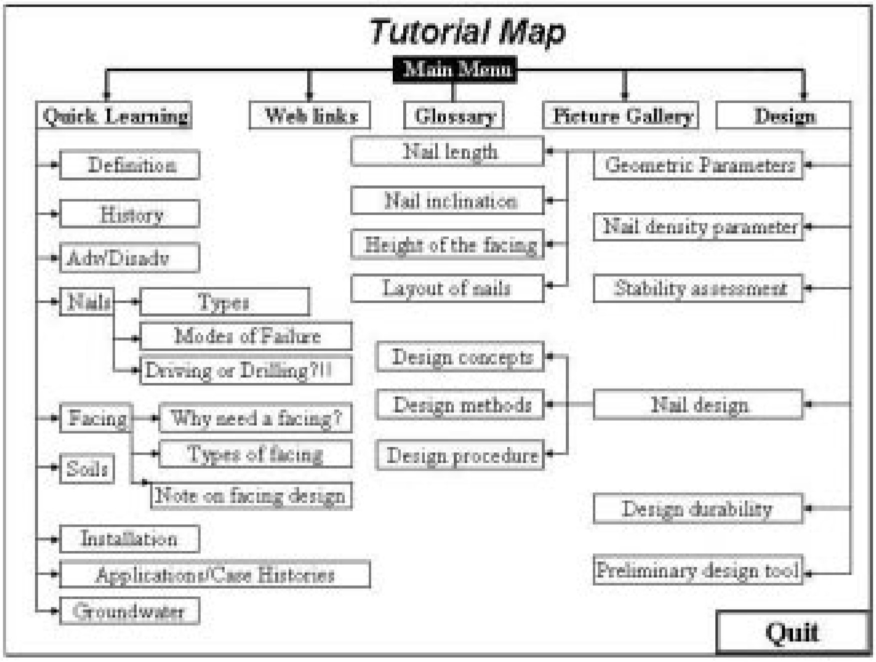

Fig. 2. Tutorial map. All items represent hotlinks to pages containing further information.

exploratory journey. The available links organized on a representative picture include:

- Definition
- Brief History
- Soils
- Nails
- Facing
- Water Effect
- Installation/Construction
- Advantages/Disadvantages
- Applications/Case Histories

Each of the above listed links leads to subsequent pages containing specific information on the related aspects/topics. The tutorial map (Fig. 2) summarizes all available pages. Every attempt was made to organize the pages/slides in an effective and appealing fashion, in order to render the learning process more interesting to first-time users. Some slides include linked video applications, enlargeable pictures, etc.

Design

To the uninitiated, soil nailing may appear to be a very simple process. Just drive steel sections into the soil, or drill holes and fill them with steel and grout, to produce a stable nailed wall! It is the deceptive simplicity of the technique that 'masks the true complexity of the design procedure' [2]. The purpose of the design section of the tutorial is to render the 'complex design procedure' as simple and easy to follow as possible, while complying with established standards and norms. In fact, all the elements required for an adequate design are presented along with suggested empirical guidelines based on the *CLOUTERRE* and/or FHWA Recommendations [3, 4]. The design section also links to *Pre-Snailz* the preliminary design/expert tool developed as part of the design teaching methodology.

The Design Tutorial page provides access to the following links/pages:

- *Geometric parameters*: Contains information related to important design parameters such as length of nails, nails inclination, general layout of the nails, etc. as a function of the nail installation technique. (driven/drilled).
- *Nail density parameter*: Consists of a definition of this non-dimensional parameter, which is related to the tensile strength of the nails and the soil/nail unit interface strength (Fig. 3).
- *Stability assessment*: Addresses failure mechanisms associated with soil nailing systems. Both external and internal failures are presented along with definitions of active/passive zones, slip surfaces, failures at the nail head and facing, etc.
- *Nail design*: Major design concepts, methods and fundamental principles.
- *Facing design*: Discussion of major failure modes and common design approach.
- *Design durability*: Explores corrosion protection and durability related issues.
- *Preliminary design tool*: Provides access to the expert tool/ program *Pre-Snailz*

The remaining links available on the main menu may be summarized as follows. The Links Page includes interesting web links related to soil nailing design, testing, case histories as found in specialized sites on the Internet. They provide additional resources for case studies, construction and design. The Picture Gallery has an assortment of pictures pertaining to soil nailing applications, equipment used, nailing techniques and construction sequence. The tutorial map (Fig. 2) shows all sections and major subsections of the tutorial.

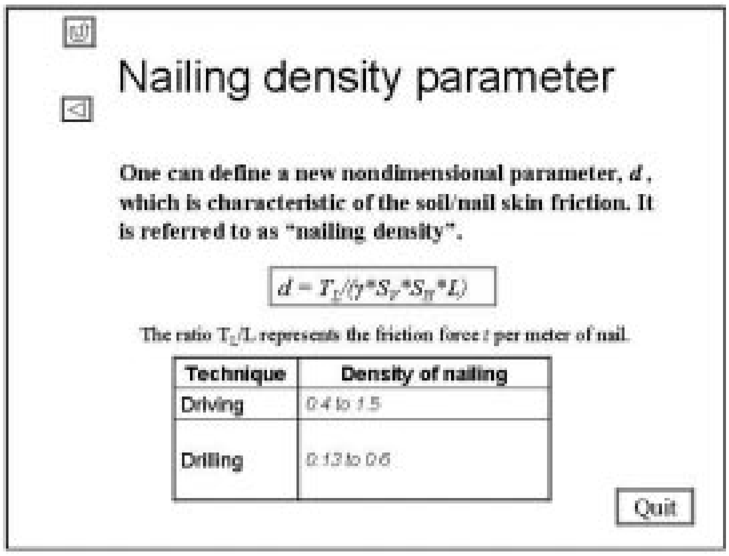

Fig. 3. The nail density parameter link in the Design section of the tutorial.

The user can access any of the subsections directly from the map. The tutorial map is accessible from all slides thus giving the user complete control and an alternate browsing scheme.

PRE-SNAILZ: PRELIMINARY DESIGN EXPERT TOOL

Pre-Snailz was written in order to allow the user to quickly and efficiently complete a preliminary soil nailing design using an expert-system approach based on existing guidelines. It assumes that the user is familiar with the different design parameters involved. Such basic knowledge could have been simply gained through the tutorial module of the tool.

The basic objective achieved through *Pre-Snailz* is the suggestion of an adequate soil reinforcement scheme for stabilizing a given slope/excavation. Pre-Snailz prompts the user to enter all the necessary soil information and guides him/her through

Fig. 4. Main menu form of *Pre-Snailz.*

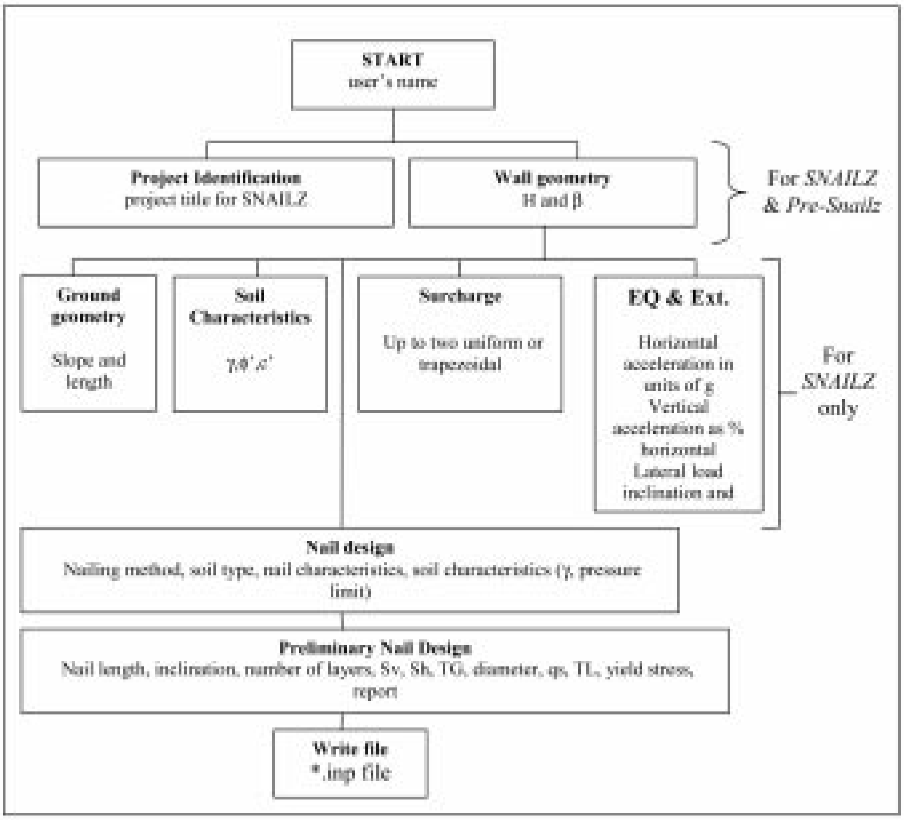

Fig. 5. Flow chart for the components and conceptual framework of *Pre-Snailz*.

the process of obtaining a preliminary soil-nailed wall design based on the *CLOUTERRE* recommendations [3]. As such, *Pre-Snailz* fills the real gap between an adequate understanding of the design procedure and developing the final analysis of a nailed wall, by suggesting initial reinforcement parameters based on given wall and soil characteristics.

The results are written to an '*.inp' file which is compatible with the specialized analysis software *SNAILZ* developed by *CALTrans* and which is now an industry standard [5]. Consequently, the file created can be used directly as an input for *SNAILZ* to obtain the failure type and failure plane shape for the wall under consideration as well as a factor of safety against this failure. An example application is provided in this paper.

Once *Pre-Snailz* is launched, the main menu form appears with a welcome note and a number of different sub-menus (Fig. 4). It is advisable to go through the menus in the following order:

1. Project identification
2. Wall geometry
3. Ground geometry
4. Soil characteristics
5. Surcharge
6. Earthquake and external force
7. Nail design
8. Write file

All forms have associated help icons which define them along with all required user input. As the wall geometry data and soil type are the only entries necessary for the preliminary design, the remaining sub-menus will be accessible only after the wall geometry data have been entered. The rest of the input data (i.e. ground geometry, soil characteristics, surcharge, earthquake and external forces) are needed to complete the input for *SNAILZ*.

Pre-Snailz provides for an interesting learning environment in addition to delivering expert design recommendations. The student/user should be encouraged to test how recommended values change with changes in input parameters. Such a procedure allows him/her to appreciate the relative importance of each factor. The various components and the conceptual framework of *Pre-Snailz* are presented in flowchart format in Fig. 5.

A brief description of each listed command:

- **Project identification**: Stores the project title for subsequent use in *SNAILZ*.
- **Wall geometry**: Height and batter of the wall.
- **Ground geometry**: Ground geometry above the cut (up to 7 slopes/segment lengths).
- **Soil characteristics**: The unit weight, cohesion and angle of internal friction of the soil for subsequent use in *SNAILZ*.
- **Surcharge**: Any additional load imposed on the surface above the nail system due to nearby structures/loads (up to 2 surcharges). The loading may be uniform or trapezoidal.
- **Earthquake and external force**: Earthquake load given in terms of horizontal and vertical

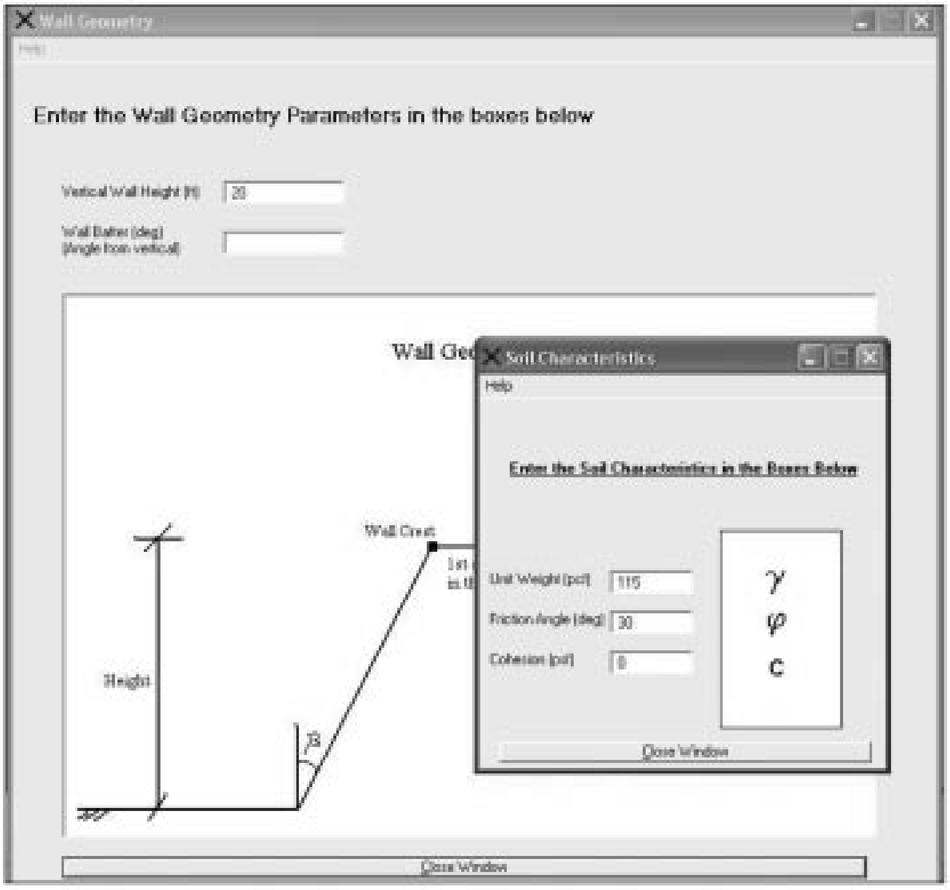

Fig. 6. Wall Geometry and Soil Characteristics forms.

acceleration coefficients. Other external forces (magnitude and direction) could also be defined. This information is required input for *SNAILZ*.

- **Nail design**: Prior to obtaining a suggested preliminary design, the user has to define the nailing technique and the soil type. Once these entities are defined, the *Preliminary Design Values* tab allows the design suggestions to be obtained based on the *CLOUTERRE* recommendations summarized in Table 1. The default values chosen from within the ranges can be changed by the user as he/she sees appropriate provided the new values remain within the tolerable range. The same applies to the preliminary design values obtained.
- **Write file**: Requires the user to enter the name and directory of *Pre-Snailz* generated output file. The file extension is .inp. It should be noted that to be able to use the output file for *SNAILZ* (DOS version) it should be located in the same folder *SNAILZ*.

Table 1. *CLOUTERRE* recommendations

Installation technique	Drilled
Length of nail	0.8H to 1.2H (H = total height of structure)
Perimeter of nail	200 to 600 mm
No. of nails per m^2 of facing	0.15 to 0.4
Tensile strength of reinforcing nail	100 to 600 kN
Vertical (S_V) & horizontal (S_H) spacing	$1\,m^2 \Leftarrow S_v$; $S_H \Leftarrow 6\,m^2$

It should be noted that while the facing design plays an important role in the overall stability of the reinforced wall, it was not included in *Pre-Snailz* since the main focus of the program is on external stability and thus on the reinforced soil composite system. As such, facing design parameters are not required as input into *SNAILZ*. It is important to note here also, that specific facing design guidelines are included in the tutorial section of the integrated approach and comprise a discussion of bending and punching checks and calculations, along with recommendations on construction details related to various facing systems.

APPLICATION EXAMPLE

The following example illustrates the basic steps in using the *Pre-Snailz* knowledge-base tool. The slope to be stabilized is of a 6 m (20 ft) vertical cut. The soil mass consists of a sand with geotechnical strength parameters $c' = 0$ and $\phi' = 30°$, and a unit weight $\gamma = 18\,kN/m^3$ ($115\,lb/ft^3$). Figure 6 shows the completed *Wall Geometry* and *Soil*

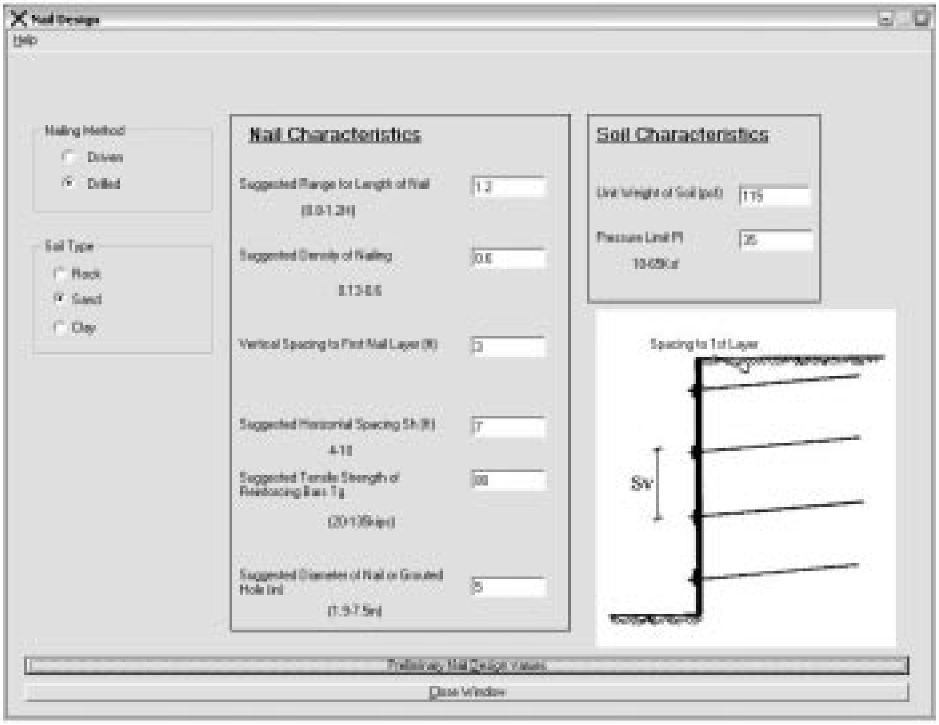

Fig. 7. The preliminary design form with the various parameters.

Characteristics forms in *Pre-Snailz*. Note that to achieve a preliminary design, the wall geometry, soil characteristics and nailing method are the only parameters needed. The remaining data (earthquake forces, surcharge, etc.) constitute input required for *SNAILZ* analysis.

The next step necessitates a decision regarding the nailing method to be used. For this example 'drilled' nails will be used. In fact, once the nailing method is chosen various ranges for parameters (nail density, nail length, etc.) are automatically suggested through the expert tool (Fig. 7). The user is advised to abide by these recommendations but remains free to change them.

The final window (Fig. 8) represents the preliminary design as recommended by *Pre-Snailz*. Note that here again the user can override the values suggested. As such, the preliminary design

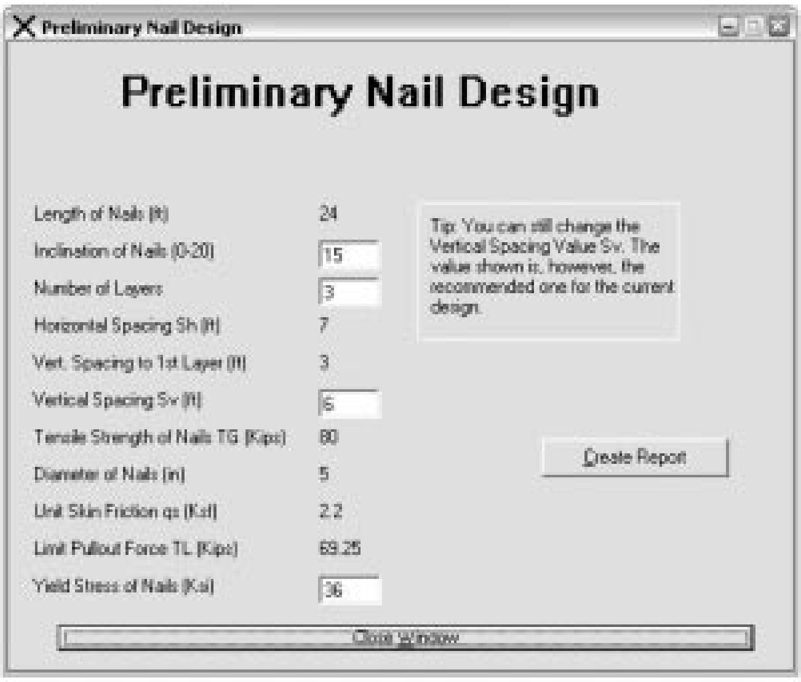

Fig. 8. Preliminary design results as recommended by Pre-Snailz.

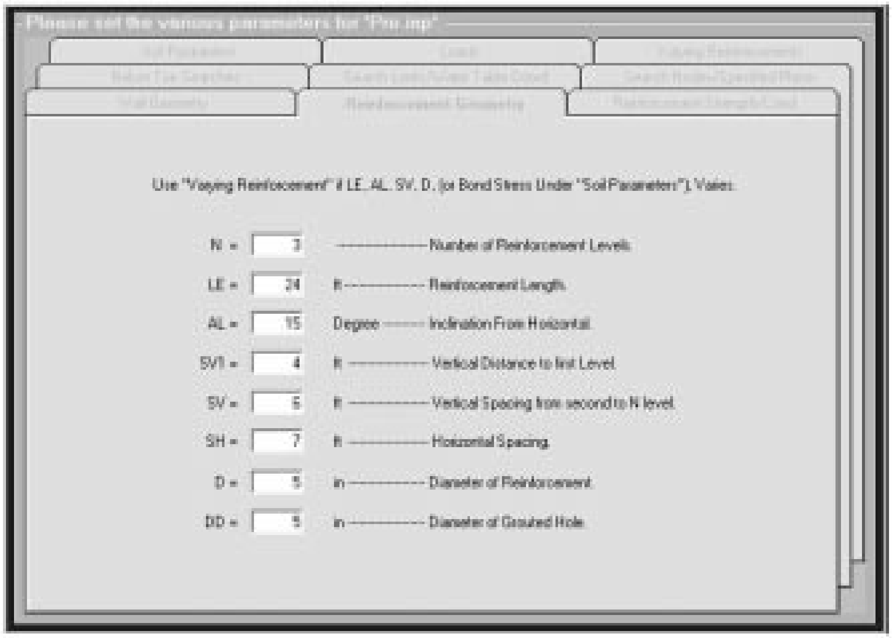

Fig. 9. *SNAILZ* Reinforcement geometry window showing the values as imported based on the Pre-Snailz output recommendations.

recommended for the particular conditions in this example consists of three layers of nails, 7.5 m (24 ft) long each, and at horizontal and vertical spacing of 1.8 m (6 ft). With these results, we can move to creating the input file for SNAILZ using 'Write File' command. The student then runs *SNAILZ* (Windows or DOS) and selects the generated file as input to the SNAILZ analysis software. All values entered in *Pre-Snailz* and the recommended preliminary design constitute the input file for *SNAILZ* (Fig. 9). The user can now proceed with the calculation of the minimum factor of safety by pressing 'execute' from within *SNAILZ.* For the particular example analyzed, a minimum factor of safety FS = 1.87 is obtained (Fig. 10). If this result is deemed unsatisfactory by the user, he/she can optimize or change the design by changing the input parameters directly from within *SNAILZ* or by returning to *Pre-Snailz* and repeating the steps outlined earlier.

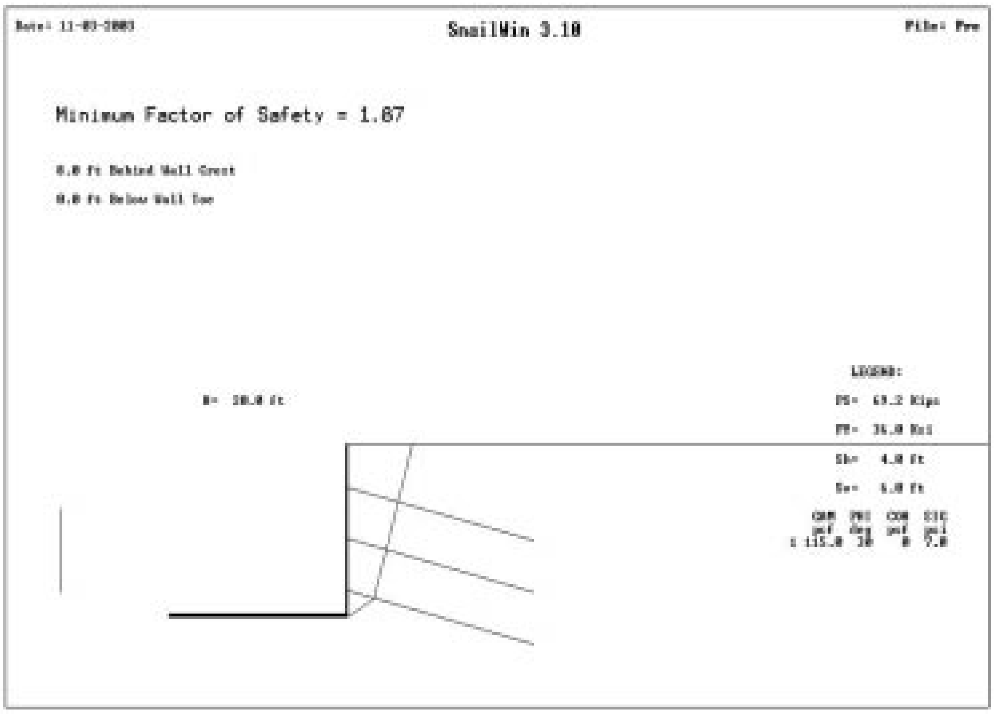

Fig. 10. *SNAILZ* analysis results based on the preliminary design. Note the reported factor of safety and the identified critical slip surface.

STUDENT EVALUATION AND FEEDBACK

The approach methodology and tools described in the previous sections were tested in a class environment at the American University of Beirut. The student population consisted of undergraduate and graduate students of civil engineering. *The ABCs of Soil Nailing* design teaching method was introduced as part of an elective design course in geotechnical engineering. The tutorial and design knowledge-base tools were presented in the context of the course section on shoring systems. Students were then assigned a real-world design problem which they had one week to submit. In an effort to quantify the effectiveness of the proposed tool and to identify areas of potential weakness and avenues for modification and improvement, the students were given an evaluation form to complete and submit along with their assignment. The evaluation rubrics centered on the following categories: Student background knowledge, Web-based Tutorial, Design-Guide and Overall evaluation. Within the *Tutorial* and *Design Guide* sections, questions addressed issues of instructional content, structure, ease of use, information management and technical aspects related to software environment, functions and stability. In addition, students were encouraged to submit written comments and suggestions in a dedicated space on the form. In total, the evaluation form included 28 questions with associated answers of 'poor', 'fair', 'satisfactory', 'good' and 'excellent'. The complete evaluation form, along with the tutorial and expert preliminary design tool, is available at: http://staff.aub.edu.lb/~salah/index.html.

In addition to AUB students, a number of graduate students in the geo-engineering group at the University of California at Berkeley were asked to participate in the evaluation effort. The main findings of the survey can be summarized as follows:

- A total of 41 responses were received.
- The majority of the respondents ranked their prior knowledge of Soil-Nailed walls as poor to fair (86%).
- In assessing the Tutorial part of the approach, the following was reported:
  - Flexibility of navigation and ease of use: 71% good to excellent.
  - Material organization and clarity: 78% good to excellent.
  - Use of photos/multimedia: 62% good to excellent.
- References, links and additional material: 53% good to excellent.
- The main findings re. the expert tool, Pre-Snailz:
  - Ease of setup and use of software: 82% good to excellent.
  - Definition of relevant parameters: 74% good to excellent
  - Sequence of design; Clarity and effectiveness: 68% good to excellent.
  - Guidance re. CLOUTERRE guidelines: 64% good to excellent.
  - Software appearance and screen display: 65% poor to satisfactory.
- Overall, the following responses are indicative:
  - The approach was deemed as useful design complement to codes: 81% good to excellent.
  - Clarity of sequence of tasks objectives and outcomes: 73% good to excellent.
  - Overall grade: 86% good to excellent.
- Some of the comments and suggestions included:
  - Improve quality of display (color contrast).
  - Improve and complement photos and video clips.
  - Increase number of example applications.
  - Improve interactive input environment by adding real-time graphing.
  - Highly beneficial experience. Effective.

The overall response is positive with a number of very useful suggestions for improving the existing tool. More importantly, the level of interest and involvement shown by students was clearly heightened by adopting this approach as compared to earlier mostly didactic efforts. The desirability of introducing such a methodology in teaching design should be encouraged and explored further. In short, the introduction of platforms which allow a greater level of independence and self-learning in a design context is highly beneficial, given the fact that educational quality contact time in design courses is typically limited. This is not to suggest that the involvement of the teacher as guide and facilitator is not essential to the process.

CONCLUSION

The ABCs of Soil Nailing introduced in this paper is part of the ongoing effort to increase the library of available educational tools related to geo-engineering applications in general and soil improvement problems in particular. The interesting and rewarding aspects of the proposed approach are related to the focus on design oriented problems which are not typically suitable for classical computer-aided learning tools and formats. The combination of a tutorial covering basic principles and definitions with an 'expert', preliminary design tool/aid based on state-of-the-practice codes allows the student to proceed with the assisted learning process in a design context, at their own pace. The role of the teacher is one of guidance and support in an environment where the time spent on design problems such as the soil-nailed walls example addressed in this effort, is efficient and effective. The feedback which was received from students who have tried the method to date has been positive overall, with particular appreciation of the simplification of the learning of design aspects and methodology along with the method structure and program interface. As such, the approach developed and efforts applied seem to have fulfilled their intended purpose: introducing users to the basics of soil nailing, and allowing them to run preliminary designs using a code-based guidance. Refinements and additions are warranted to improve the material presented, the teaching effectiveness and the software menus and displays. Finally, given the flexibility and ease of deployment of this educational methodology, it may act as a template for the development of similar tools related to other design-oriented and code-based courses in civil engineering in general and geo-engineering in particular.

REFERENCES

1. S. Sadek and G. Khoury, Soil and site improvement guide: an educational tool for engineered soil improvement solutions, *Int. J. Applied Eng. Educ.*, **16**(6), 2000, pp. 499–508.
2. P. F. Jekyll, *Soil Nailing of Excavations: An Introduction to Design*, McGill University (1996).
3. French national research, recommendations, *CLOUTERRE*, English translation, Presse de l'ENPC (1991).
4. US Department of Transportation, Federal Highway Administration, *Manual for Design and Construction Monitoring of Soil Nail Walls*, FHWA-SA-96–069b (1996).
5. CALTrans, Geotechnical Services. Available at: http://www.dot.ca.gov/hq/esc/geotech. (2003).
6. A. Di Millo, Ground Improvement Project, online resource. Available at: http://www.tfhrc.gov/structur/gtr/century/chap03/chpt03.htm
7. Microsoft Visual Basic 6.0.
8. C. Patrick, Soil nailing and a case study of the home depot project, *Geotechnical Group NewsLetter, ASCE* (2002). Available at: http://sections.asce.org/colorado/newsletters/0105.pdf

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