GeoSuite – A Modular System for Geotechnical Design

S. Lacasse
Norwegian Geotechnical Institute (NGI), Norway, suzanne.lacasse@ngi.no

H. P. Jostad, J.-S. L'Heureux and Ø. Torgersrud
NGI, Oslo, Norway
R. Sandven
Multiconsult AS, Norway

ABSTRACT
Remarkable advances in the analysis tools of, for example slopes, embankment stability and settlements have happened since the 90s. Many are due to the information technology revolution in all aspects of geotechnical practice. Although the tools in use today are more sophisticated than earlier, experience, judgment and quality control remain the key to reliable foundation design. Experts agree that one should do calculations with two methods (or two codes) to check "that you have not missed anything of importance". Software is not what differentiates among consultants today. The competence and experience of the personnel and the appropriateness of the parameters and soil models used in the analyses gives the competitive edge. In 2002, the geotechnical profession of Norway and Sweden (consultants, research organizations, universities and government agencies worked) entered an alliance to develop GeoSuite. The development work was funded by the Research Council of Norway in addition to the partners. The first version of GeoSuite was issued in 2006. A new generation was completed in 2015 and a third generation is planned for 2019. The objective of GeoSuite is to make design calculations as simple as possible for the user, and to provide user-assistance along the way. The software provides the practitioner with tools for one-, two- and three-dimensional calculations and visualization, and an integration of geotechnical input data, calculations and results. The paper describes "GeoSuite", a software with modules for the design of geotechnical foundations on land, with stability, settlement, bearing capacity, pile and excavation calculations. Plans are made for add-ons with slope calculations, soil profile decisions and statistical analyses of soil parameters. The paper describes the modules in GeoSuite and gives examples of stability and settlement calculations.

Keywords: Stability, settlement, bearing capacity, software, three dimensions.

1 INTRODUCTION

Civil engineering is moving towards three-dimensional (3D) oriented design for construction and lifelong maintenance. Geotechnical design and calculations need to be compatible with these technologies. GeoFuture has the aim to meet this challenge. As our profession moves forward into the 21st century, Duncan (2013), Wright (2013) and Finn and Wu (2013) recommended to always use more than one computer code when doing geotechnical calculations, to check "that you have not missed anything of importance". It is not the software used that differentiates between two consultants. The knowledge and experience of the personnel and the appropriateness of the specific soil models in the calculations make the difference between two consultants.

GeoFuture is a Norwegian research project funded by the Research Council of Norway, with a budget of 22.4 million NOK (2.5 million EURO, 2016). The project was completed in 2015. Twelve partners from Norway and Sweden, representing industry, research, the university sector and public organisations, formed an alliance to carry out the research. The partners were Skanska AS, Norconsult AS, Multiconsult AS, GeoVita AS, Vianova Systems AS, Vianova GeoSuite AB, AutoGRAF-föreningen AB, the Norwegian Public Roads Administration, the

Norwegian National Rail Administration, NTNU, SINTEF Byggforsk and NGI.

The primary objective of GeoFuture was to supply the building, construction and transport industry with methods and tools for geotechnical calculations for everyday design. The results of the research were implemented in a software package called the GeoSuite Toolbox. At project completion, GeoFuture had developed the prototype of an integrated package for geotechnical calculations, with options for 1D, 2D and 3D calculations and with 3D presentation of geotechnical data together with other infrastructure data (roads, railways, earlier construction).

A series of 1D, 2D and 3D models, finite element formulation and codes were developed for the calculation of stability, settlement and bearing capacity. For each of the calculation modules, GeoFuture developed a knowledge-based system for assisting the practicing engineer to assess and verify geotechnical parameters and calculation results. This "Wizard" is a wiki-based user-assistance available for all steps of the calculation, from the interpretation of laboratory and *in situ* test results, selection of design parameters, the calculation (e.g. choice of method) to the interpretation of the results. The user is enabled, with the option of additional assistance, to do the calculations, integrating either or both classical methods (e.g. limit equilibrium, 1D settlement approximation and closed-form solutions) and advanced finite element formulations with simple or advanced soil models for improved 2D and 3D calculations.

GeoFuture delivered a seamless solution for the life cycle management of 3D data with the development of a new and open 3D soil data model, called the "Ground Observation Model". This model provides geo-solutions that are integrated with the Building Information Models (BIM) and Infrastructure Information Models (IIM) used by other sectors of civil and construction engineering. With the new 3D soil data model in three dimensions, realistic foundation geometry, spatial relationships, interpolation and extrapolation around 3D data volumes are possible. The methods and tools integrate 3D calculations within 3D visualisation, with the option of simple or advanced soil models and simple or advanced calculation methods for the most common foundation problems in the building, construction and transportation industry.

The prototype with a user-friendly and seamless tool for geotechnical design is planned to be commercialized through the company created for the developed software GeoSuite.

The project will continue until 2019 with further enhancements. Some of these are mentioned herein. The paper presents the GeoSuite system, describes the calculations and provides examples of the assistance provided to the user.

2 NEED FOR INTEGRATED SOLUTION

Compared to earlier, solutions are moving towards 3D interactive models and Building Information Modeling (BIM), where different disciplines and work flows interact. The human relationships have also evolved as the engineers and scientists work less in isolation, but increasingly in collaborative, integrated teams.

Contractors, consultants, universities and public infrastructure organizations need a common and integrated 3D engineering model in their work. In a survey, geotechnical engineers also prioritised the need for help with the selection of input parameters and the need for a seamless integration of input data, analysis modules and results. They wished means to model and represent realistic foundation geometries, illustrate and account for spatial extent and variability of geo-data, integrate geo-calculations and enable an "interactive" modelling of foundations. And yes, they felt that there were large uncertainties in even the simpler of analyses.

3 GEOSUITE SOFTWARE

GeoSuite has a series of computer programs especially developed for a designer of geotechnical problems, including stability, settlement, bearing capacity, pile and excavation calculations.

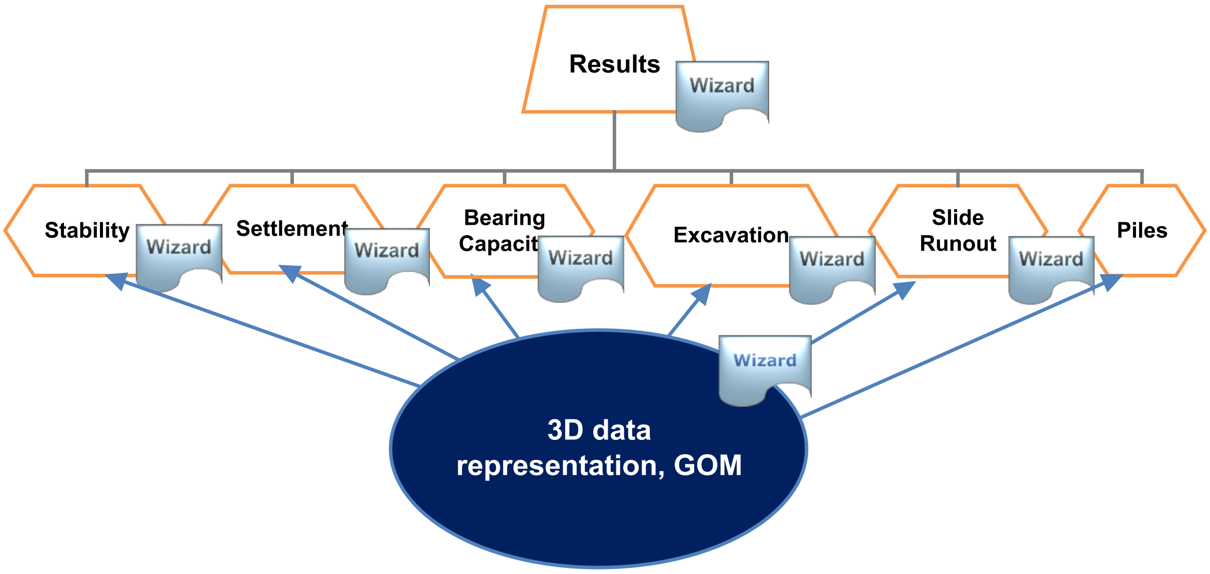

Figure 1. GeoSuite 's six calculation modules and Wizard function.

Figure 1 presents the GeoSuite software package schematically, with each of the calculation modules and the "Wizard" function. In 2015-2016 a module for slide run-out analysis will be included.

The main objective of the software is to address everyday design situations, and to make the calculations efficient for the user[1]. Figure 1 illustrates schematically the geotechnical components of the GeoSuite software. The key development features in recent years have been the integration of a 3D calculation engine, integrated input data and result presentation with possibilities of 1D, 2D and 3D visualization, series of assistance panels for the user for the selection of the soil parameters and the analysis and interpretation of the resultsThe 3D data representation model (the ground observation model, GOM) is the heart of the system and enables the user to build his model accounting for other installations already in the ground and integrating the measurements of soil properties, as available. User assistance (called 'Wizard' in Fig. 1) is provided to help establish the soil profiles for analysis. Each of the calculation modules had an input, calculation and results interpretation part, with a 'Wizard' (user assistance) available when desired by the user.

4 3D DATA REPRESENTATION

4.1 Open data model

The open data model manages the geotechnical data throughout its life cycle, for GeoSuite calculations and for use by other software/systems. The goal of the integrated open data model, is to present in the digital terrain model the input and results in three dimensions.

Geotechnical properties and geological description in the building and construction and infrastructure sectors have gradually become a part of the Building Information Modelling (BIM[2]). The model in GeoSuite meets the requirements in ISO/TC211[3].

The BIM infrastructure requires open standards, integrated and easy import and export of data between the BIM models and

[1] http://www.-vianovasystems.no/Nedlasting/Nova-point-GeoSuite

[2] BIM (Building information modeling) involves the generation and management of digital representations of physical and functional characteristics as a function of location.

[3] ISO/TC 211 is a standard Technical Committee within ISO, covering the areas of digital geographic information, such as used by GIS and geomatics and preparing International Standards and Technical Specifications.

the processes governing several parties collaborating during design.

The open data model provides the geotechnical engineer with not only the data, the subsurface layers and the model used for the analysis, but also provide a visualization of the data and other implementations, such as roads, buildings, excavations and other structures/installations.

4.2 *Ground Observation Model (GOM)*

One of the key elements of the development was the creation of a ground observation model (GOM) directly from the open data model, and to have it act as an analysis tool for geotechnical design. A 3D part of the open data model can then be selected and analysed.

The 3D data representation module (GOM) integrates seamlessly the information from geological, seismic and geotechnical *in situ* and laboratory investigations and creates a 3D graphical interface. The module creates a subsurface model for input in the geotechnical calculations. GeoSuite also aims at documenting who did what, the parameters used, and the history of the parameters and the analyses. The ground layers, represented in 3D, include all the attributes and parameters relevant for the geotechnical calculations and expertise provided by the Wizard for user assistance (Section 7).

Figures 2 and 3 give two examples of 3D representation: a 3D volume of soil to be analysed (Fig. 2), and the layers in tehclaculation area in 3D (Fig. 3).

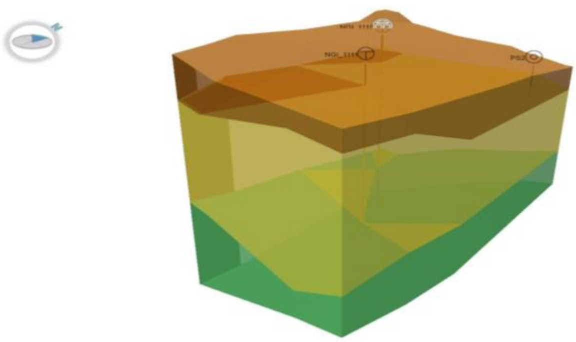

Figure 2. Example of generated 3D soil volume model.

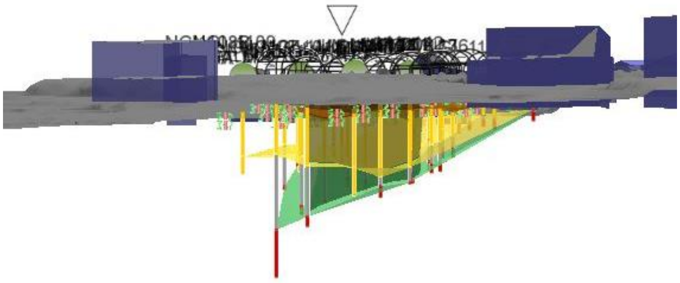

Figure 3. Interpreted layers and calculation area.

5 SETTLEMENT MODULE

The new calculation engine developed at NGI (Jostad and Lacasse 2015) was used to check a simple case of settlement of an OC clay under a uniform load.

Three software were used: Plaxis3D (www.plaxis.nl/plaxis3d), Settle^{3D} (www.rocscience.com/settle3D) and GeoSuite (denoted GS 1D and 3D). Figure 4 compares the results at the centerline and at the corner of the loading. The Boussinesq stress distribution with depth was used in the calculations.

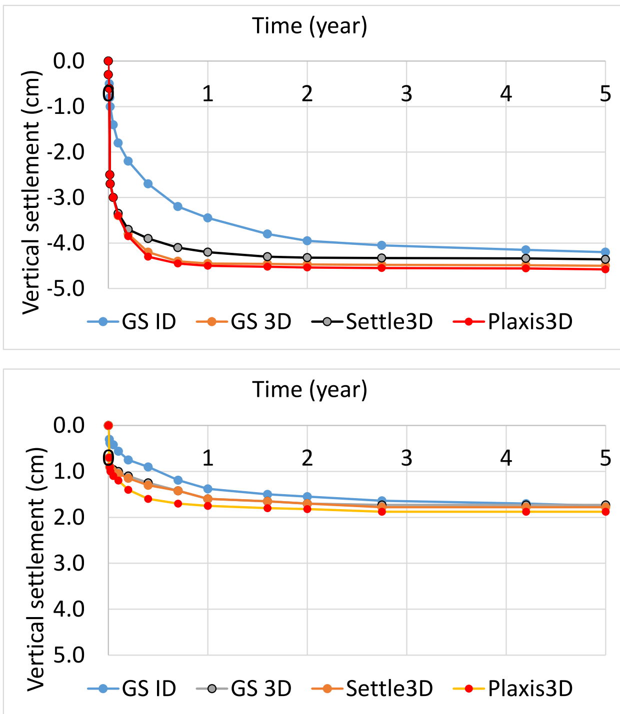

Figure 4. 1D and 3D consolidation settlements, OC clay, at centerline (upper diagram) and under corner (lower diagram) (S. Johanson NTNU, MSc thesis, personal comm. June 2015).

The 3D settlement (initial and consolidation settlements) were significantly larger than the 1D settlements. The GeoSuite3D, Plaxis 3D and Settle^{3D} calculations in 3D agreed well. The GeoSuite and Plaxis results in 1D also agreed well.

Jostad *et al* (2016) and Lacasse et al (2015) present another example of 3D settlement calculations.

6 STABILITY MODULE – 3D EFFECTS

The 3D effects were illustrated for an idealized case (Fig. 5). The effect of slope inclination was checked for inclinations 1:b with b=1, 2 and 3. The effect of the depth of the slip surface $d = D/H$ (i.e. depth to a strong soil layer or rock) was checked for d of 0 and 1, where D is the depth from the toe level to the bottom fixed boundary (or to a strong layer/bedrock) and H the height of the slope (from toe to crest). The effect of the width of the slide $w = W/H$ was checked for w of 1, 2, 4 and infinity.

The NGI-ADP constitutive model, a strain-hardening elasto-plastic total stress model with stress path dependent or anisotropic undrained shear strength was used in the analyses. The input for this constitutive model are the spatial distribution of the undrained active shear strength $s_u^A(x,y,z)$ and the anisotropy strength ratios s_u^{DSS}/s_u^A and s_u^P/s_u^A [4], the corresponding shear strains at failure, γ_f^A, γ_f^{DSS} and γ_f^P, and the initial elastic shear modulus ratio, G_o/s_u^A. The factor of safety FS was calculated from:

$$FS = F_{3D} \cdot N_o \cdot s_u / \gamma H \qquad [1]$$

where F_{3D} is the 3D effect factor, N_o the geometry dependent stability number, s_u the isotropic average undrained shear strength, γ the total unit soil weight and H the height of the slope.

Failure was obtained by gradually increasing the total weight γ by a load factor p. For a total stress analyses, the FS is then equal to p. This gives the same result as an analysis with shear strength reduction, where the s_u is gradually reduced by a material factor γ_m until failure. Failure was defined when the tangential stiffness of the system became very small (see also Jostad and Lacasse 2015). At failure, the displacement increased significantly for an infinitesimal increase in the load factor.

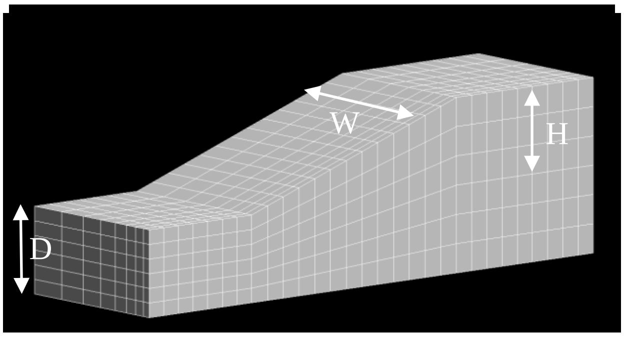

Figure 5. Finite element mesh (1/2 model) for b=3, D=H and w=4 (inclination 1:b; slope height H; slope width W)

The 2D limit equilibrium analyses and 3D finite element analyses gave similar failure mode at the centerline. The 2D and 3D slip surfaces for plane strain conditions differed slightly near the bottom of the slip surface. The factor of safety from limit equilibrium analyses (2D analysis) was 1.26 and the 3D finite element analyses gave a factor do safety of 1.24 for w equal to infinity (roller boundary at the side), The two factors of safety were very close.

However, the incremental displacements at failure differed significantly, as illustrated in Figure 6. On the left, the figure shows the incremental displacements. On the right, the contours are show at a vertical cross-section slightly above the toe, in the plane normal to the paper. The figure illustrates that the slip surface in the direction normal to the sliding mass is elliptical.

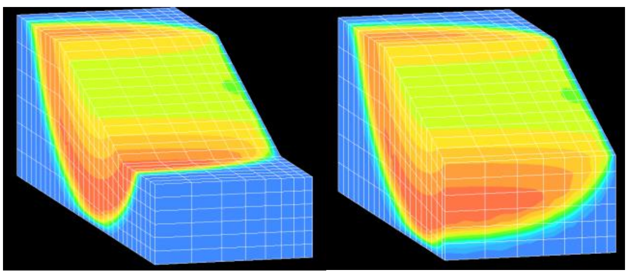

Figure 6. Incremental displacements in entire volume and with a cross-section slightly above

[4] s_u^A, s_u^{DSS}, s_u^P: s_u from triaxial compression, direct simple shear and triaxial extension tests, respectively.

the toe for b=3, D=H and W = 4H (Jostad and Lacasse 2015).

Figure 7 illustrates the importance of the 3D effects as a function of the inverse of the width ratio $1/w = H/W$ (plane strain conditions for $H/W = 0$).

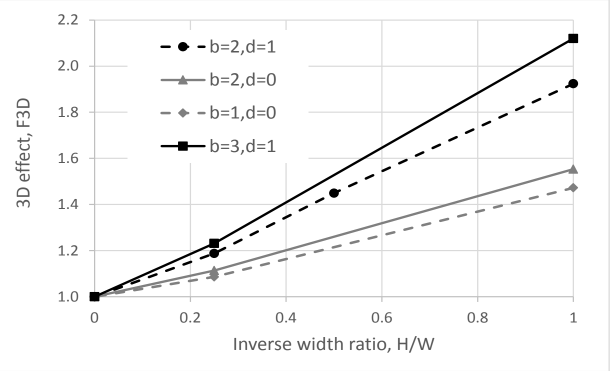

Figure 7. 3D effects vs the inverse of the width ratio H/W for different slope inclinations b and depth ratios d =D/H.

The 3D effect factor F_{3D} represents the increased capacity compared to a 2D plane strain analysis. The factor F_{3D} increases approximately linearly with the H/W ratio. It also increases with the depth down to the strong layer ($d=D/H$), and increases slightly with increasing slope inclination *b*.

7 BEARING CAPACITY MODULE

The bearing capacity module introduces simple calculations, such as Brinch-Hansen's formulas and local guidelines in Norway. In addition, the 3D calculation engine is used for finite element modelling in 2D and 3D loading situations. The FEM modelling is suitable for complex (perhaps more realistic conditions), for example, layered soils, varying strength parameters vertically or horizontally, complex geometries and loadings.

The linear elastic-perfectly plastic Mohr-Coulomb and NGIADP (Grimstad et al. 2012) constitutive laws are implemented in the calculation tool. Figure 8 illustrates an embedded footing analysed in two dimensions, under moment (M), horizontal (H) and vertical (V) loading.

8 WIZARD

Lacasse *et al* (2013; 2016) described briefly the Wizard function used in GeoSuite. Wizard is an optional, interactive assistance popping up with information on how to develop a soil profile, select a parameter, interpret *in situ* or laboratory test results, select a type of analysis, do the analysis or interpret the results of an analysis. Wizard has some but not all of the wiki-characteristics: Wizard invites the user to note down its comments within the Web site; Wizard makes topic associations with links; Wizard seeks to involve the user in an on-going process of improvement.

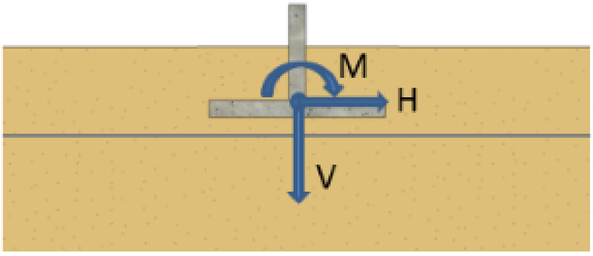

Figure 8. Bearing capacity case analysed

GeoSuite aims at providing efficient calculation tools for day-to-day design, where a balance is held between sophisticated analyses -requiring advanced soil models and parameters and offering answers of higher accuracy-, and less sophisticated and simplified models, leading to less accuracy yet still realistic answers.

For example for settlement analysis, the initial flow diagram presents to the user five steps (see Lacasse *et al* 2013 for diagram): 1) Define problem; 2) Input soil profile, models and parameters; 3) Input stress and pore pressure distributions: 4) Do settlement analysis; 5) Show the results. With the help of the Wizard, the user can initialize the data, the foundation geometry, foundation type and foundation stiffness, the construction history, ground improvement options and the load history. The user can also initializes the stress distribution (e.g. elastic theory, *n*:1 stress distribution with depth or finite element analysis of the stresses), the distribution of the initial steady state pore water (hydrostatic or non-hydrostatic conditions) and any excess pore water distribution.

Wizard also provides assistance on how to obtain soil parameters from cone penetration tests (CPTU) and laboratory tests. For example, the undrained shear strength, s_u, can be derived from the measured cone resistance, the measured excess pore pressure during CPTU testing or the net cone resistance. The preconsolidation stress, as obtained from three methods and the end-of-primary deformation parameters, again by three methods, can be considered in light of earlier experience and in terms of the effects of sample disturbance. The undrained shear strength and overconsolidation ratio can also be obtained from or compared with relationships in the literature. Figure 9 presents an example of a recent correlation for the permeability.

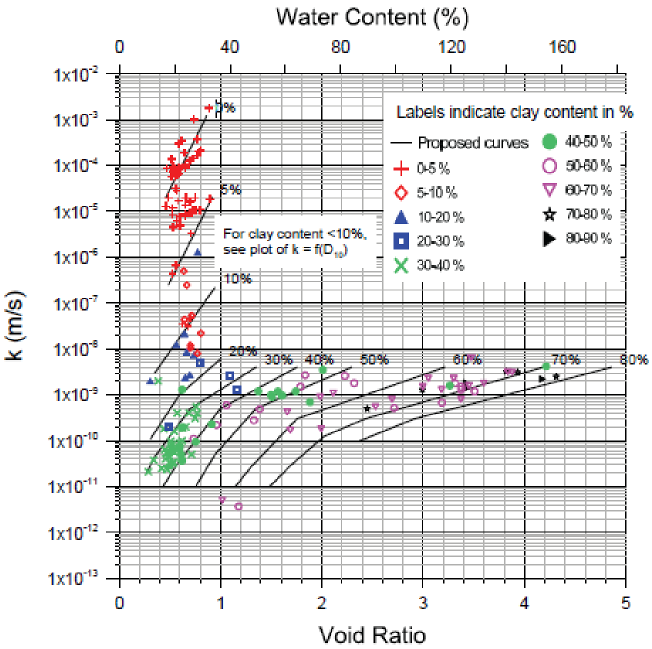

Figure 9. Permeability k vs void ratio, water content and clay content (Andersen and Schjetne 2013).

9 OTHER GEOTECHNICAL MODULES

The other modules (Piles, Excavation and Slide runout) have similar capabilities. In particular, the Piles module looks into both axial pile capacity and soil-pile interaction, and the Excavation module will use the same 3D engine as the other geotechnical modules (3D version to be completed by 2018). The Slide runout module is a recent addition and will present simplified calculation by 2017, with more advanced runout models by 2018. Statistical analyses associated with the selection of parameters will be included in 2016.

10 SUMMARY

The challenge in GeoSuite lies in maintaining a balance between sophisticated analyses, requiring advanced soil models and parameters –and thus offering answers of high accuracy, and less sophisticated and simplified models, leading to less accuracy, often lower design costs –and yet still realistic answers.

The GeoSuite code provides the practitioner the possibility of running one-, two- and three-dimensional calculations and visualization, and helps the user with geotechnical input data, establishing soil profiles, doing the calculations and interpreting the analysis results.

The paper briefly presented the concepts behind the GeoSuite software, and some calculation examples. The system is under continuous development. GeoSuite is a software that can be useful both in design and for checking one's calculation. The authors fully support that one should use more than one computer code when doing geotechnical calculations, to check that one has not missed any significant aspect of the problem.

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