Integrating soil suction in geotechnical education: a case study on partially saturated slope stability analysis in Sweden

A. Abed & M. Karstunen

Chalmers University of Technology, Gothenburg, Sweden
ayman.abed@chalmers.se, minna.karstunen@chalmers.se

ABSTRACT: This paper explores the teaching of shear strength in partially saturated soils, emphasizing the role of suction in slope stability—a key concept in geotechnical engineering in the face of growing climate-related challenges. Through a problem-based coursework, students analyse a silty slope in Sweden under two scenarios: one following the traditional approach of neglecting suction and another incorporating it using established theoretical models. Students are provided with comprehensive in-situ data, including slope geometry, CPT data, water content, bulk density, grain size distribution, Soil Water Characteristic Curves (SWCC), and precipitation data, to simulate real-world conditions. Missing parameters are estimated using empirical correlations. Through GeoStudio software (Slope/W and Seep/W), students evaluate slope stability under hydrostatic and varying infiltration conditions. Findings highlight the importance of soil suction in slope stability, particularly in regions like Sweden, where increased rainfall and wetting/drying cycles have made this a critical issue. The coursework has been well received, providing students with practical skills to address soil stability in changing environmental conditions while also highlighting the importance of integrating soil suction into geotechnical education.

Keywords: Teaching, Slope stability, Unsaturated soil mechanics, Suction

1 Introduction

With climate change causing rising temperatures and more extreme weather events—such as heavy rainfall and prolonged dry periods—significant shifts in Sweden's climate are expected over the next 25 years (SOU, 2007). This will create a significantly partially saturated zone at the ground surface, which is a key concern in practical civil engineering applications. To address this, future engineers cannot rely solely on classical soil mechanics; they must also develop at least a basic understanding of unsaturated soil mechanics (Fredlund et al., 2012).

In Sweden, shear strength has traditionally been taught under the assumption that the soil is fully saturated or fully dry. The primary focus has been on Terzaghi's effective stress as the key parameter for analysing soil behaviour in terms of deformation and stability. One of the most challenging aspects of this field is the stability of natural slopes. In particular, the stability of natural silty slopes has been a longstanding concern in Sweden, with an increasing number of documented slope failures in this type of soil (BIG A2022-01, 2024).

At Chalmers University of Technology, third-year students are introduced to fundamental concepts of soil mechanics (Knappett and Craig, 2019). They develop a strong understanding of undrained shear strength for short-term analysis and effective shear strength parameters for long-term drained conditions, always assuming that the soil consists of only two components: solid and water. Students are briefly introduced to capillary rise above the groundwater table and its effect on generating negative (tensile) pore water pressure. While the term "suction" is mentioned in this context, its implications for soil strength and stiffness are not explored in depth. As a result, students receive little formal education on unsaturated soil mechanics and the role of suction in the mechanical behaviour of soil.

This was one of the key motivations behind developing a relatively new course for fifth-year master's students in Civil Engineering at Chalmers: Contemporary Topics in Geomechanics (ACE230). This course is designed to provide students with advanced knowledge in geomechanics, equipping them to tackle contemporary challenges related to climate change and sustainability. The curriculum covers essential topics such as effective stress principles for partially saturated soils, variations in soil shear strength and stiffness due to saturation changes, and slope stability assessment under different conditions. Students also explore tunnelling methods in both soils and rocks, gaining an understanding of their environmental impacts. Sustainable ground improvement techniques—such as vertical drains, stone columns, deep mixing, and grouting—are examined as alternatives to traditional piling methods. Additionally, the course introduces soil dynamics, addressing key considerations for high-speed rail foundations and renewable energy projects. The course is delivered through a combination of lectures, tutorials (including computer-based exercises), and consultation sessions for design projects. Coursework is completed in groups (max four students), with individual assessments incorporated. The course is designed so that the students will have the expertise to analyse and apply geotechnical solutions that contribute to climate resilience and sustainable infrastructure development. However, only the part related to the unsaturated soil mechanics of the course will be discussed here.

This paper presents a case study of a student coursework project designed to teach the principles of soil suction and its impact on slope stability. It offers several key contributions by presenting a real-world case study of a silty slope in Sweden, demonstrating how suction influences slope stability analysis, providing an example of an effective educational approach to teaching this complex topic, and outlining the positive student response to the course.

2 Background

The coursework is designed to align with key concepts from the lectures, ensuring a constructive alignment between the intended learning outcomes and learning activities (Biggs, 2014). The lectures cover the following topics:

- Unsaturated soil characterization
- Stress measures in unsaturated soil
- Soil suction and the soil-water characteristic curve
- Groundwater flow in unsaturated soil
- Unsaturated slope stability
- A brief introduction to expansive soils

A key focus of the course is for students to understand the concept of suction, its components, and its relationship to stiffness and strength. The students are introduced to Bishop's effective stress and net stress, emphasizing the two main approaches to describing the mechanical behaviour of partially saturated soil:

1. The single stress measure method (Bishop's effective stress)
2. The two independent stress measures method (net stress and suction)

The advantages and drawbacks of each approach are discussed in detail (Gens et al., 2006). Ultimately, the course adopts the two independent stress measures as the preferred method for application in the coursework.

After establishing a solid understanding of suction and stress measures, the course introduces another important concept: the soil-water characteristic curve (SWCC). This includes an explanation of its physical meaning, experimental methods for measuring it, and the most common mathematical models used to fit experimental data, such as the van Genuchten (Van Genuchten, 1980), Fredlund-Xing (Fredlund and Xing, 1994), and Brooks-Corey (Brooks and Corey, 1966) functions. Additionally, the possibility of estimating the SWCC in the absence of experimental data—using basic soil properties like grain size distribution and Atterberg limits—is explored (Aubertin et al., 2003).

The effect of suction on soil hydraulic conductivity is also examined, introducing the hydraulic conductivity function and discussing how it can be derived based on the SWCC (Fredlund et al., 2012). Furthermore, the influence of suction on both water content and hydraulic conductivity is clarified through an analysis of the hydraulic behaviour of unsaturated soil, including an explanation of the water mass balance equation under transient conditions.

Two lectures are dedicated to discussing the shear strength of unsaturated soils and how it compares to the shear strength of fully saturated soils. A key focus is on the contribution of suction to increasing the shear strength of partially saturated soil by introducing an additional cohesion component, commonly referred to as capillary cohesion or apparent cohesion. The lectures also cover common methods for evaluating apparent cohesion, including its linear relationship with matric suction and its nonlinear increase as expressed in terms of the SWCC (Vanapalli et al., 1996).

To analyse the impact of suction on slope stability, the classical limit equilibrium method is first reviewed. Then, a modified approach that incorporates the effect of suction is introduced using the extended Mohr-Coulomb failure criterion for partially saturated soils (Fredlund et al., 2012).

Most importantly, the significance of considering suction variations in calculations is emphasized. The course also highlights the need to solve the unsaturated groundwater flow equation for accurate slope stability analysis. This is illustrated through examples that assess the evolution of safety factor under various hydraulic boundary conditions, such as infiltration and evaporation.

The hydraulic boundary conditions, influenced by extreme rainfall events and prolonged dry seasons, are particularly relevant, as observed in Sweden in the context of climate change. By reducing shear strength through a decrease in suction, they are strongly suspected to be a key triggering factor in the rising number of recorded failures in natural silty slopes. Stemming from these suction-related issues, a problem-based coursework was designed as problem-based learning is expected to improve knowledge retention (Beers and Bowden, 2005). Students were tasked with applying the knowledge gained in the course to analyse the stability of an actual natural slope, including the effect of suction under the effect of recorded precipitation data.

3 Case study: Silty slope in Sweden

The case study focuses on a silty slope located at the Skedomsravinen test site in Sollefteå, Sweden, situated on a bank by the river Ångermanälven (Öberg, 1997). The site features a ravine, about 50 meters deep, at its northern boundary, with a steep, vegetated slope to the south. The surrounding area is developed with houses on the crests on both sides. A sliding event occurred near the houses in the early 1980s, prompting the installation of a gravel protection layer in the river at the bottom of the ravine to prevent further sliding. The soil at Skedomsravinen consists mainly of non-cohesive materials, including medium and fine sand in the uppermost 5 meters, followed by silty sand down to about 10 meters, and silty soil at greater depths. The bedrock is located at the bottom of the river in the ravine.

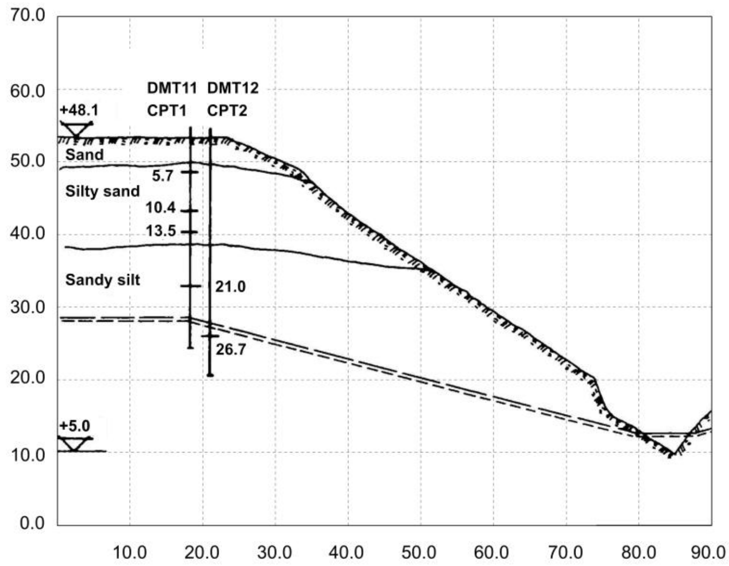
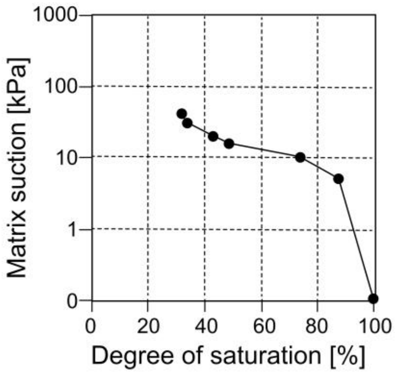
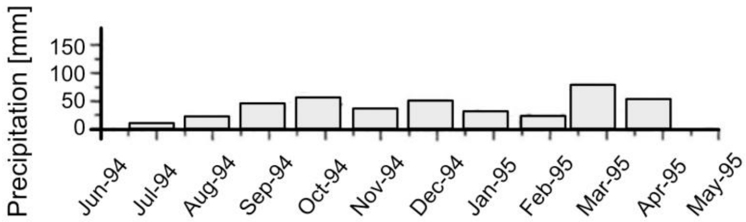


Figure 1. Slope geometry modified after Öberg (1997). Levels +5.0 and +48.1 are relative to sea level; soil sample depths (5.7, 10.4, 13.5, 21.0 and 26.7 m) are measured from ground level





(a) (b)

Figure 2. Example of the provided data to students: a) measured SWCC at a depth of 5.7 m; b) measured precipitation at the location of the slope modified after Öberg (1997)

For the analysis of stability of the slope, the students were provided with a range of in-situ data. This includes detailed slope geometry, which is outlined in documents showing sections and views of the test site, along with locations of boreholes and piezometers, see Figure 1.

The Cone Penetration Test (CPT) data reveals that the friction angle is approximately 32° in the upper 18 meters, decreasing to around 30° at greater depths. The natural water content of the soil varies between 5-15%, with the bulk density of saturated soil estimated to be around 1.8-1.9 t/m³ (18-19 kN/m³). Grain size distribution curves show that the soils range from coarse silt to fine sand, with a clay content of about 2-3%. Soil Water Characteristic Curves (SWCCs), determined in the laboratory for samples from various depths, see Figure 2(a) as an example, illustrate the relationship between degree of saturation and matric suction. Real precipitation data for one full year is also provided, as it clear in Figure 2(b), to assess the impact of infiltration on the stability of the slope.

In addition to this data, the students were tasked with estimating some missing properties such as the saturated hydraulic conductivity using empirical correlations derived from the grain size distribution curves and basic geotechnical properties.

4 Methodology

4.1 Software used

For the slope stability analyses, students utilized GeoStudio software, specifically the Slope/W and Seep/W modules. GeoStudio is a well-known comprehensive suite of geotechnical software used for analysing slope stability, seepage, and other geotechnical problems. Slope/W is designed for slope stability analysis, allowing the inclusion of partial saturation and suction effects, while Seep/W is used to analyse groundwater seepage.

4.2 Analysis scenarios

4.2.1 Scenario 1: Neglecting the effects of suction (classical approach)

In the first scenario, students analysed the slope stability without considering the effects of suction. This classical approach neglects the effect of suction in the partially saturated zone by setting its value to zero. The input parameters and assumptions used in this scenario include:

- Slope geometry: The geometry of the slope, including the height, angle, and stratigraphy, was defined based on the provided site data.
- Soil properties: The soil properties, such as cohesion, friction angle, and unit weight, were obtained from the provided CPT data and laboratory tests.

- Pore-water pressure: The pore-water pressure and phreatic level were calibrated by running a steady-state water flow analysis based on the provided hydraulic boundary conditions, including the water level in the river and measured piezometric levels in different locations on the slope.

4.2.2 Scenario 2: Considering the effects of suction

In the second scenario, students analysed the slope stability by considering the effects of suction using different theoretical models for shear strength and for the SWCC. The explored models for SWCC include the van Genuchten (VG) model and the Fredlund-Xing (FX) model as well as deriving the SWCC based on basic soil properties (Aubertin et al., 2003). The later analysis was carried out to mimic the situation in the absence of measured SWCC data and to check the accuracy of such an approximation. The input parameters and assumptions used in this scenario include:

- Slope geometry: The same slope geometry as in Scenario 1 was used.
- Soil properties: The soil properties were the same as in Scenario 1, with additional parameters for the SWCC.
- SWCCs: The Soil Water Characteristic Curves (SWCCs) were determined from laboratory tests and used to define the relationship between soil suction and water content. The VG and FX models were used to fit the SWCC data using an in-house Python script, which was run using Jupyter Notebook.
- Pore-water pressure: The pore-water pressure distribution was calculated using Seep/W, considering both saturated and unsaturated flow conditions.
- Precipitation data: Real precipitation data, Figure 2(b), was used to simulate infiltration events and their impact on pore-water pressure and slope stability. The effects of suction variation were incorporated into the stability analysis once, assuming a linear relationship between apparent cohesion and suction, and another time assuming a nonlinear relationship (Vanapalli et al., 1996).

4.3 Student workflow

The group work process was designed to guide students through the analysis in a structured manner. The workflow included the following steps:

- Data collection: Students collected and reviewed the provided site data, including slope geometry, CPT data, soil properties, SWCCs, and precipitation data.
- Software familiarization: Students were introduced to GeoStudio software and its modules, Slope/W and Seep/W. They learned how to input data, define analysis parameters, assign different types of hydraulic boundary conditions and interpret results.
- Parameter estimation: Students estimated any missing parameters, such the saturated hydraulic conductivity, using empirical correlations and engineering judgment.
- Scenario analysis: Students performed the slope stability analysis for both scenarios. They first analysed the slope using the classical approach (Scenario 1) and then considered the effects of suction (Scenario 2) using the VG, FX and estimated SWCC models.
- Results interpretation: Students compared the results of both scenarios, discussing the impact of suction and SWCC on slope stability. They evaluated the differences in factor of safety and identified potential failure mechanisms.
- Reporting: Students documented their analysis, results, and conclusions in a comprehensive report. They included detailed descriptions of the input data, analysis methods, and findings.

Throughout the process, students were guided by the instructor who provided feedback and support. The structured workflow ensured that students gained hands-on experience with GeoStudio software and developed a thorough understanding of groundwater flow and slope stability analyses considering partial saturation and suction effects.

5 Students' results

5.1 Scenario 1: Neglecting the effects of suction (classical approach)

In the classical approach, the slope stability analysis was performed without considering the effects of suction. The factor of safety (FoS) was calculated by most of the students' groups to be just below 1.0, indicating that the slope should have failed. However, in reality, it remains stable. This already satisfies one of the pedagogical learning outcomes by helping students understand the contribution of suction in maintaining slope stability. It also highlights that the slope is marginally stable. The critical slip surface was identified as shallow, indicating potential instability near the surface. It was observed, however, that even in this relatively simple task, the reported FoS varied among the groups. This variation may be attributed to slight differences in the adopted geometry, decisions regarding soil layering, and assumptions made about missing data.

5.2 Scenario 2: Considering the effects of suction

In this scenario, slope stability analysis was conducted by incorporating the effects of suction using the VG and FX models, along with estimated SWCCs based on basic geotechnical data. The slope was subjected to recorded precipitation data for one full year as an infiltration boundary condition.

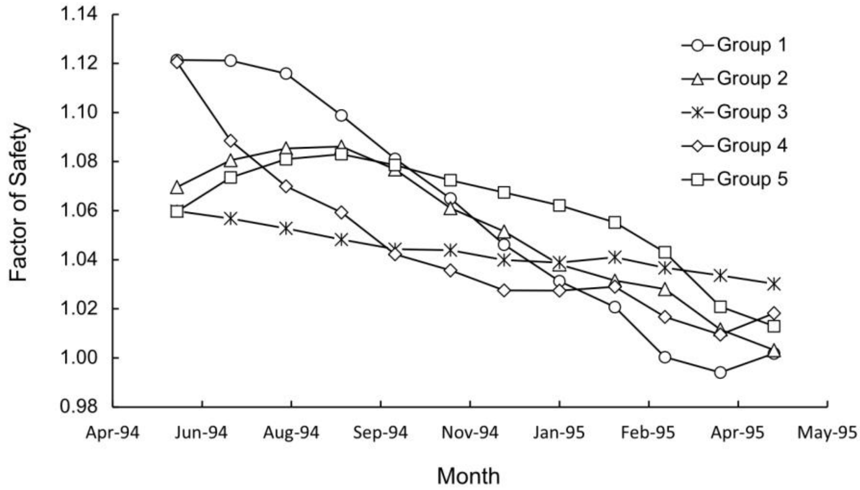


Figure 3. Students' predictions for the variation of FoS assuming FX model for SWCC and a linear relationship between suction and apparent cohesion

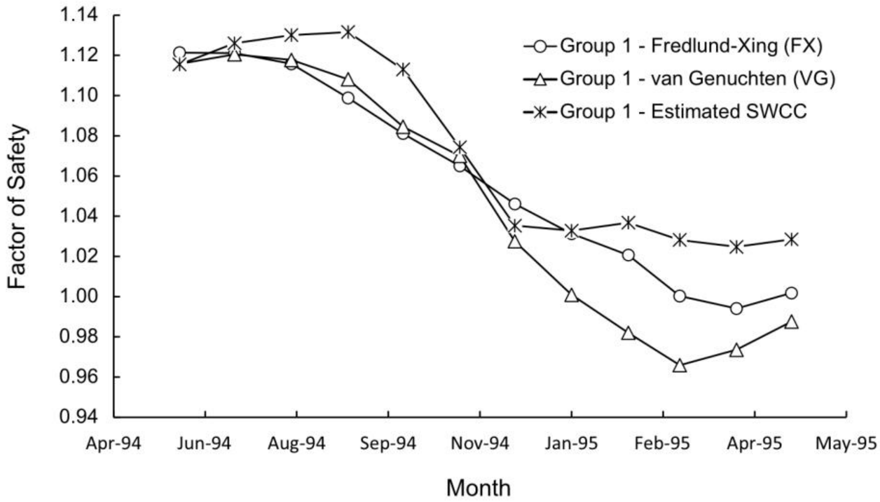


Figure 4. Group 1 predictions for the variation of FoS assuming different models for SWCC and a linear relationship between suction and apparent cohesion

On the one hand, Figure 3 presents an example of the predictions made by different student groups using the FX model for SWCC. The results in this figure correspond to the case where apparent cohesion was assumed to have a linear relationship with matric suction. On the other hand, Figure 4 shows the results of Group 1 when assuming different models for the SWCC (i.e., VG, FX, and those estimated based on basic geotechnical properties).

6 Educational impact and student feedback

6.1 Effect of suction variation on slope stability

This coursework provided students with a deeper understanding of how variations in suction influence the stability of partially saturated natural slopes. They observed that rainfall events significantly alter suction levels, leading to fluctuations in the factor of safety (FoS). Unlike in conventional saturated soil analyses, where FoS is typically a fixed value, students recognized that in unsaturated conditions, it is highly dynamic. The safety factor is not a single, constant number but varies as a function of suction and applied environmental loads, such as infiltration from rainfall.

6.2 The role of SWCC in unsaturated soil analysis

The Soil Water Characteristic Curve (SWCC) played a crucial role in this study, providing the necessary relationship between soil suction and water content. Students learned that the accuracy of slope stability predictions in unsaturated conditions is highly sensitive to how the SWCC is estimated. The van Genuchten (VG) and Fredlund-Xing (FX) models both provided reliable results, as they both rely on fitting measured data, demonstrating their effectiveness in capturing unsaturated soil behaviour. However, the students also recognized the potential risks of applying these models in the absence of sufficient experimental data. When data is limited, careful estimation of SWCC parameters is critical to avoid misrepresenting the slope’s response to environmental changes.

6.3 Student insights and key takeaways

Through their analyses, students concluded that incorporating matric suction into slope stability assessments provides a more realistic representation of slope behaviour. They observed that the FoS increased remarkably when suction was considered, highlighting the stabilizing effect of reduced pore water pressure. However, they also noted that during intense rainfall, suction decreases, leading to a reduction in the FoS, reinforcing the need for mitigation measures in marginally stable slopes.

The variability in FoS across different student groups further emphasized how different assumptions about soil layering, SWCC estimation, and missing data impact the final stability predictions. This variability underscored the importance of using well-calibrated SWCC models and ensuring that input data accurately represent site-specific conditions.

As a complementary part of the coursework to mitigate rainfall-induced shearing failure, students explored stabilization strategies such as horizontal drains and nature-based solutions (NBS), including live crib walls. These measures were recommended to enhance slope stability by controlling infiltration and maintaining sufficient suction levels in the soil.

7 Conclusions

Integrating suction effects into slope stability assessments helped students understand the transient nature of the factor of safety (FoS) in unsaturated conditions. They recognized the need for advanced methods beyond traditional saturated soil mechanics, particularly for rainfall-induced instability. The coursework output emphasized the careful selection of SWCC models, which become particularly challenging when data is limited.

While the project looked at how different ways of representing the SWCC affect the factor of safety, there are other important sources of uncertainty—like how we estimate soil strength from CPT tests, which is still a difficult and developing area in unsaturated conditions. Also, the role of the hydraulic conductivity function was not fully discussed, even though it strongly affects how water moves through the soil and influences suction during infiltration events. In future, more attention will be given to this function, so students understand its importance, rather than seeing it as something secondary. It would also be beneficial to emphasize the idea that soils behave differently when wetting and drying, and that using different curves for each case makes the analysis more realistic, especially when dealing with long periods of rainfall and evaporation.

Introduced three years ago, the ACE230 course has received consistently excellent feedback from students for its structured coursework, clear learning outcomes, and the constructive alignment between learning outcomes, learning activities and examining parts. Its success underscores the value of teaching unsaturated soil mechanics, equipping future engineers with essential skills to address evolving geotechnical challenges.

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Authors' bios

Ayman A. Abed, Chalmers University of Technology (Sweden)

Dr. Ayman abed is a Senior Lecturer in the Division of Geology and Geotechnics, research area Geotechnics. He is interested in studying the coupled thermo-hydro-mechanical-chemical (THMC) behaviour of unsaturated soil. One of the main purposes of his research is to provide practical engineering solutions to confront the challenges associated with global climate change. Ayman is an expert in unsaturated soil mechanics, constitutive modelling, and numerical analyses. His dedication to education was recognized when he was awarded the Student's Pedagogical Prize 'Teacher of the Year 23/24' at Civil and Environmental Engineering, Chalmers University of Technology.

Minna Karstunen, Chalmers University of Technology (Sweden)

Minna Karstunen is Professor in Geotechnical Engineering at Chalmers University of Technology, and a Fellow of the Institution of Civil Engineers, UK. Minna got her PhD at the University of Wales Swansea in 1998 followed by a successful academic career in the UK, at the Universities of Glasgow (1996-2005) and Strathclyde (2005-2013). Minna joined Chalmers in 2012, where she is leading a dynamic research group working on modelling and characterisation of complex natural and engineered geomaterials, aiming to bridge fundamental understanding with applications in engineering practice. Even though Minna is internationally known for her research on constitutive model development, in parallel, she has been working on other topics, including novel numerical techniques for representing periodic ground improvement on soft soils.