Chapter

Introductory Chapter: Geotechnical Engineering in a Broad Perspective - New Advances in Emerging Fields

Mehmet Barış Can Ülker

1. New advances in geotechnical engineering

Geotechnical engineering is the branch of civil engineering that studies soils, structures, or structural components residing on or inside these soils. The mechanics of soils provides the necessary physical attributes to be used to understand the mechanisms that play a key role in what happens to soils under external effects, such as those induced by structural loads or changes in the water content. Thus, soil mechanics is mainly interested in the deformation characteristics of soils such that failure loads can be predicted more accurately. Therefore, it is more convenient and perhaps more accurate to think of the problem as a soil-structure system which is composed of a porous soil medium (as a soil profile with number of layers) and a foundation or another geotechnical engineering structure. As for the design of such soil-structure systems, settlement and the ultimate bearing capacity become the two major criteria that must be satisfied to withstand any external static or dynamic load. Once such stability criteria are set, it is expected that any soil-structure system achieves these requirements during the lifetime of the project.

Geotechnical engineering consists of the collection of subfields in a wide range of practical problems related to soils, rocks, slopes, foundations, walls, etc. While the principles of soil mechanics is the ultimate cookbook, recipe for each problem changes, and the engineers who are the chefs of the practice must be able to deduce the most edible and desired cuisine (i.e., engineering solution) employing their ultimate material, mathematics. As the current technology is advancing, it is more and more common that such engineering solutions follow the emerging technology that can be incorporated into geotechnical engineering research and practice to develop the most efficient, most viable, and most accurate solution. In order to achieve such an elaborate task, we, as geotechnical engineers, still make use of three tools at our disposal: (i) experimental methods, (ii) numerical methods, and (iii) analytical methods.

In this introductory chapter, three emerging fields of geotechnical engineering where there have been significant developments in the last couple of decades are touched upon. Those are the (i) numerical methods in geotechnical engineering, (ii) unsaturated soils, and (iii) offshore geotechnics. A short summary of the basic notion of what each field mainly investigates and what has been recently done in each topic in recent years is also given.

1.1 Numerical methods in geotechnical engineering

Numerical methods provide approximate solutions to complex engineering problems. Soils are heterogeneous, anisotropic, and multiphase particulate materials with nonlinear stress-strain relationships. Thus, any geotechnical engineering problem containing soils as a material or as an entire domain exhibits a certain level of complexity demanding robust numerical methods to tackle the issue. Such complexity is often associated with material behavior or boundary conditions or both. As it is obvious that no analytical solutions are available to such intricate problems, numerical methods are found to be quite handy and surely the only available option that yields approximate solutions with an acceptable error margin. Some of the commonly used numerical methods today are finite element method (FEM), finite difference method (FDM), boundary element method (BEM), discrete element method (DEM), finite volume method (FVM), material point method (MPM), hybrid methods, etc. While it is no straightforward task to decide what method to use, for most of the cases, the numerical method to employ is mostly problem-dependent. That is, the desired unknowns in the problem and the crucial details of what variables need to be calculated, where they are to be calculated and to what accuracy is wanted, will actually determine the most appropriate method.

In a brief summary of how numerical methods are employed, it should be noted that in most of these methods, the physical problem is first defined in the spatial domain, and if the problem is time-dependent, a temporal domain exists as well. Then the governing equations are written in these domains (or only along the boundaries, see BEM) in terms of the field variables which are simply the unknowns in the problem. In geotechnical engineering problems, field variables are mostly the displacements of the solid skeleton and the pore pressures in the voids of soils, that is, pore water or pore air pressures depending on whether the soil is modeled as a two-phase or a three-phase medium, respectively. Then the governing equations are either discretized in existing domains or simply defined at specified locations in the soil material, and the necessary boundary and initial conditions are prescribed in terms of field variables (or the degrees of freedom) and their derivatives with respect to Cartesian coordinates and/or to time. When the discretized forms of the governing equations are obtained, they are to be solved using an available numerical method for each load or time step. While such a clear-cut process is sufficient to provide some sort of a numerical solution to the problem, it is important to note that the ultimate solution will only be as accurate as how much the problem is simplified in the beginning of the process. Once the field variables are calculated, stresses (or any other stress-state variable) are computed at material points (i.e., convergence or integration points) in the soil elemental level through constitutive models using the strain field. Strains are essentially calculated utilizing the kinematic strain-displacement relations. For the soil skeleton, constitutive law is the effective stress-strain relationship, and for the soil pores, the necessary constitutive equation is the Darcy's law governing the flow of pore fluid due to differences in the total head between two points of interest in the soil.

Some of the trending problems encountered in geotechnical engineering in recent years, where numerical analysis is the key element, are:

- Constitutive theories for transient soil response. Here, particularly the theoretical models developed for predicting the cyclic behavior of soft soils and impact-induced response of special soils and rocks entail certain issues. Such a behavior can be physically modeled on a cyclic triaxial apparatus and numerically simulated in [1] (see **Figure 1**).

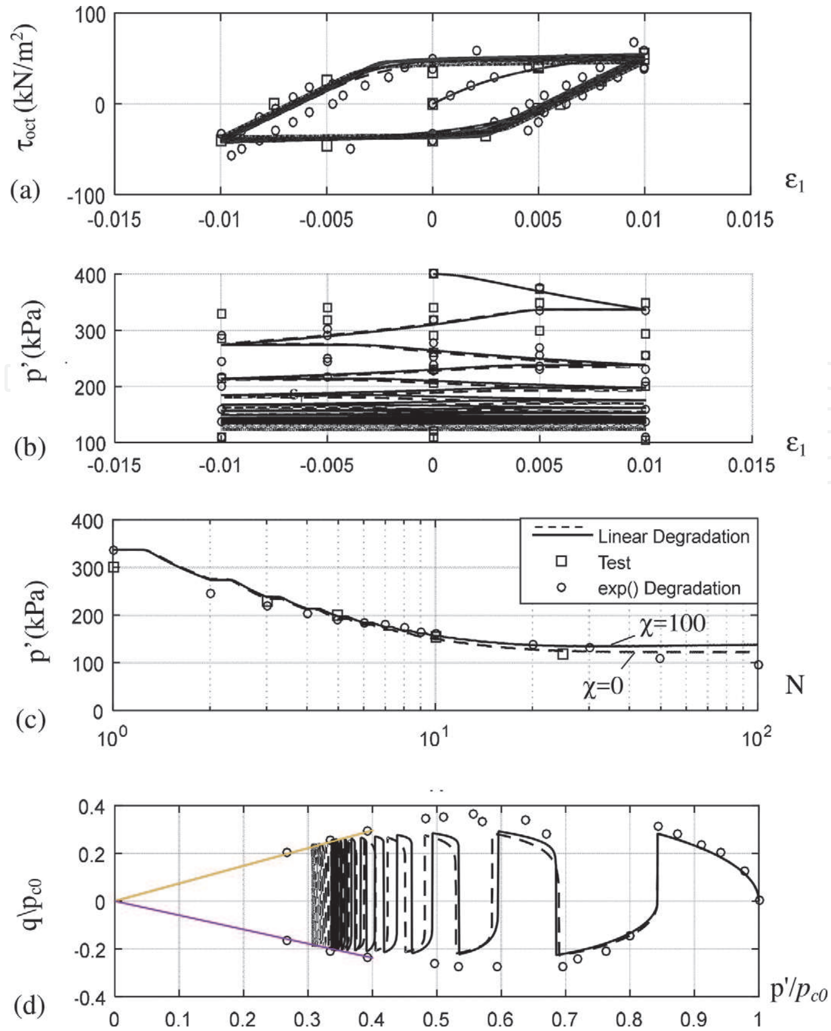

Figure 1.
Two-way strain-controlled undrained triaxial test simulation of kaolin clay as compared with [2] Grenoble workshop tests and [3]. (a) Shear stress-axial strain relationship. (b) Decreasing mean effective stress with axial strain of $\varepsilon_1 = \pm 1\%$. (c) Mean effective stress variation. (d) Stress path.

- Large deformation or post-failure behavior of soft soils. A serious issue related to soft ground is "post-liquefaction behavior" as well as settlements and lateral spreading of loosely deposited saturated sands subject to seismic motions. Another one is the pile-driving problem or modeling the penetration of piles into soil deposits. This is a typical example of a large deformation and post-failure behavior, which may pose a challenge in terms of numerical modelling.

- Uncertainties in distributions/initial conditions of mechanical quantities of soils. Geotechnical problems always suffer from lack of knowledge on soil properties and initial conditions. Inadequate and insufficient information in geotechnical problems frequently lead to a discrepancy between prediction and measurement, which implies that the prediction in these problems is accompanied with several types of uncertainties. While deterministic approach has since been quite useful in providing an estimate solution provided that there is certain amount of data assimilation and inverse analyses back the approach, probabilistic approach is also promising. On the latter approach, stochastic analysis is a technique that considers the uncertainty as a probabilistic variable. It is employed to assess the possibility of failure or other limit states of soil-structure systems. Probabilistic approach is directly related to reliability analysis and performance-based design.

1.2 Unsaturated soils

Another emerging field in geotechnical engineering is related to unsaturated soils. The response of unsaturated soils (USS) constitutes an important consideration for many problems in geotechnical engineering and geomechanics. Current geotechnical practice that models unsaturated soil mechanical properties as if they represent fully saturated conditions results in unsafe design due to a potential rise in the water content of soil. On the other hand, saturating natural soil samples in the laboratory, which normally would represent partially saturated state with in situ water contents, softens the soil which might lead to overdesign. Since such soil layers in the field are anticipated to have varying degrees of saturation during seasonal changes, this elevates the associated risks.

The developments in the field of "unsaturated soil mechanics" have lagged behind those of "saturated soil mechanics," and the study of unsaturated soils has only recently gained importance. Although there have been many studies conducted in the last 30 years, there still needs experimental and theoretical works to be done to understand the USS hydromechanical behavior. Upon laboratory testing, predicted results should be calibrated such that the developed model could subsequently be employed to solve a practical problem through available numerical methods. This requires the model to be implemented into a computer program in terms of numerical algorithms developed for an elemental soil using USS parametric relations in a multiparametric space. This means, the development in the USS mechanics is in direct relation with the developments in the previous topic. On the one hand, there is the objective of eliminating the downsides of treating USS as fully saturated and therefore reducing the associated unconservative design owing to unpredicted behavior of USS. On the other hand, there is the uneconomical design to be reduced due to overconservative approach.

Water content in unsaturated soils plays an important role in evaluating the hydromechanical response in relation to suction. Behaviors of USS under static loadings are affected significantly by their volume changes as a function of the change in their water content. This is, however, directly related to the difference in the pressures of pore water and pore air which is called "matric suction," s. The major stress variable controlling the deformation characteristics of USS is suction. As the matric suction increases, stiffness and shear strength of USS increase as well under constant net mean stress. As for the stress state, while a single effective stress is sufficient to describe the stress-strain relationship of saturated soils, this is not the case for USS. Hence, effective stress equation needs to be modified in formulating a constitutive model for USS. This issue has been the main subject of debate among the researchers since the pioneering study of [4]. Bishop [5] is the first to propose a relation for effective stress that accounts for the air phase on the average stress acting on the solid skeleton. The "Bishop stress" is written as the modified effective stress:

$$\sigma'' = \sigma - \chi s \qquad (1)$$

where χ is called the Bishop parameter which is a function of the water degree of saturation. While some researchers claim that there is a "smooth" transition to the new definition of the effective stress [6–9], others say that there needs to be two independent stress variables, that is, the net stress, σ_{net} or $\overline{\sigma}$, and matric suction to govern the response of USS [4, 10, 11]. Net stress is defined as:

$$\overline{\sigma} = \sigma - u_a \qquad (2)$$

It is important that in developing a constitutive model that accounts for hydro-mechanical behavior of USS, *hydraulic hysteresis* observed in the water retention behavior is taken into account. Such a behavior is self-evident in a typical constitutive relationship called the "soil-water characteristic curve (SWCC) or water retention curve (WRC)" irrespective of the soil type. During a drying-wetting cycle causing changes in saturation and suction, USS exhibits such hysteretic behavior. Therefore, it is necessary that the hysteretic response is incorporated in the mathematical formulation of a constitutive model for USS. Some of the common relationships are given in **Table 1**. There, θ is the volumetric water content, θ_s is the saturated water content (%), θ_r is the residual volumetric water content, and Ψ is the suction head with parameters, λ, a, m, and n, being empirical constants. **Figure 2** shows the data obtained by [12] using the HYPROP device which fits the curve by [13].

Recent elastoplastic models incorporating the hysteresis effect are distinguished in twofold: (i) models that account for hydraulic hysteresis through defining more yield surfaces [7, 16, 17] and (ii) models in which the effect of hydraulic hysteresis is included in the evolution of a so-called *load collapse*, (LC) curve [6, 18]. LC curve defines the evolution of "pre-consolidation pressure," p_0, of the soil with increasing plastic strains. Also, there are two other yield curves controlling the yielding of USS as matric suction changes called the *suction increase* (SI) and *suction decrease* (SD) yield curves (i.e., [16, 19]).

Model	Relation
[14]	$\theta(\Psi) = \theta_r + (\theta_s - \theta_r)(\alpha\Psi)^{-\lambda}$
[13]	$\theta(\Psi) = \theta_r + \frac{\theta_s - \theta_r}{\{ln[e + (\alpha\Psi)^n]^m\}}$
[15] (m = 1 − 1/n)	$\theta(\Psi) = \theta_r + (\theta_s - \theta_r)[1 + (\alpha\Psi)^n]^{-m}$
[15] (m, n independent)	$\theta(\Psi) = \theta_r + (\theta_s - \theta_r)[1 + (\alpha\Psi)^n]^{-m}$

Table 1.
Some commonly used SWCC relations.

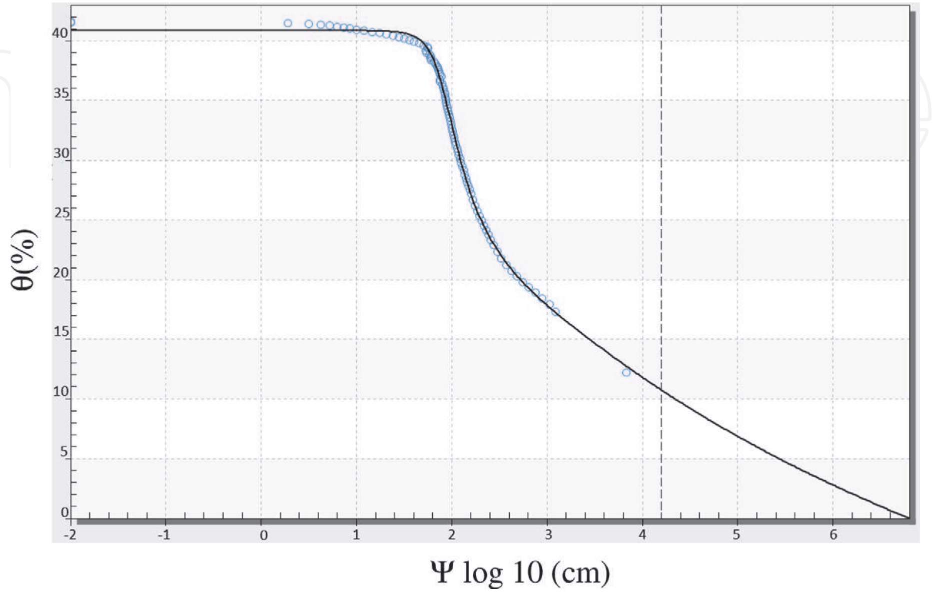

Figure 2.
SWCC of Mersin silt fitted to Fredlund and Xing [13] (after [12]).

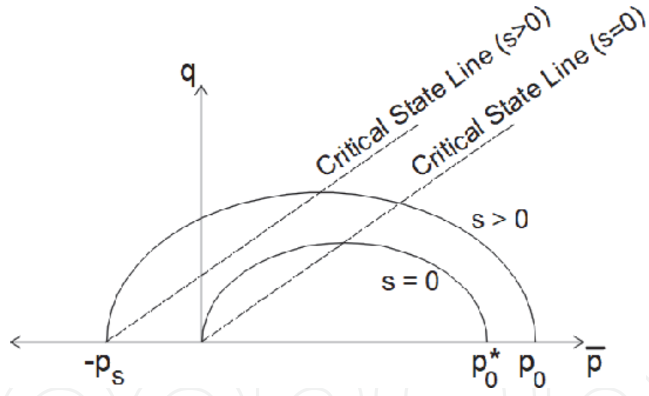

Figure 3.
Dependence of the yield surface on suction.

Barcelona Basic Model (BBM) [4] is considered to be the pioneering study that explicitly proposes an elastoplastic framework to understand the hydromechanical behavior of USS. The model is based upon the critical state theory with a classical plasticity framework employing a nonassociated flow rule. BBM adopts the yield surface of Modified Cam-Clay (MCC) model in the constant suction surface (Eq. (3)), whose size depends on suction (**Figure 3**). The yield function is written in triaxial stress components as:

$$q^2 - M^2(\overline{p} + p_s)(p_0 - \overline{p}) = 0 \tag{3}$$

As far as hydromechanical coupling, generally speaking, the yield criterion should consist of a hardening parameter that is a function of both suction and plastic strain, since stiffness and strength characteristics of unsaturated soils increase with increasing values of hardening parameters. Thus we have:

$$f(\overline{\sigma}, h) = 0 \tag{4}$$

$$h = h(\varepsilon^p, s) \tag{5}$$

where h is the "hardening parameter." In BBM per (3), $h = p_0$ emphasizes that the consistency condition written for the yield surface must include suction as well as net mean stress. Consistency condition for the yield surface is then written as:

$$df = \frac{\partial f}{\partial \overline{\sigma}}^T d\overline{\sigma} + \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial \varepsilon^p}^T d\varepsilon^p + \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial s}^T ds + \frac{\partial f}{\partial p_s}\frac{\partial p_s}{\partial s} ds = 0 \tag{6}$$

While the formulation of the mechanical part of USS continues with the steps of classical plasticity starting from (Eq. (6)), the hydraulic part essentially starts off with the partial derivative of volumetric water content written as:

$$d\theta = S_r * dn + n * dS_r \tag{7}$$

where S_r is the degree of saturation and n is porosity. This equation can be expanded to yield a form employing matric suction and volumetric strain [20]. Derivation of S_r with respect to suction can then be obtained using the water retention behavior in terms of the soil-water characteristic curve. The final form of the coupling relation is obtained as:

$$d\overline{\sigma} = D_{hm}^{ep}\, d\varepsilon_{hm} \tag{8}$$

where $D^{ep}{}_{hm}$ is the *hydromechanical elastoplastic stiffness matrix*. An example of predicted behavior of USS can be seen in **Figure 4** as compared to the BBM.

In summary, factors controlling the USS response are complicated due to soils' particulate, multiphase, and nonlinear nature. Particularly, the volume-saturation relation and water retention behavior of USS, unlike saturated soils, provide additional complexity due to existence of matric suction. Hydraulic hysteresis is another response of USS observed in water retention behavior regardless of the soil type. Therefore, a constitutive model developed to understand the hydromechanical response of unsaturated soils has to account for these facts observed in specialized laboratory tests.

1.3 Offshore geotechnics

The last field of interest that gains popularity mainly in the last two decades is offshore geotechnical engineering. Offshore structures that reside on or around seabed soil are essential for energy, protection, or transmission. The stability of the whole soil-structure system relies not only on the structural integrity under wave action but that the seabed soil must be able to withstand the induced stresses and pore pressure buildup against various loadings due to wave and currents. Geotechnical considerations are important in identifying such conditions leading to instability of seabed-offshore structure systems under wave action. Therefore, it is important that wave-induced soil behavior is modeled via appropriate theoretical frameworks.

The developments in this field depend upon three interrelated subtopics: (i) wave mechanics, (ii) structural mechanics, and (iii) soil mechanics. Hence, the fluid-soil-structure interaction (FSSI) is an indispensable field of study that one who is working on offshore geotechnics needs to tackle with diligence. In addition, the studies made in this field are also related to the topics discussed in the previous sections in that numerical methods are frequently employed to provide approximate engineering solutions to related problems. Also, while it is not common to observe unsaturated soils in offshore environments (except the air voids made up due to sea shells), aspects of soil constitutive modeling associated with unsaturated soils are indirectly applicable to the elemental-level response of saturated soils encountered in seabed soils. Thus, in this section of this introductory chapter, the focus is on such relationships between seabed soils and their constitutive behavior under cyclic wave loading as opposed to specific offshore structures and their analysis details. Interested readers can refer to the recent proceedings published by the International Society of Offshore and Polar Engineers (ISOPE) [21–23].

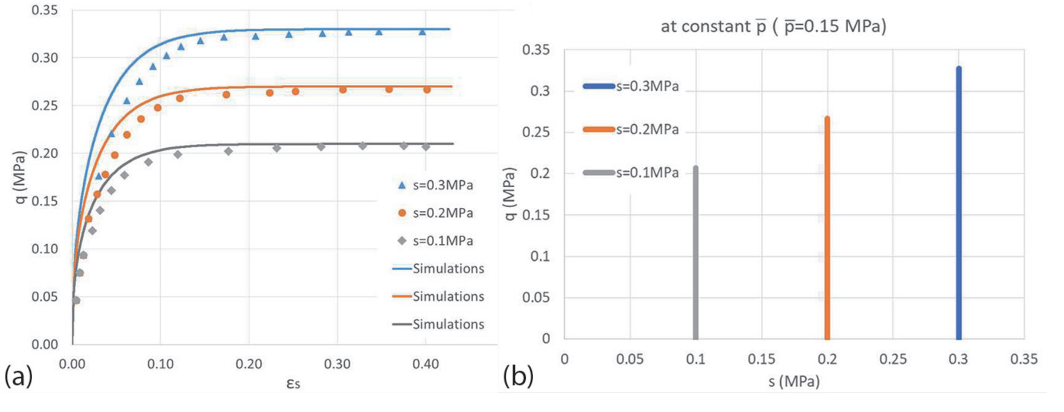

Figure 4.
Prediction of hydromechanics of USS. (a) Verification with BBM [4] and (b) stress paths (after [20]).

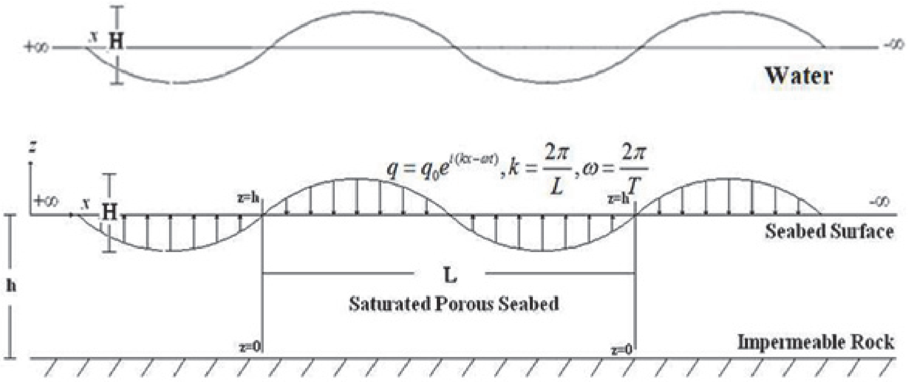

Figure 5.
Free field wave-induced saturated porous seabed response.

Figure 5 shows the progressive wave-induced seabed problem in the free field. Here, wave loading induces a similar harmonic stress variation on a localized seabed layer. The goal is to calculate the displacements and pore pressures in the seabed under wave action. Surely the actual wave effect will have an irregular structure, but this is a sufficient representation of the wave-induced response of the system.

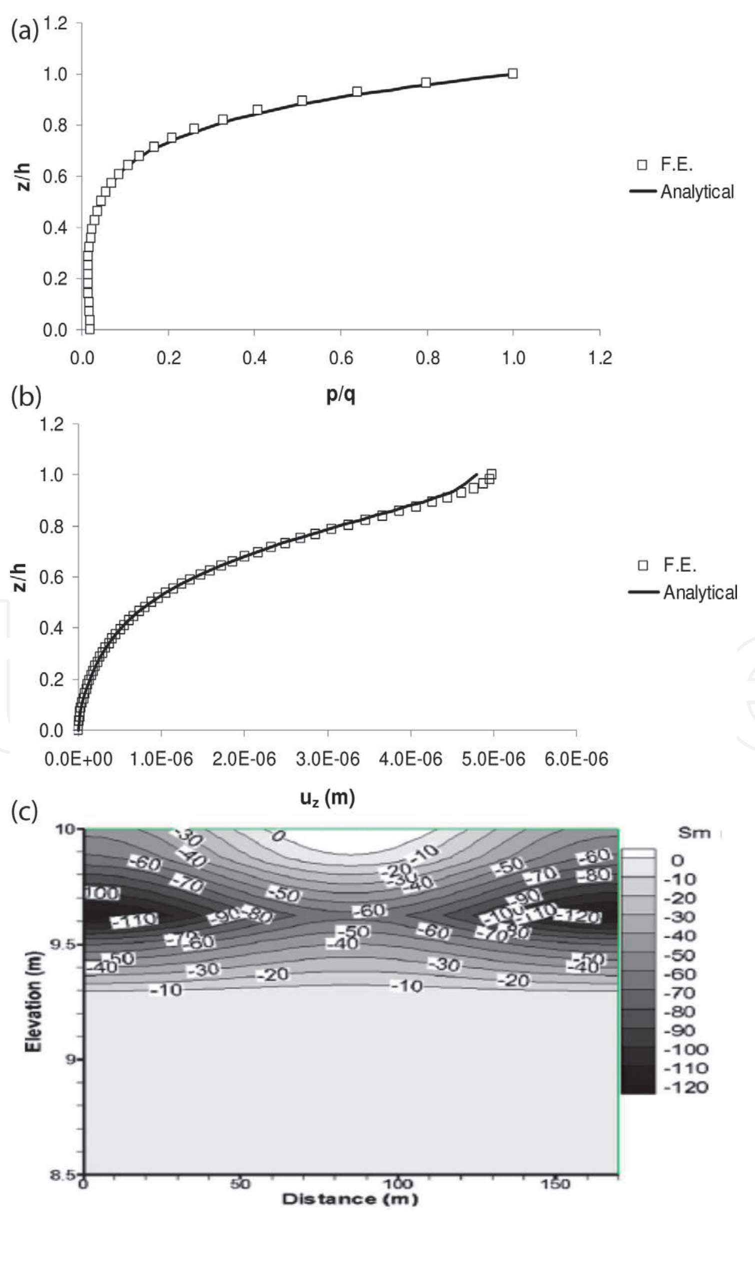

Figure 6.
(a) Pore pressure, (b) displacement distribution and (c) liquefaction response within the seabed.

The solution of this problem using analytical and numerical means where the equations governing the dynamic response of seabed soil are that of coupled flow and deformation of Biot poroelasticity [24, 25] is given in **Figure 6a**, **b** [26, 27]. Prior to employing any numerical methods in developing an associated formulation, it is highly recommended that the researchers dealt with the free field response problem so that they have a better understanding of the elemental behavior of saturated porous seabed. In addition, in this way the wave-induced instantaneous liquefaction phenomenon observed in seabed based on mean effective stress (Sm) criterion can also be modeled [28] (**Figure 6c**). Interested readers for more on the subject matter in this field can refer to the wide literature available on the topic, some of which can be found in [28–31].

Author details

Mehmet Barış Can Ülker
Institute of Disaster Management Earthquake Engineering Program, Istanbul, Turkey

*Address all correspondence to: mbulker@itu.edu.tr

References

[1] Ülker MBC. A new hardening interpolation rule for the dynamic behavior of soils using generalized plasticity framework. In: ICSMGE 2017—19th International Conference on Soil Mechanics and Geotechnical Engineering; 2017

[2] Kuntsche K. Tests on clay. In: Proc. International Workshop on Constitutive Behavior of Soils; Grenoble; 1982

[3] Zienkiewicz OC, Leung KH, Pastor M. Simple model for transient soil loading in earthquake analysis. I. Basic model and its application. International Journal for Numerical and Analytical Methods in Geomechanics. 1985;**9**:453-476. DOI: 10.1002/nag.1610090505

[4] Alonso EE, Gens A, Josa A. A constitutive model for partially saturated soils. Geotechnique. 1990;**40**:405-430

[5] Bishop A. The principle of effective stress. Teknisk Ukeblad. 1959;**39**:859-863

[6] Gallipoli D, Gens A, Sharma R, Vaunat J. An elasto-plastic model for unsaturated soil incorporating the effects of suction and degree of saturation on mechanical behavior. Géotechnique. 2003;**53**:123-136

[7] Wheeler SJ, Sharma R, Buisson M. Coupling of hydraulic hysteresis and stress–strain behavior in unsaturated soils. Geotechnique. 2003;**53**:41-54

[8] Jommi C. Remarks on the constitutive modelling of unsaturated soils. In: Tarantino A, Mancuso C, editors. Experimental Evidence and Theoretical Approaches in Unsaturated Soils. Rotterdam: Taylor & Francis; 2000. pp. 121-138. ISBN: 90-5809-186-4

[9] Sun D, Sheng D, Xiang L, Sloan S. Elastoplastic prediction of hydro-mechanical behaviour of unsaturated soils under undrained conditions. Computers and Geotechnics. 2008;**35**:845-852

[10] Fredlund D, Morgenstern N. Stress state variables for unsaturated soils. Journal of Geotechnical and Geoenvironmental Engineering. 1977;**103**:447-466

[11] Fredlund DG, Pham HQ. Independent roles of the stress state variables on volume–mass constitutive relations. Theoretical and Numerical Unsaturated Soil Mechanics. Berlin, Heidelberg: Springer; 2007:37-44. DOI: 10.1007/3-540-69876-0_5

[12] Eyupgiller M, Ulker M. Determination of the relation between hydrolic conductivity and matric suction in silty soils with respect to saturation. In: 17th National Soil Mechanics and Geotechnical Engineering Conference; 2018

[13] Fredlund D, Xing A. Equations for the soil-water characteristic curve. Canadian Geotechnical Journal. 1994;**31**:521-532

[14] Brooks AT, Corey RH. Hydraulic properties of porous media and their relation to drainage design. Transactions of ASAE. 1964;7:26-28

[15] Van Genuchten MT. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal. 1980;**44**:892-898

[16] Vaunat J, Romero E. An elastoplastic hydro-mechanical model for unsaturated soils. In: Tarantino A, Mancuso C, editors. Experimental Evidence and Theoretical Approaches in Unsaturated Soils. Rotterdam: Taylor & Francis; 2000. pp. 121-138. ISBN: 90 5809 186 4

[17] Gens A, Sheng D, Sloan SW. A constitutive model for unsaturated soils: Thermomechanical and computational aspects. Computational Mechanics. 2004:**33**:453-465

[18] Tamagnini R. An extended Cam-clay model for unsaturated soils with hydraulic hysteresis. Geotechnique. 2004;**54**:223-228

[19] Sheng D. Review of fundamental principles in modelling unsaturated soil behaviour. Computers and Geotechnics. 2011;**38**:757-776. DOI: 10.1016/j.compgeo.2011.05.002

[20] Eyupgiller M, Ulker MBC. Effect of plastic deviatoric strains on the hardening of unsaturated soils in relation to their hydromechanical behavior. In: 8th National Geotechnical Symposium; 2019

[21] Ulker MBC. Constitutive modeling of cyclic seabed behavior around coastal and offshore structures: Two robust models and their predicting capabilities. In: Proc. 29th International Ocean and Polar Engineering Conference; Honolulu, HI: ISOPE; 2019

[22] Baksi HG, Ülker MBC. Analysis of dynamic response of a caisson type gravity quay wall—Seabed soil system under waves. In: Proceedings of the International Offshore and Polar Engineering Conference; 2017

[23] Ülker MBC, Fard MM. Instantaneous liquefaction of seabed around rubble mound breakwater under waves. In: Proceedings of the International Offshore and Polar Engineering Conference; 2016

[24] Biot MA. General theory of three-dimensional consolidation. Journal of Applied Physics. 1941;**12**:155-164. DOI: 10.1063/1.1712886

[25] Biot MA. Theory of elasticity and consolidation for a porous anisotropic solid. Journal of Applied Physics. 1955; **26**:182-185. DOI: 10.1063/1.1721956

[26] Ulker MBC, Rahman MS. Response of saturated and nearly saturated porous media: Different formulations and their applicability. International Journal for Numerical and Analytical Methods in Geomechanics. 2009;**33**:633-664. DOI: 10.1002/nag.739

[27] Ulker MBC, Rahman MS, Jeng DS. Wave-induced response of seabed: Various formulations and their applicability. Applied Ocean Research. 2009;**31**:12-24. DOI: 10.1016/j.apor.2009.03.003

[28] Ulker MBC. Pore pressure, stress distributions, and instantaneous liquefaction of two-layer soil under waves. Journal of Waterway, Port, Coastal, and Ocean Engineering. 2012; **138**:435-450. DOI: 10.1061/(ASCE)WW.1943-5460.0000155

[29] Ülker MBC. Wave-induced dynamic response of saturated multi-layer porous media: Analytical solutions and validity regions of various formulations in non-dimensional parametric space. Soil Dynamics and Earthquake Engineering. 2014;**66**:352-367. DOI: 10.1016/j.soildyn.2014.08.005

[30] Ülker MBC. Instantaneous liquefaction in a multi-layer seabed under nonlinear progressive waves. AIP Conference Proceedings. 2012:1479-1484. DOI: 10.1063/1.4756444

[31] Ulker MBC, Tatlioglu E, Lav MA. Dynamic response and liquefaction analysis of seabed-rubble mound breakwater system under waves. Applied Ocean Research. 2018;**78**:75-87. DOI: 10.1016/j.apor.2018.06.008