This editorial highlights the motivations, historic perspectives, future prospects, and some details of the technical contents of the special issue on Principle of Effective Stress in Variably Saturated Porous Media.

Ning Lu, Dep. of Civil and Environmental Engineering, Colorado School of Mines, Golden, CO 80401; Nasser Khalili, School of Civil and Environmental Engineering, Univ. of New South Wales, Sydney 2052, NSW, Australia; Ehsan Nikooee, Dep. of Civil Engineering, Shiraz Univ., Engineering Bldg. 1, Zand St., Shiraz, Iran 71348-51156; S. Majid Hassanizadeh, Dep. of Earth Sciences, Utrecht Univ., Budapestlaan 4, 3584CD Utrecht, The Netherlands. *Corresponding author (ninglu@mines.edu).

Principle of Effective Stress in Variably Saturated Porous Media

Ning Lu,* Nasser Khalili, Ehsan Nikooee, and S. Majid Hassanizadeh

In 1961, in the wake of emerging geotechnical problems under unsaturated conditions, the British Royal Society held a conference on the effective stress principle. Much of the debate stemmed from pressing needs to go beyond Terzaghi's (1923, 1936) effective stress for saturated porous media and issues encountered with Bishop's (1959) effective stress for unsaturated soils. The next three decades witnessed a great deal of expansion in research on the state of stress in variably saturated porous media, yet little consensus has been reached. This was a period of waning interest, when the effective stress principle was largely abandoned and alternatives, such as the two independent stress state variable approach, were explored. Around the turn of the new millennium, in light of some new evidence (Khalili et al., 2004), new insightful knowledge has been gained in better defining effective stress. This new evidence sparked a renewed interest in effective stress in unsaturated porous media in several disciplines, including soil and rock mechanics, vadose zone hydrology, and granular mechanics.

After more than half a century, a milestone was recently reached when leading researchers from around the world in different disciplines gathered in Utrecht in August 2012 for the Euromech Colloquium 539 on effective stress in porous media. These researchers represent broad disciplines of science and engineering, such as vadose zone hydrology, soil and rock mechanics, granular physics, applied mathematics, and computational mechanics. Many advances have been made along the fronts of theory, experiment, and application of effective stress principles in porous media. In this special issue in *Vadose Zone Journal*, we disseminate the latest developments in our understanding of the effective stress principle applied to unsaturated soils ranging from micromechanics to thermodynamics, and from theories to numerical formulations. The collection of 16 peer-reviewed papers covers a broad range of pressing topics on defining the effective stress principle in variably saturated porous media, including topics such as conceptualization, micromechanical formulations, thermodynamic formulations, experimental validation, unification of effective stress with soil water retention and hydraulic conductivity characteristics, and hysteresis behavior of both soil water retention and effective stress. We highlight these contributions in three general categories: theoretical development, experimental validation, and numerical implementation.

Theoretical Development

Using an ideal porous medium with spherical glass beads under pendular water retention regime as an example, Toker et al. (2014), in "Effective Stress and Shear Strength of Moist Uniform Spheres," theoretically showed that the effective stress principle may be represented by the suction-stress characteristic curve (SSCC)-based concept of Lu and Likos (2006). They used the SSCC to predict shear strength behavior measured using triaxial tests for saturated and unsaturated materials. Their study suggests that measured shear strength is greater than the shear strength predicted by the SSCC inferred from apparent

Abbreviations: SSCC, suction-stress characteristic curve; SWRC, the soil water retention curve.

cohesion, implying that suction stress may not be equivalent to isotropic effective stress externally applied to the material. Along a similar line of inquiry, in "Stress Measures Affecting Deformation of Granular Materials," Molenkamp et al. (2014) derived an expression for intergranular stress from a micromechanics perspective by taking into account the spatial distribution of capillary water bridges at particle contacts. They decomposed the effects of capillary water into isotropic and deviatoric parts, and show that the former exclusively describes the suction-induced intergranular stress tensor according to Bishop's effective stress expression.

In recent years, the effective stress principle has been extended to describe mechanical behavior for unsaturated porous media with double porosity. In "A Modified Effective Stress Principle for Unsaturated Swelling Clays Derived from Microstructure," Mainka et al. (2014) present an effective stress expression for unsaturated porous media with dual porosity by taking into consideration electro-chemo-mechanical effects. Their approach uses the self-consistent homogenization technique and shows that the resulting expression reduces to the well known Bishop's expression for unsaturated single porosity media and the Murad and Moyne (2008) expression for swelling saturated porous media.

In "Effective Stress for Saturated and Unsaturated Porous Media—A Differential Approach," Schreyer-Bennethum (2014) revisited Terzaghi's effective stress for saturated and unsaturated isotropic porous media filled with compressible fluids. She presents a theoretical framework based on previously derived thermodynamic definitions of the drained and unjacketed compressibility and total differentials (Bennethum, 2006), which determines how the total pressure relates to strain and changes in fluid pressures. It is shown under simplifying assumptions that one can obtain various forms of the Biot coefficient for saturated porous media and the Bishop parameter for unsaturated porous media. Results are compared with the differential approach of Wang (2000) and the mixture theoretical approaches of Coussy (1995), Borja (2006), and Gray and Schrefler (2007). The formulation helps to clarify definitions of the solid compressibility coefficient, the unjacketed and drained compressibility, and the differential form of the generalized Terzaghi stress principle.

The role of interfaces and interfacial energy on effective stress is one area of focus in recent investigations. This role is further explored in "A Thermodynamic Approach to Effective Stresses in Unsaturated Soils Incorporating the Concept of Partial Pore Deformations," by Dangla and Pereira (2014). Also see Likos (2014), who explored the role of fluid interfaces through pore-scale simulations, discussed below in the Numerical Implementation section. Dangla and Pereira (2014) explored the effect of interface energy on the mechanical behavior of unsaturated soils. In their framework, the concept of the Lagrangian saturation degree, first proposed by Coussy (2007), has been employed. Moreover, the interface energy is assumed to be a function of partial pore deformations rather than total porosity.

◆ Experimental Validation

Experimental tools are the key to validating any theoretical development. Here a few new ways of measuring unsaturated soil behavior are sampled. In "Tensile Strain-Rate Dependency of Pore Water Pressure and Failure Strength of Soil," Hallett et al. (2014) presented details on design and fabrication of a new tensiometer for rapid measurement of suction under both static and dynamic conditions. An extended theory of the Kelvin–Voigt model is developed to interpret the rheological behavior of unsaturated porous materials under dynamic loading conditions. In "Seismoelectric Conversion for the Detection of Porous Medium Interfaces between Wetting and Nonwetting Fluids," Smeulders et al. (2014) designed an experimental setup in which acoustic to electromagnetic wave conversions at the interfaces of wetting and nonwetting phases can be measured, a potential application of which is the detection of interfaces. In addition to the investigation of the interfacial phenomena in unsaturated soils, the method proposed by Smeulders et al. (2014) can be utilized for monitoring oil spills during soil remediation.

It is encouraging to see that many different experimental methods other than the traditional shear strength methods have been explored to validate the effective stress principle. In "Effective Stress in Clays of Various Mineralogy," by Baille et al. (2014), the effective stress principle in clays with different minerals like kaolinite, illite, and montmorillonite was experimentally examined using the SSCC-based effective stress description. Instead of using the Bishop's effective stress parameter χ to define the changes in effective stress due to changes in matric suction or soil water content, Lu and Likos (2004, 2006) defined a unified effective stress concept using the SSCC in lieu of the product of the effective stress parameter and matric suction. This approach avoids the many challenging difficulties in experimental determination or theoretical development of the Bishop's effective stress parameter χ. Lu and Likos (2006) showed that, using the ample existing experimental data in the literature, the SSCC-based effective stress principle is valid for describing the shear strength of variably saturated soils. Lu et al. (2010) further proposed a closed form equation for the SSCC applicable for all types of soils that can be uniquely linked to the soil water retention curve (SWRC). Baille et al. (2014) experimentally demonstrated that the closed form equation for the SSCC can be used to describe void ratio-effective stress relationships for different clays under unsaturated oedometer conditions. The study sheds new light on using the SSCC-based effective stress representation for deformation behavior of variably saturated soils.

The validity of the SSCC-based effective stress principle representation is further demonstrated in "Comparison of Measured and Predicted Suction Stress in Partially Saturated Compacted

Mixtures of Sand and Clay," by Pourzargar et al. (2014) through unsaturated triaxial shear strength tests and unsaturated tensile strength tests for kaolinite–sand mixtures. The work shows that the closed form equation for the SSCC proposed by Lu et al. (2010) can represent both shear strength and tensile strength behavior for soils with non-monotonic behavior in the SSCC. Such behavior is important for soils with a large variation in pore size distribution like sandy soil and fine-coarse soil mixtures. The nonmonotonic behavior poses a theoretical challenge for Bishop's effective stress representation, where the effective stress parameter χ could be either zero or elusively hard to be theorized, when soils are at low water content or high matric suction.

To explore the effect of hydraulic regimes on mechanical soil behavior, Alsherif and McCartney (2014), in "Effective Stress in Unsaturated Silt at Low Degrees of Saturation," presented an experimental evaluation of the effective stress concept in unsaturated compacted silt at low degrees of saturation. Their results reveal that the use of SWRC model parameters obtained from axis translation tests at low suction values can lead to a significant overestimation of the suction stress at high suctions. The careful characterization of the SWRC is, therefore, important when predictions of SSCC at high suction values are sought.

In "Effect of Confining Stress on Soil Water Retention Curve and its Impact on the Shear Strength of Unsaturated Soils," Dastjerdi et al. (2014) re-examined the validity of the effective stress principle by conducting shear strength tests under both wetting and drying conditions. The effect of net normal stress on the hysteresis of both SWRC and the effective stress parameter χ was experimentally examined. They showed that the hysteretic behavior can diminish as the net normal stress increases. They also proposed a new empirical equation for the effective stress parameter χ under both wetting and drying conditions. In "Uniqueness of the Suction Stress Characteristic Curve under Different Confining Stress Conditions," Oh and Lu (2014) showed experimentally that, if the net normal stress is <200 kPa, and if the effective degree of saturation, instead of the volumetric water content, is used to express the SWRC, the hysteresis effect can be ignored. Furthermore, they showed that the hysteresis effect on the SSCC for net normal stress <200 kPa can also be practically ignored. Their results indicate that under wetting conditions, a nearly unique SWRC or SSCC could be defined, provided that the effective degree of saturation is used. Under drying conditions, such uniqueness is not as clear as that of the wetting branch.

⬦ Numerical Implementation

A tangible approach to assess the role of the air–water interface in the effective stress formulation has been provided in "Effective Stress in Unsaturated Soil: Accounting for Surface Tension and Interfacial Area," by Likos (2014). The pore-scale simulations of Likos (2014) indicate that, for drying processes, the percent difference between suction stress, calculated with and without accounting for interfacial forces is zero at 100% saturation, negligible for saturation greater than ~70%, ~10% at 50% saturation, and reaches a maximum of ~50% at 10% saturation. During wetting, the difference increases to as much as 140% at 10% saturation. Experimental determination and detection of such interfaces can be a challenging task, so these simulations shed important new light on the influences of liquid menisci and surface tension on mechanical unsaturated soil behavior.

In "Poroelastic Theory of Consolidation in Unsaturated Soils," Lo et al. (2014) presented a study of three-dimensional consolidation in unsaturated soils. This work is based on the theory of poroelastic behavior in a deformable porous medium containing two immiscible viscous compressible fluids developed by Lo et al. (2002, 2005). Governing equations were derived and formulated in terms of three unknown variables: displacement vector of solid, excess pore water pressure, and air pressure. These equations generalize the Biot consolidation model by replacing the wetting fluid pore pressure with the average fluid pressure. Under the assumption of uniaxial strain and constant total compaction stress, these equations simplify to two coupled diffusion equations for excess pore water and air pressures. A closed-form expression was then derived that specifies the excess pore water and air pressures induced by instantaneous compression under undrained conditions. Analytical solutions for the temporal and spatial evolution of excess pore water and air pressures under various boundary drainage conditions were obtained using the Laplace transform. The analytical solution also yields effective stress and total settlement. Numerical calculations were implemented for unsaturated clay as a representative example. The results revealed that excess pore water pressure dissipates faster in wetter clay, leading to higher effective stress. The loading efficiency was found to be highly sensitive to the initial water saturation.

The effective stress principle has been implemented into computational methods to describe finite deformation for both continuum media and discontinua. In "Finite Deformation and Fluid Flow in Unsaturated Soils with Random Heterogeneity," Song and Borja (2014) presented a finite element model for coupled solid deformation–fluid flow phenomenon in unsaturated porous media with spatially varying density and degree of saturation. They demonstrated that bifurcation of the hydromechanical response appears not only in the form of a softening behavior but also brings about the bifurcation of the state paths on the water retention surface. For discontinua, Wan et al. (2014), in "Micromechanical Analysis of Force Transport in Wet Granular Soils," investigated the effect of pendular water bridges on intergranular stress and demonstrated that such effects are directional or anisotropic in nature and depend on suction as well as packing of the soil grains and fabric. They employed a discrete element method to validate the effective stress principle and examined the anisotropic effects of water bridges at a pendular state on the effective stress variables.

Summary

In summary, we hope that this volume provides the reader with a fresh sample of the vibrant field of the current global research on the principle of effective stress in variably saturated porous media. It was the consensus view at the end of the Utrecht Colloquium that it is not a question of whether or not the principle of effective stress is valid, but rather, it is a question of how effective stress can be further refined, such that its full potential to describe the mechanics of unsaturated soils can be fully exploited.

We envision that another era of renewed interest in refining effective stress principles and subsequently applying them to emerging societal challenges is on the horizon. Researchers from many disciplines, such as vadose zone hydrology, geomorphology, soil science, geotechnical engineering, and environmental engineering, will work together to tackle emerging and outstanding challenges, such as rainfall-induced landslides due to precipitation extremes, infrastructure damages due to swelling and collapsing soil behavior, subsurface waste remediation and containment, and landscape evolution due to changes in climate patterns and the hydrologic cycle. These practical challenges will ensure vibrant advancements in our fundamental understanding of effective stress, hysteretic water retention and effective stress behavior, and water flow and stress–strain laws of variably saturated porous media.

References

Alsherif, N.A., and J.S. McCartney. 2014. Effective stress in unsaturated silt at low degrees of saturation. Vadose Zone J. 13 doi:10.2136/vzj2013.06.0109 (this issue).

Baille, W., S. Tripathy, and T. Schanz. 2014. Effective stress in clays of various mineralogy. Vadose Zone J. 13 doi:10.2136/vzj2013.06.0112 (this issue).

Bennethum, L.S. 2006. Compressibility moduli for porous materials incorporating volume fraction. J. Eng. Mech. 132:1205–1214. doi:10.1061/(ASCE)0733-9399(2006)132:11(1205)

Bishop, A.W. 1959. The principle of effective stress. Tek. Ukebl. 106:859–863.

Borja, R. 2006. On the mechanical energy and effective stress in saturated and unsaturated porous continua. Int. J. Solids Struct. 43:1764–1786. doi:10.1016/j.ijsolstr.2005.04.045

Coussy, O. 1995. Mechanics of porous continua. John Wiley and Sons, New York.

Coussy, O. 2007. Revisiting the constitutive equations of unsaturated porous solids using a Lagrangian saturation concept. Int. J. Numer. Anal. Methods Geomech. 31:1675–1694. doi:10.1002/nag.613

Dangla, P., and J.M. Pereira. 2014. A thermodynamic approach to effective stresses in unsaturated soils incorporating the concept of partial pore deformations. Vadose Zone J. 13. doi:10.2136/vzj2013.06.0110 (this issue).

Dastjerdi, M.H.T., G. Habibagahi, and E. Nikooee. 2014. Effect of confining stress on soil water retention curve and its impact on the shear strength of unsaturated soils. Vadose Zone J. 13. doi:10.2136/vzj2013.05.0094 (this issue).

Gray, W.G., and B.A. Schrefler. 2007. Analysis of the solid phase stress tensor in multiphase porous media. Int. J. Numer. Anal. Methods Geomech. 31:541–581. doi:10.1002/nag.541

Hallett, P.D., T. Baumgartl, J.P.K. Seville, R. Horn, and A.R. Dexter. 2014. Tensile strain-rate dependency of pore water pressure and failure strength of soil. Vadose Zone J. 13. doi:10.2136/vzj2013.06.0098 (this issue).

Khalili, N., F. Geiser, and G.E. Blight. 2004. Effective stress in unsaturated soils: Review with new evidence. Int. J. Geomech. 4:115–126. doi:10.1061/(ASCE)1532-3641(2004)4:2(115)

Likos, W.J. 2014. Effective stress in unsaturated soil: Accounting for surface tension and interfacial area. Vadose Zone J. 13. doi:10.2136/vzj2013.05.0095 (this issue).

Lo, W.C., G. Sposito, and H. Chu. 2014. Poroelastic theory of consolidation in unsaturated soils. Vadose Zone J. 13. doi:10.2136/vzj2013.07.0117 (this issue).

Lo, W.C., G. Sposito, and E. Majer. 2002. Immiscible two-phase fluid flows in deformable porous media. Adv. Water Resour. 25(8–12):1105–1117.

Lo, W.C., G. Sposito, and E. Majer. 2005. Wave propagation through elastic porous media containing two immiscible fluids. Water Resour. Res. 41. doi:10.1029/2004WR003162

Lu, N., J. Godt, and D.T. Wu. 2010. A closed-form equation for effective stress in unsaturated soil. Water Resour. Res. 46:1–14 doi:10.1029/2009WR008646.

Lu, N., and W.J. Likos. 2004. Unsaturated soil mechanics. John Wiley and Sons, New York.

Lu, N., and W.J. Likos. 2006. Suction stress characteristic curve for unsaturated soil. J. Geotech. Geoenviron. Eng. 132:131–142. doi:10.1061/(ASCE)1090-0241(2006)132:2(131)

Mainka, J., M.A. Murad, C. Moyne, and S.A. Lima. 2014. A modified effective stress principle for unsaturated swelling clays derived from microstructure. Vadose Zone J. 13. doi:10.2136/vzj2013.06.0107 (this issue).

Molenkamp, F., R.R. de Jager, and F.A.J.M. Mathijssen. 2014. Stress measures affecting deformation of granular materials. Vadose Zone J. 13. doi:10.2136/vzj2013.07.0130 (this issue).

Murad, M.A., and C. Moyne. 2008. A dual-porosity model for ionic solute transport in expansive clays. Comput. Geosci. 12:47–82. doi.org/10.1007/s10596-007-9060-z

Oh, S., and N. Lu. 2014. Uniqueness of the suction stress characteristic curve under different confining stress conditions. Vadose Zone J. 13. doi:10.2136/vzj2013.04.0077 (this issue).

Pourzargar, A., D. König, G. Heibrock, M. Datcheva, and T. Schanz. 2014. Comparison of measured and predicted suction stress in partially saturated compacted mixtures of sand and clay. Vadose Zone J. doi:10.2136/vzj2013.06.0114 (this issue).

Schreyer-Bennethum, L. 2014. Effective stress for saturated and unsaturated porous media—A differential approach. Vadose Zone J. 13. doi:10.2136/vzj2013.06.0108 (this issue).

Smeulders, D.M.J., N. Grobbe, H.K.J. Heller, and M.D. Schakel. 2014. Seismoelectric conversion for the detection of porous medium interfaces between wetting and nonwetting fluids. Vadose Zone J. 13. doi:10.2136/vzj2013.06.0106 (this issue).

Song, X., and R.I. Borja. 2014. Finite deformation and fluid flow in unsaturated soils with random heterogeneity. Vadose Zone J. 13. doi:10.2136/vzj2013.07.0131 (this issue).

Terzaghi, K. 1923. Die Berechnung der Durchlässigkeitsziffer des Tones aus dem Verlauf der hydrodynamischen Spannungserscheinungen. (In German.) Sitz. Akad. Wissen. Wien, Math-Naturw. Kl. Abt. IIa. 132:105–124.

Terzaghi, K. 1936. The shear resistance of saturated soils. In: Proc. 1st Int. Conf. Soil Mech. Found. Eng. Cambridge, MA. p. 54–56.

Toker, N.K., J.T. Germaine, and P.J. Culligan. 2014. Effective stress and shear strength of moist uniform spheres. Vadose Zone J. 13. doi:10.2136/vzj2013.07.0129 (this issue).

Wan, R., S. Khosravani, and M. Pouragha. 2014. Micromechanical analysis of force transport in wet granular soils. Vadose Zone J. 13. doi:10.2136/vzj2013.06.0113 (this issue).

Wang, H.F. 2000. Theory of linear poroelasticity with applications to geomechanics and hydrogeology. Princeton Univ. Press, Princeton, NJ.