Post-Construction Deformation of Compacted Fills Caused by Wetting

Timothy D. Stark, Ph.D.[1]**; and Stephen T. Wilk**[2]

[1]Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana-Champaign, Urbana, IL 61801. E-mail: tstark@illinois.edu
[2]Dept. of Civil and Environmental Engineering, Univ.of Illinois at Urbana-Champaign, Urbana, IL 61801. E-mail: swilk2@illinois.edu

Abstract

This paper presents a modified constitutive model to predict post-construction movements of compacted fills due to wetting based on the results of anisotropically-consolidated undrained (ACU) triaxial compression tests. The constitutive model is coded in the FISH language of the finite difference numerical software FLAC. The model allows deformation along the major and minor principal stress directions instead of the vertical and radial directions and user-defined wetting fronts to predict movement with time. The lateral and vertical progressive surface movement induced by top-down wetting is simulated and the results illustrate how the differential vertical and lateral movement at the ground surface can change during the course of top-down wetting.

INTRODUCTION

This paper presents a modified constitutive model for predicting post-construction movement of compacted fills due to wetting. This is an important topic due to the large number of residential and commercial developments on or near compacted fill slopes. Predicting the magnitude and location of deformation are important for developing initial design and/or a repair strategy. Post-construction movement usually does not pose a threat to the structural aspects of the structure but results in cosmetic damage, such as cracked or separated concrete flatwork, cracks in masonry walls and concrete slabs, poor performance of pavements, and ineffective drainage features. However, some cases have resulted in structural damage and demolition of the impacted structure (Day 1999). The level of damage appears to be related to the magnitude of wetting, soil type, degree of compaction, fill depth and confinement, slope height and inclination, and structure setback from the slope crest.

In attempt to better understand and predict soil and slope response to loading and progressive wetting, the two-dimensional (2D) finite difference numerical software FLAC v6.0 distributed by Itasca (2008) was used to predict ground surface and structure deformations near a compacted fill slope. The FISH language code incorporated into FLAC incorporates multi-dimensional swelling and hydrocompression mechanisms to predict post-construction movement of compacted fills with time. In this paper, the FISH code is used to analyze a typical slope to investigate slope movement with time and wetting.

BACKGROUND

Compacted soils can display significant volume change when subjected to changes in moisture content (Brandon et al. 1990; Stark and Bixby 1991; Coduto 2001; Noorany and Scheyhing

2015). This soil movement can cause heave, hydrocompression/settlement, and lateral movement depending on depth and location, all of which can damage flatwork, foundations, basements, and patios.

In a one-dimensional (1D) situation, e.g., confined fill, moisture content variation and overburden pressure (σ_{yy}) are the two important factors controlling volume change in compacted soil and especially expansive soils (Terzaghi et al. 1996; Coduto 2001). On a microscopic level, water influx results in an electrical interaction between the clay particle and surrounding environment, which can cause the soil to swell and/or hydrocompress depending on the depth, i.e., applied stress. This swelling/hydrocompression is more common with smaller, more platey clay particles such as montmorillonite and clays with higher plasticity indices (PI >25) (Coduto 2001). Expansion occurs when small overburden pressures cannot counteract the expansive stresses generated by the clay particles absorbing water, which causes separation of the clay minerals (Stark and Bixby 1991). Conversely, hydrocompression occurs when large overburden pressures resist the expansive stresses described above by rearranging the clay particles into a more compact state. The *swelling pressure* (σ_s) is the overburden stress that resists the expansive stresses so no volume change occurs due to equilibrium of expansive and contractive forces (Stark and Bixby 1991). Therefore, the overburden stress determines the swell/hydrocompression potential, i.e. whether the soil swells or hydrocompresses and magnitude of swelling/hydrocompression when fully wetted, which is typically constant once the fill and structural construction has been completed. The moisture content determines the extent of swelling/hydrocompression to its potential and is expected to change over time from the gradual wetting of the slope fill.

Post-construction overburden stresses often remain constant with time so swell/hydrocompression behavior becomes problematic following changes in moisture content or soil suction due to precipitation, evaporation, subsurface water, irrigation, etc., beneath or nearby existing structures. In general, hydraulic conductivity of compacted fill is low due to soil type and densification by compaction so equilibrium of fill wetting may take months to years depending on the rate and magnitude of water infiltration (Stark and Bixby 1991). This infiltration is facilitated by the suction pressures present in compacted fill because the fill is initially unsaturated. During infiltration, the advancing wetting front raises the moisture content, "activating" the swell or hydrocompression behavior of the soil with the behavior being dictated by the surrounding *in-situ* stresses.

The surface movement is dependent on the depth of wetting which triggers expansion at stresses less than or equal to σ_s and hydrocompression at stresses greater than σ_s. This results in expansion and hydrocompression occurring at different times and different depths as the wetting front moves through a compacted fill. For example, shortly after construction the ground surface will heave if expansive soils are present because generally only the near surface soil, i.e., low overburden pressures, will experience wetting, i.e., an increase in moisture content. As the wetting front proceeds to greater depths where the overburden pressure is greater than σ_s, hydrocompression will occur and the ground surface will begin to settle due to hydrocompression of deeper soil. This may result in situations where a structure is repaired due to expansive soil damage only to be further damaged by subsequent hydrocompression. It is also possible that the depth of wetting is such that zero net ground surface displacement is observed even though expansion and hydrocompression are occurring in the fill, which is important when designing foundations. In summary, it is important to model the time-dependent nature of wetting front migration and surface displacements with time through compacted fills, which is the objective of the proposed model.

DEFORMATION MODELS

In situations where structures are constructed near a compacted fill slope or the fill is not confined by valley or canyon walls, fill movement will be multi-dimensional resulting in lateral fill extension (LFE) (Noornay and Scheyhing 2015). This produces an anisotropic stress state at and near the slope face, which along with anisotropic swelling, is not adequately captured using a 1D expansion or hydrocompression model (Noorany et al. 1992). The results of isotropically-consolidated undrained (ICU) and anisotropically-consolidated undrained (ACU) triaxial swelling tests (Noornay et al. 1992) show the vertical and radial swelling behavior to be logarithmically related to their respective stress components and different than 1D oedometer test results. Triaxial swelling tests performed at various K-values ($K = \sigma_h/ \sigma_v = \sigma_3/ \sigma_1$) show: (1) isotropic triaxial stress conditions (vertical stress = radial stress) result in isotropic volume changes (vertical swelling strain = radial swelling strain) and (2) as the K-value decreases, the radial (minor) swelling strain increases while the vertical (major) swelling strain decreases due to a reduction in confinement in the radial direction (Noorany et al., 1992). This implies the value of K affects the swelling behavior. The swelling reaction due to K is unclear but Noorany and Scheyhing (2015) suggest K-values of 0.7 for compacted fills prior to swelling.

The constitutive relation used by Noorany and Scheyhing (2015) is implemented herein because of its simplicity and laboratory-based development. Noorany et al. (1992) present vertical and radial swelling strains measured in ACU triaxial swell tests for various vertical and radial stresses. Thus, the resulting constitutive relation is limited to situations that are represented by the ACU triaxial compression data in Noorany et al. (1992) but is still useful in predicting the general deformation of compacted fill slopes. Noorany et al. (1999) implemented the model in a 2D finite difference model using FLAC because the FISH option in FLAC allows the coding of user-defined constitutive models. This allows user defined expansion and compression relationships to be included in the model.

This paper updates the plane strain FISH code created by Noorany et al. (1999) to reflect the updated swelling model from Noorany and Scheyhing (2015) and makes swelling/compression strains a function of the major and minor principal stresses (σ_1 and σ_3) instead of the vertical and horizontal stresses (σ_{yy} and σ_{xx}). This will better simulate compacted fill slope behavior because the major principal stress is likely to be oriented away from the vertical direction (see Figure 1). A logarithmic constitutive relationship is used in the code and is shown below where compression is positive and expansion is negative.

$$e_1 = n_1 n_2 n_3 c_1 \log\left\{a_1\left(\frac{\sigma_1}{p_a}\right)\right\} \qquad e_{yy} \leq e_{yy,max} \qquad (1)$$

$$e_3 = n_1 n_2 n_3 c_3 \log\left\{a_3\left(\frac{\sigma_1}{p_a}\right)\right\} \qquad e_{xx} \leq e_{xx,max} \qquad (2)$$

Here, e is the swelling/compression strain, a_1, c_1, a_3, and c_3 are non-dimensional constants estimated from laboratory triaxial swell tests (Noorany et al. 1992), p_a is atmospheric pressure (101.3kPa), n_1 is a reduction factor from partial wetting, n_2 is a reduction coefficient to account for oversize particles in the fill material, and n_3 is a reduction coefficient for testing scale effects (Noorany and Scheyhing 2015).

Constants a_1 and a_3 relate to the swelling pressure (σ_s) and c_1 and c_3 relate the change in swelling strain with a logarithmic change in major principal stress (Noorany et al. 1992). These values can be determined from ACU triaxial compression tests (Noorany and Scheyhing 2015) or back-calculated from field measurements. The reduction factors are included to give the user flexibility to incorporate the influence of partial wetting, oversized particles, and scale effects without changing the material constants *a* and *c* (Noorany and Scheyhing 2015). In the FISH code, reduction factors n_2 and n_3 are treated as material properties while the partial wetting reduction factor (n_1) is treated as an external condition in which n_1=0.0 represents the compacted soil moisture content and n_1=1.0 represents the fully saturated condition. This gives the user the option to apply complex wetting fronts, e.g., top-down wetting or side wetting, in the analysis. This paper assumes n_2 or n_3 are equal to 1.0, the typical value for fill analyses, and more in-depth explanations of n_2 and n_3 can be found in Noorany and Scheyhing (2015). To clarify, the model is a purely mechanical model with a manually inputted wetting front and hydro-mechanical behavior is not simulated.

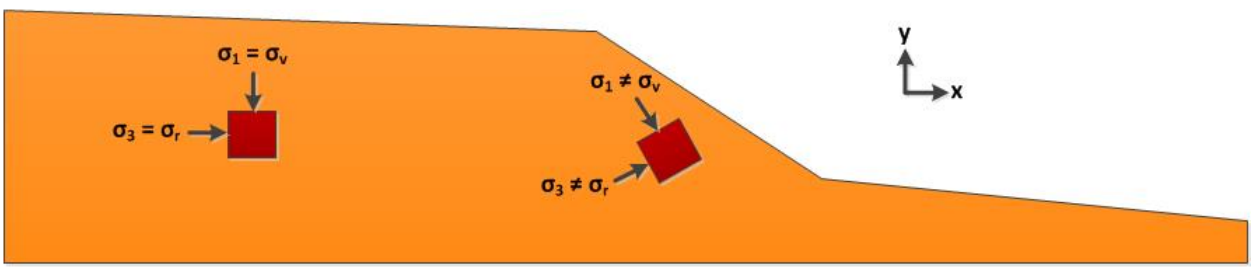


Figure 1. Illustration showing the major and minor principal stress directions near the slope face.

COMPACTED FILL SLOPE MODEL

The proposed FISH swelling model incorporates the following three main factors: (1) stress state, (2) plane strain two-dimensional swelling, and (3) partial wetting. The stress state of the compacted fill slope is difficult to replicate exactly but the magnitudes and orientations of the major principal stress (σ_1) can be reasonably estimated. In FLAC, the initial fill stress state is generated by simulating a single row of elements, compacting that row with gravity loads, and repeating the process until the entire slope is built-up as in typical construction. The value of K is assumed within the swelling properties of the soil so an accurate confining pressure (σ_3) is not a required input parameter for the numerical model.

With the numerical model estimating the major principal stress magnitude and direction, the 2D swelling of each element is replicated by initializing the internal stresses using a FISH code. The user selects which elements will experience wetting and the reduction factor (n_1) is used to simulate partial wetting of these elements. This setup can simulate the final wetting behavior or intermediate wetting steps if tracking slope movement with time.

A typical example of the expansive behavior of a fully wetted unconfined fill slope is displayed in Figure 2. This slope is identical to the fully wetted slope in Figures 3 and 4 and the swell/shrink material properties used in the analysis are shown in Table 1 (Noorany et al. 1999).

The arrows in Figure 2 represent the swell/shrink displacement vector of each element within the model and conceptually illustrate the differential heave along the ground surface and lateral extension near the slope face. The magnitudes of surface heave/compression and lateral extension are dependent on the expansive/compressive potential of the fill soil, i.e. soil makeup and water content, and depth and shape of the fill.

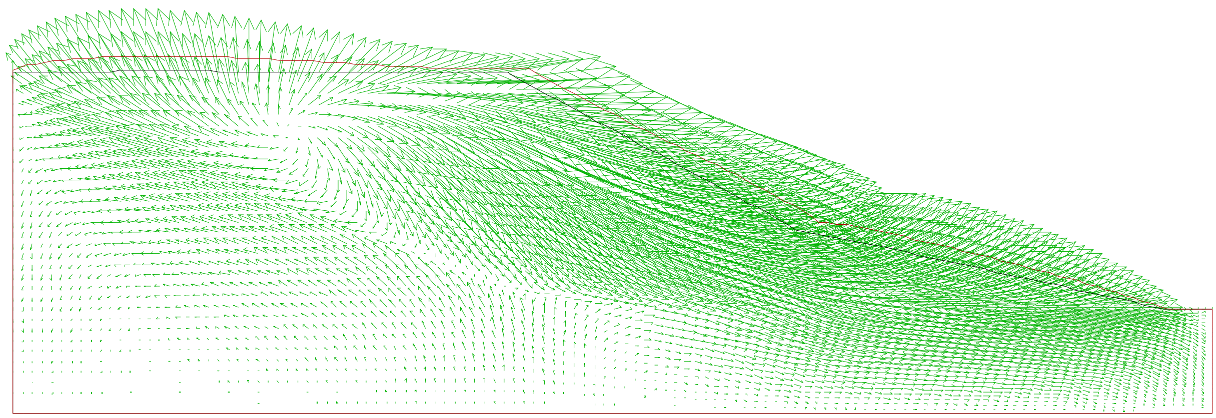


Figure 2. Illustration of vertical and lateral expansion from wetting of unconfined fill slope (maximum vector length = 186 mm = 7.33 inches).

Table 1. Swell/shrink constants used in analysis shown in Figure 2.

a_1	a_3	c_1	c_3	n_1	n_2	n_3
1.533	0.436	-0.215	-0.0187	0.85	1.0	1.0

Time-dependent Behavior. In compacted fills, moisture infiltration is expected to start after rainfall or irrigation and can eventually wet the entire slope. The exact sources and mechanics of wetting vary, however irrigation, excessive watering, precipitation, side seepage, and broken pipes are expected to play a significant role in the wetting (Dye 2008). This gradual wetting behavior will "activate" the swelling and hydrocompression behavior of the fill material at different time periods, causing surface profiles to change with time. This behavior can be simulated in the swelling model with the partial wetting reduction factor (n_1). The fully wetted fill assumes an n_1 value of 0.85 because moisture contents in the field rarely reach laboratory levels (Coduto 2001).

The top-down wetting of an unconfined fill is used to illustrate the use of the partial wetting reduction factor (n_1). If the top-down wetting is simulated in a 1D situation, e.g., confined fill, the ground surface will experience initial heaving followed by hydrocompression as the phreatic surface migrates further into the fill. By simulating top-down wetting on an unconfined fill, the effect on both the lateral and vertical movement can be analyzed. It is assumed the phreatic surface descends from the ground surface at a constant pace, with simulations occurring every 1.5 m (5 feet) until the maximum 13.8 m (45 foot) fill depth is reached. According to Stark and Bixby (1991), wetting depths of 3, 6, 9, and 12 meters require wetting times of around 1, 2, 3, and 4 years, respectively, assuming Stadium Conglomerate Formation fill that is common in the San Diego area. Diagrams of the fill slope with wetting depths of 3, 6, 9, and 13.8 meters are displayed in Figure 3 along with the fill dimensions. The swelling values are displayed in Table 1.

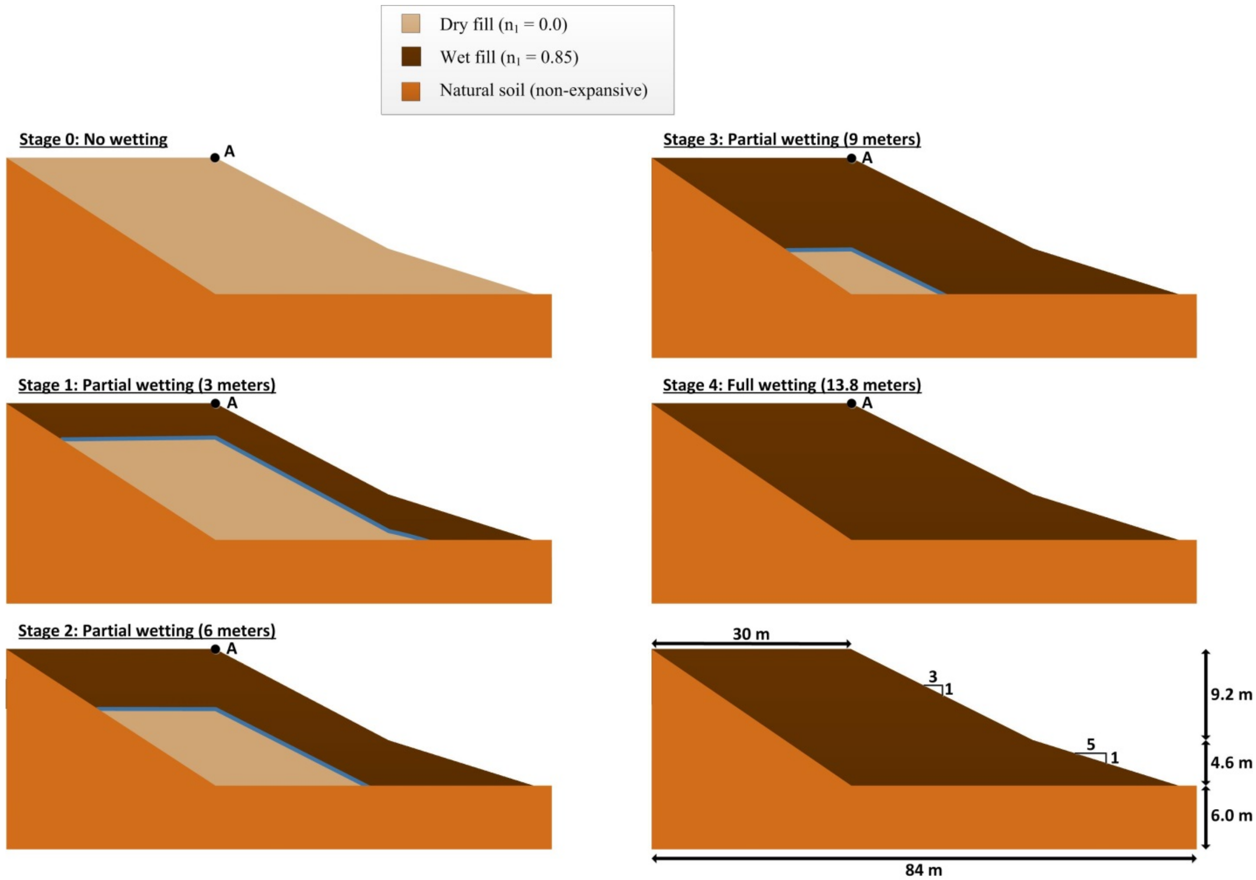
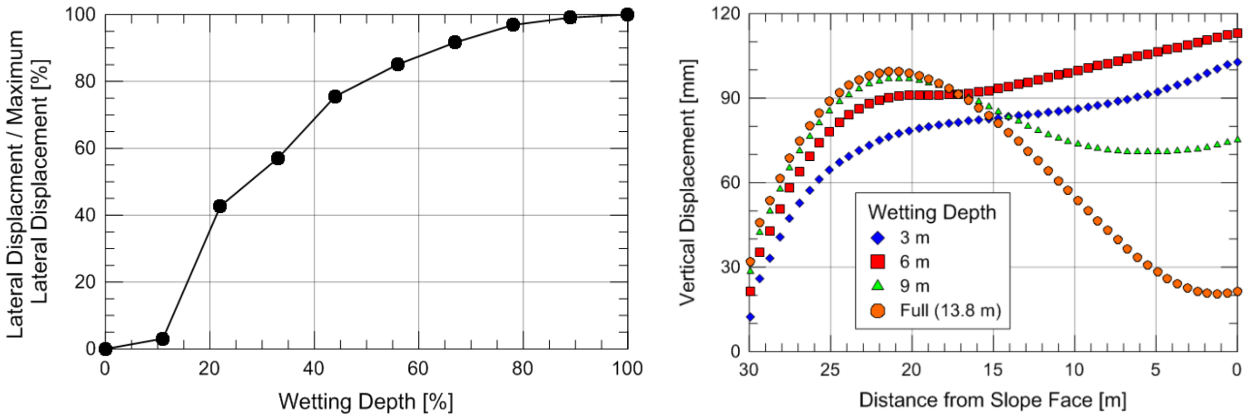


Figure 3. Top-down wetting of unconfined fill slope with wetting depths of 3, 6, 9, and 13.8 meters.

Assuming the moisture movement in Figure 3, the lateral displacement at the slope face (location A in Figure 3) is plotted with increasing wetting depth (see Figure 4(a)). The maximum lateral displacement at Location A is 110 mm (4.33 inches). The majority of ground surface lateral displacement occurs between 20 to 60% of the wetting depth, with 80% of the lateral displacement occurring within the first 50% of wetting. Results from Noorany et al. (1992) and Noorany and Scheyhing (2015) also show that lateral movement is minimal during the later stages of wetting. This is important because pre-wetting of the fill in advance of construction may reduce the amount of lateral movement experienced by buildings and footings.

Figure 4(b) shows the change in differential vertical displacement at the ground surface as wetting occurs. Location A in Figure 3 represents x=0. While the lateral displacement continually increases with wetting, e.g., expands outwards from the slope, the differential vertical displacement changes significantly during wetting. In the initial wetting stages of 3 to 6 meters (10 to 20 feet), represented by the blue diamonds and red squares, respectively, the greatest surface heave is located at the slope face. However, as the lower soil becomes wetted, hydrocompression begins and the ground surface near the slope face begins to settle. This results in significant changes in differential vertical movement along the ground surface over time and is likely to cause structural and foundation damage. While this analysis shows only a single example, the exact behavior of each slope will be dictated by the unique fill geometry and final vertical displacements will be dependent upon fill depth.



(a) (b)

Figure 4. (a) Lateral displacements at slope face and (b) vertical displacements along ground surface for various wetting depths.

CONCLUSION

Slope movement from the swell, shrink, and compression of structural fill has cost millions of dollars in structural and aesthetic repairs. A numerical model that can predict compacted fill movement especially near fill slopes may be valuable in addressing these problems by allowing engineers to understand the pattern, magnitude, and rate of fill movement. Such a model is presented herein and can be used in conjunction with the FLAC software to replicate the three important factors causing lateral slope movement, i.e., initial stress state, 2D swelling, and degree of saturation.

While the exact lateral movement behavior is dependent on fill geometry, a few trends were observed from the progressive wetting FLAC analysis presented herein:

- The majority (~80%) of lateral surface displacement occurs during wetting of the upper half of the slope while the differential vertical surface displacements change significantly during the course of wetting.
- Soil at the slope face may initially heave during early stages of wetting then subsequently hydrocompress as the wetting reaches deeper depths so slope movement and distress will be time dependent.
- If expansive soils are present, lateral movement will occur near the slope face and differential heave will occur in areas of varying fill depth.
- Possible remedial measures include pre-wetting the fill slope or compacting wet of optimum, constructing structures with a greater setback, and/or allowing the slope to equilibrate before structure construction proceeds to reduce post-construction lateral movements.

ACKNOWLEDGMENTS

The authors would like to acknowledge the many helpful suggestions provided by Iraj Nooray for improving the analysis and this paper.

REFERENCES

Brandon, T.L., Duncan, J.M., and Gardner, W.S. (1990). "Hydrocompression settlement of deep fills." *J. Geotech. Eng*., 10.1061/(ASCE)0733-9410(1990)116:10(1536), 1536-1548.

Coduto, D.P. (2001). *Foundation Design: Principles and Practices*, 2nd Ed., Prentice-Hall, Upper Saddle River, New Jersey, 655.

Day, R.W. (1999). *Forensic Geotechnical and Foundation Engineering*, McGraw-Hill, New York, NY.

Dye, H.B. (2008). "Moisture movement through expansive soil and impact on performance of residential structures." Ph.D. Dissertation, Arizona State Univ., Tempe, AZ.

Itasca Consulting Group, Inc. (2008). "FLAC – Fast Lagrangian Analysis of Continua," Version 6.0, Itasca Consulting Group, Inc., Minneapolis, MN.

Noorany, I., Sweet, J.A., and Smith, I.M. (1992). "Deformation of fill slopes caused by wetting." *Proc., Stability and Performance of Slopes and Embankments II,* Geotechnical Special Publication No. 31, ASCE, New York, NY, 1244 – 1257.

Noorany, I., Frydman, S., and Detournay, C. (1999). "Invited Lecture: Prediction of soil deformation due to wetting." *FLAC and Numerical Modeling in Geomechanics*. A.A. Balkema, 101 – 107.

Noorany, I. (2013). "Invited Lecture: Lateral Extension in Expansive Soils." ASCE GeoCongress, San Diego, California.

Noorany, I., and Scheyhing, C. (2015). Lateral Extension of Compacted-Fill Slopes in Expansive Soils. *Journal of Geotechnical and Geoenviornmental Engineering,* Vol 14. No 1.

Stark, T.D., and Bixby. W.G. (1991). "Finite element analysis of partially saturated seepage through compacted fills." In: *Transportation Research Record 1309,* TRB, National Research Council, Washington, D.C., 25 – 34.

Terzaghi, K., Peck, R.P., and Mesri, G. (1996). *Soil Mechanics in Engineering Practice*, Wiley & Sons, New York, NY.