The effect of microbes on the stability of an unsaturated tropical slope

Bruna de Carvalho Faria Lima Lopes[1*]

[1]Newcastle University, Civil and Geospatial Engineering, NE1 7RU School of Engineering. Newcastle upon Tyne, UK

Abstract. Conventional geotechnical practice considers that soil is an inert construction material and its engineering properties do not change with time. However, soil is a living ecosystem, and its engineering properties naturally change as a stable ecological system is gradually established following initial construction. Over the last few decades, researchers started exploring a way to engineer some microorganisms' activities in order to solve problems in geotechnical engineering. This paper assesses the effect of a biostimulated Microbial Induced Calcite Precipitation (MICP) on the stability of an unsaturated tropical slope. For that, data from an experimental characterisation study carried out for a tropical soil was used. For the assessment of the stability of the slope, a critical rainfall for the region was considered and the pore water pressure distribution was obtained. The stability of the slope was assessed using a 'simplified' shear strength criterion formulated in terms of unsaturated cohesion. Results show that the MICP treatment contributes to the stability of the slope. This positive contribution is more significant than the contribution of suction towards the stability of the slope.

1 Introduction

Conventional geotechnical practice considers that soil is an inert construction material and its engineering properties do not change with time. However, soil is a living ecosystem, and its engineering properties naturally change as a stable ecological system is gradually established following initial construction, and these changes alter system performance [1,2]. Up until very recently, when biogeotechnics emerged as a field of study, biological activity was rarely acknowledged, except when it impacted negatively on geotechnical properties of soils [3]. It is now recognised that some of those microorganisms' activities could be harnessed to solve problems in geotechnical engineering. Over the last few decades, microbial applications have been explored more widely [4].

Most of the research efforts on the field of biogeotechnics is directed to biocementation through Microbial Induced Calcite Precipitation (MICP) [5]. MICP is a biogeochemical process, that occurs in soil and produces permanent inorganic precipitate serving as a binding between soil grains [6]. The majority of MICP research has concentrated on applications for soil strengthening in temperate climate [4], even if it is well known that biocementation also influences soil structure and consequently other soil properties. MICP research efforts also focuses on the addition of bacteria to the soil, an approach known as bioaugmentation [6]. However, injection of specialised foreign bacterial strains is associated with a number of challenges, such as survivability of exogenous bacteria, uneven distribution in the soil, time needed for the permeation of bacteria, additional costs for the cultivation of the bacteria and special cautions required while mixing the bacterial material [7–9]. Besides, the approach can also raise environmental concerns associated with introducing bacteria into the soil [10]. Recent research has revealed that MICP may occur in soils using bacteria that are naturally present, a process known as biostimulation [8,11]. The biostimulated approach has the potential to be scalable, economically advantageous and poses less risks to the environment [12].

The biostimulated MICP process relies on the community of microbes that naturally exist in soil. And although major knowledge gaps in soil biogeography still exists [13–15], microbial communities are expected to vary widely. Thus, understanding the susceptibility of the technique for any application is not a straightforward task. The challenge gets even more complicated when the application involves complex soils, such as tropical residual soils.

In this light this paper assesses the effect of biostimulated MICP on the stability of a slope on a tropical residual soil. For that, data from an experimental characterisation study carried out for a tropical soil [16] from Brasilia, Brazil, is used. For the assessment of the stability of the slope, two scenarios are considered: a reference one where the soil is not stimulated to produce MICP and a second scenario where the soil is stimulated to produce MICP. For both scenarios, a critical rainfall for the tropical region is considered and the pore water pressure distribution was obtained. The stability of the slopes was assessed using a 'simplified' shear strength criterion formulated in terms of unsaturated cohesion. In this way the

---

* Corresponding author: bruna.lopes@newcastle.ac.uk

contribution of suction to the shear strength of the soil is taken into account in the two scenarios considered.

2 Materials and methods

2.1 Control and inoculated specimens' characterisation

The experimental work was carried out by Gonzalez [16]. Undisturbed block samples (0.3 x 0.3 x 0.3m) were collected at 1, 2, 3, 4, and 5m depth in Santa Maria (Federal District, Brazil) in April when the groundwater level was approximately 6m below ground surface. The material in this region is a tropical residual soil classified as Low Plasticity Clay (CL) according to the Unified Soil Classification System (USCS). The minerals identified by X-ray diffraction are Gibbsite, Kaolinite, Quartz, Hematite, Goethite and Anatase.

Half the undisturbed blocks received a one-off injection of B4 nutrients [17,18] and were left for 15 days at environmental conditions similar to the average conditions recorded at the site (25°C and 60% relative humidity) to stimulate the grow of MICP bacteria (inoculated specimens), while the other half received no treatment (control specimens).

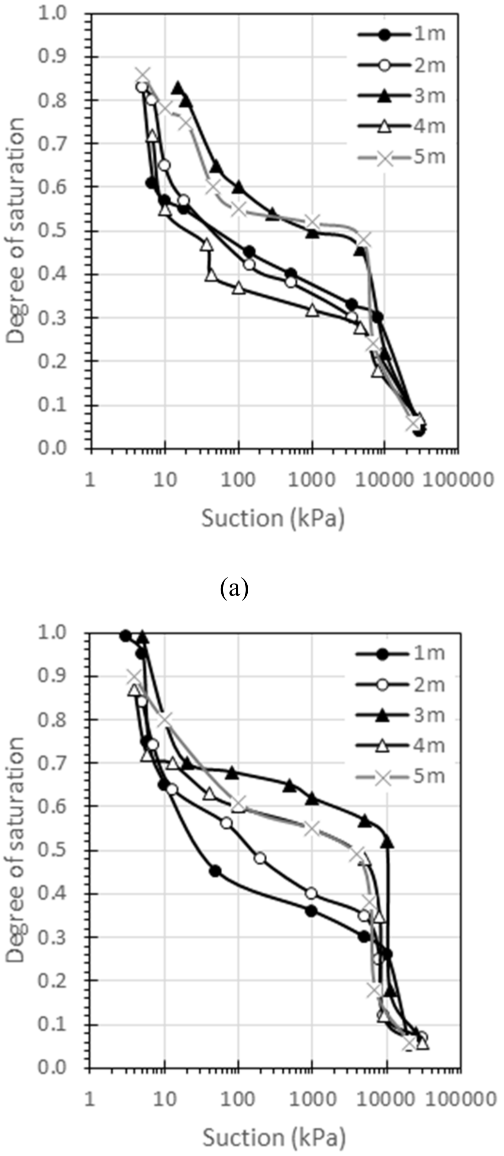
Specimens of all undisturbed blocks underwent several characterisation tests. The bulk unit weight, void ratio, shear strength parameters (obtained via direct shear tests), and saturated permeability (obtained via constant head test) of control and inoculated specimens are presented in Table 1 while soil water retention curves (obtained via filter paper technique) are presented in Fig. 1.

Table 1. Soil parameters (after [16])

	Depth (m)	γ (kN/m^3)	e_o	c' (kPa)	ϕ' (°)	k_{sat} (m/day)
Control	1	16	1.9	7	29	3.6
	2	16	1.8	15	22	2.7
	3	18	1.1	6	25	1.6
	4	19	0.9	5	35	2.0
	5	19	0.9	8	38	6.2
Inoculated	1	16	1.8	5	29	1.4
	2	16	1.7	5	24	1.0
	3	18	1.1	16	26	1.8
	4	19	0.9	12	39	2.0
	5	19	0.8	23	36	1.8

2.2 Slope geometry and ground conditions

A hypothetical 1:1 slope, 5m tall was considered. The groundwater table was considered at 6m below ground level. The ground profile assumed is presented in Fig. 2, with each layer characterised by the soil parameters of the respective representative specimens collected at different depths on site. To access the effects of biostimulated MICP, two scenarios were considered: the first one where the soil layers are representative of control specimens and the second one where the soil layers are representative of inoculated specimens.



(a)

(b)

Fig. 1. Soil water retention curves (a) control and (b) inoculated specimens. (after [16])

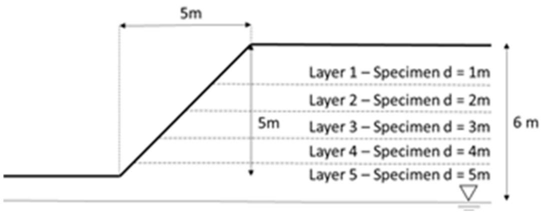


Fig. 2. Slope geometry and ground conditions

2.3 Design rainfall

In order to determine the appropriate design rainfall to assess the stability of the slope, the rainfall data recorded by the meteorological station located in Gama (Ponte Alta A046), Brazil [19] was analysed using the double exponential probability distribution known as the

Gumbel distribution. The Gumbel distribution curve is written as follows.

$$P(H < h; a, b) = e^{-e^{-(\frac{h-a}{b})}} \tag{1}$$

where H and h are precipitations in mm, a and b are Gumbel fitting parameters (for 24hrs rainfall a = 68mm, b = 11mm, for 48hrs rainfall a = 78mm, b = 24mm) and P (H < h; a, b) is the probability that precipitation H is smaller than h. The return period (T) curves for both precipitation durations derived from Gumbel distribution, are given by:

$$T = \frac{1}{1-P(H<h;a,b)} \tag{2}$$

Fig. 3 shows the return period of the maximum precipitation with durations of 24 and 48hrs data series of the past five years fitted with Gumbel distribution. A return period of 100 years was considered representative and significant for the analyses. Thus, two analyses were performed, taking as design intensity 130mm/day for 1 day and 105mm/day for 2 days (for a total of 210mm). At first, these numbers might seem unrealistically high however tropical storms are becoming more frequent, therefore the use of such values are justifiable.

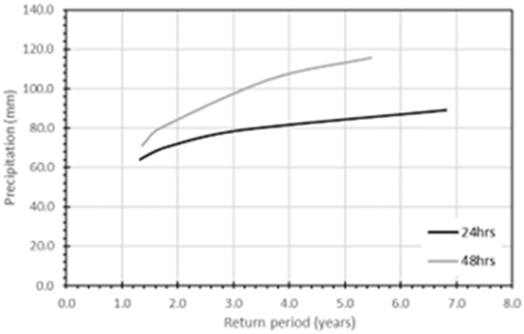


Fig. 3. Return period of the maximum precipitation with durations of 24 and 48hrs data series of the past five years fitted with Gumbel distribution (Gama Ponte Alta - A046).

2.4 Water flow analysis

The water flow partial differential equation was solved via a numerical code based on Finite Element Method under transient analysis. The mesh consisted of 1305 nodes and 1230 elements, the boundary conditions at ground level were water flux equivalent to the design rainfall considered, which is a conservative simplification.

The initial pore water pressure distribution was assumed hydrostatic with groundwater table at 6m below ground level.

The unsaturated hydraulic conductivity, k_{unsat}, was determined following Kozeny-Carman model [20] with:

$$k_{unsat} = k_{sat}.Sr^3 \tag{3}$$

where Sr is the degree of saturation.

The experimental water retention functions complete the input data required to solve the water flow partial differential equation.

2.5 Simplified shear strength failure criteria

The shear strength criteria for soils subjected to suction can be written as follows [21–26]:

$$\tau = c' + \sigma.tan\phi' + f(s, Sr).tan\phi' \tag{4}$$

where τ is the shear strength, c' is the cohesion, σ is the total normal stress to the failure plane, ϕ' is the saturated angle of shearing resistance *f(s,Sr)* is a function of suction (s) and degree of saturation (Sr), that represents the contribution of suction and degree of saturation to the shear strength of the soil, $\Delta\tau_{s,Sr}$.

Tarantino and El Mountassir [27] showed that for sandy and silty soils the simplest assumption for this function is supported by experimental evidence in which:

$$f(s, Sr) = s.Sr \tag{5}$$

However, for clayey soils eq. (5) overpredicts the shear strength of the soil. Tarantino and El Mountassir [27], then discussed that the failure criterion for clayey soils should be written by considering a different function for *f(s,Sr)* as suggested by Vanapalli et al. [25]:

$$f(s, Sr) = s.Sr^k \tag{6}$$

where k is a constant.

The shear strength criterion given by eq. (6) is difficult to use in engineering practice because the parameter k is soil-specific and requires tests on unsaturated samples to be carried out. However, a simplified, more conservative, shear strength criterion, can be developed making use of information more readily available or easier to estimate. The contribution of suction to the shear strength of the soil, $\Delta\tau_{suction}$, can be written as:

$$\begin{aligned} \Delta\tau_{suction} &= s.tan\phi' \qquad s \le s_{AEV} \\ \Delta\tau_{suction} &= s_{AE}.tan\phi' \qquad s > s_{AEV} \end{aligned} \tag{7}$$

where s_{AEV} is the suction at air entry value.

The stability of the slope for scenarios 1 and 2 were assessed via limit equilibrium [28] using this simplified shear strength failure criteria.

3 Results

The initial (hydrostatic) pore-water pressure profile together with the pore-water pressure profiles after 1 and 2 days of constant rainfall of 130 mm/day and 105 mm/day respectively, for the control (C) and inoculated (I) material property scenarios are shown in Fig. 4.

In all simulations the water table has risen (1.0m for 1 day rainfall with control material properties, 1.5m for 1 day rainfall with inoculated material properties, 2.8m for 2 days rainfall with inoculated material properties, and 3.0m for 2 days rainfall with control material properties).

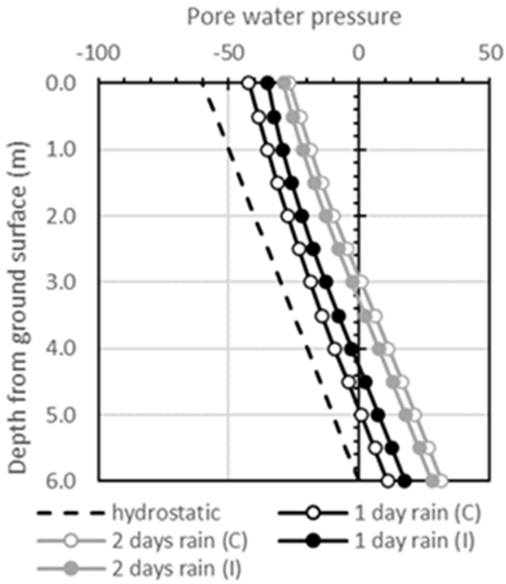


Fig. 4. Effect of rainfall of 130 and 105mm/day for 1 and 2 days respectively on the pore water pressure profile on the back of the slope, where (C) represents scenario 1 in which soil profile has parameters of control specimens and (I) represents scenario 2 in which soil profile has parameters of inoculated specimens.

Using this new distribution of pore-water pressure the contribution of suction to the shear strength of the soil was calculated using eq. (7) as presented in Table 2 and Fig. 5.

Table 2. Contribution of suction to shear strength

Layer	$\Delta\tau_{suction}$ (kPa)			
	Scenario 1 (C)		Scenario 2 (I)	
	1 day rainfall	2 days rainfall	1 day rainfall	2 days rainfall
1	3	3	3	3
2	3	3	2	2
3	7	0	2	0
4	5	0	0	0
5	0	0	0	0

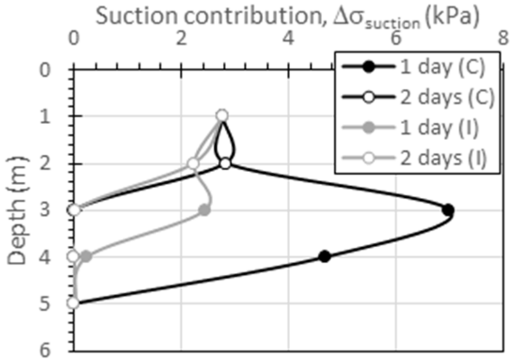


Fig. 5. Contribution of suction to shear strength for 1 and 2 days of critical rainfall vs depth.

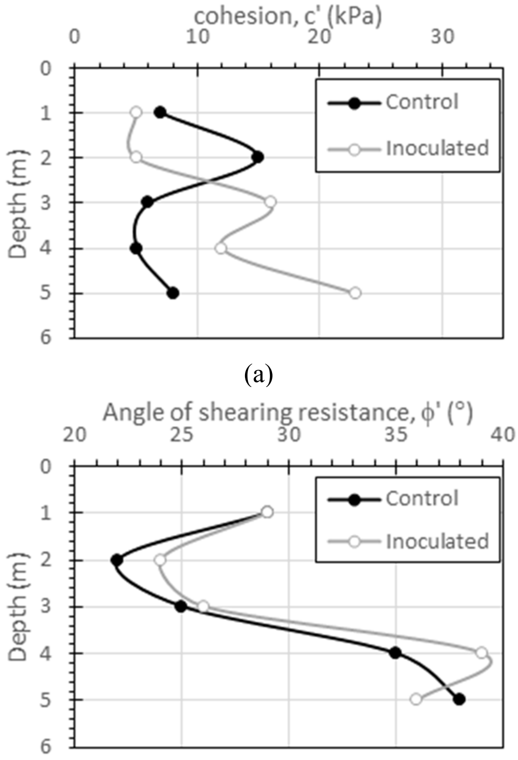
Then the stability of the slope with ground properties of control samples (scenario 1) and inoculated samples (scenario 2) was assessed via limit equilibrium [28]. The factors of safety obtained for 1 day rainfall were 1.9 and 2.3 for control and inoculated soil properties respectively, while the factors of safety obtained for 2 days rainfall were 1.8 and 2.4 for control and inoculated soil properties respectively.

4 Discussions

The effect the MICP had on the shear strength properties of the soil are presented in Fig. 6. Cohesion has reduced for samples collected at 1 and 2m depth while it increased in samples between 3 and 5m depth (Fig. 6a).

The angle of shearing resistance improved for samples collected between 2 and 4m depth, it was slightly smaller for sample at 5m depth and the same for the sample at 1m depth (Fig. 6b).

However, it is unclear whether these variations are associated with the statistical variability of the properties, since Gonzalez [16] did not reported this information.



(a)

(b)

Fig. 6. (a) cohesion and (b) angle of shearing resistance for control and inoculated samples (after [16])

In order to really appreciate the effects of the MICP on the stability of the slope it is important to separate it from the stability effects of suction. For that, two additional assessments were carried out switching off the simplified shear strength failure criteria, i.e., making $\Delta\tau = 0$.

The additional scenarios involved were the use of soil properties for control samples without including any contribution of suction to shear strength and the use of soil properties for inoculated samples without including any contribution of suction to shear strength.

The factors of safety obtained for these additional scenarios for 1 day rainfall were 1.6 and 2.2 respectively and for 2 days rainfall were 1.7 and 2.3 respectively (Fig. 7). This means that the MICP alone increases the factor of safety of the slope in 0.6 for both critical rainfalls (from 1.6 to 2.2 and from 1.7 to 2.3 for 1 and 2 days of critical rainfall respectively), while suction alone increases the factor of safety of the slope in 0.3 and 0.1 for 1 and 2 days of critical rainfall respectively (from 1.6 to 1.9 and from 1.7 to 1.8 for 1 and 2 days of critical rainfall respectively). The joined contribution of MICP and suction improves the factor of safety of the slope in 0.7 for both critical rainfalls (from 1.6 to 2.3 and from 1.7 to 2.4 for 1 and 2 days of critical rainfall respectively).

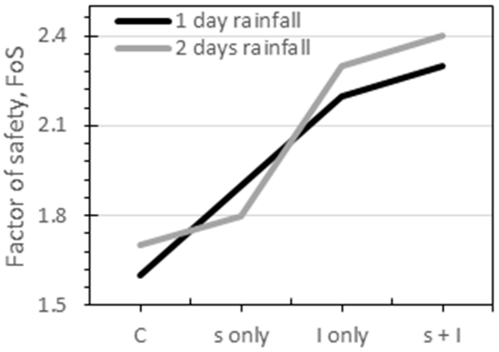


Fig. 7. Factors of safety for the different slope scenarios considered, where *C* involves soil properties of control samples and $\Delta\tau = 0$, *s only* involves soil properties of control samples and $\Delta\tau > 0$, *I only* involves soil properties of inoculated samples and $\Delta\tau = 0$, *s* + *I* involves soil properties of inoculated samples and $\Delta\tau > 0$,

5 Final considerations

This paper analysed the effect of biostimulated MICP on the stability of a slope on a tropical residual soil. Data from an experimental characterisation study [16] that included bulk unit weight, void ratio, shear strength parameters, saturated permeability and soil water retention curves carried out for control and inoculated specimens of a tropical soil from Brasilia, Brazil, was used. The stability of hypothetical slopes with control and inoculated soil properties were assessed considering critical rainfalls of 1 and 2 days for the tropical region using a 'simplified' shear strength criterion formulated in terms of unsaturated cohesion.

Results indicated that the MICP alone increases the factor of safety of the slope in 38 and 35% for 1 and 2 days of critical rainfall respectively, while suction alone increases the factor of safety of the slope in 19 and 6% for 1 and 2 days of critical rainfall respectively. The joined contribution of MICP and suction improves the factor of safety of the slope in 44 and 41% for 1 and 2 days of critical rainfall respectively.

The author would like to thank Universidade de Brasilia for granting access to the experimental data.

References

1. J. T. Dejong, K. Soga, E. Kavazanjian, S. Burns, L. A. van Paassen, A. Al Qabany, A. Aydilek, S. S. Bang, M. Burbank, L. F. Caslake, C. Y. Chen, X. Cheng, J. Chu, S. Ciurli, A. Esnault-Filet, S. Fauriel, N. Hamdan, T. Hata, Y. Inagaki, S. Jefferis, M. Kuo, L. Laloui, J. Larrahondo, D. A. C. Manning, B. Martinez, B. M. Montoya, D. C. Nelson, A. Palomino, P. Renforth, J. C. Santamarina, E. A. Seagren, B. Tanyu, M. Tsesarsky, and T. Weaver, Géotechnique **63**, 287 (2013)
2. J. DeJong, M. Tibbett, and A. Fourie, Environ. Earth Sci. **73**, 1067 (2015)
3. G. El Mountassir, J. M. Minto, L. A. van Paassen, E. Salifu, and R. Lunn, in *Adv. Appl. Microbiol.* (Elsevier, 2018), pp. 39–78
4. N.-J. Jiang, C.-S. Tang, T. Hata, B. Courcelles, O. Dawoud, and D. N. Singh, Soil Use Manag. **36**, 185 (2020)
5. J. He, J. Chu, Y. Gao, and H. Liu, Geotech. Res. **6**, 144 (2019)
6. M. M. Rahman, R. N. Hora, I. Ahenkorah, S. Beecham, M. R. Karin, and A. Iqbal, Sustainability **12**, (2020)
7. J. A. van Veen, L. S. van Overbeek, and J. D. van Elsas, Microbiol. Mol. Biol. Rev. **61**, 121 (1997)
8. M. Tsesarsky, D. Gat, and Z. Ronen, Environ. Geotech. **5**, 69 (2018)
9. J. T. DeJong, B. M. Mortensen, B. C. Martinez, and D. C. Nelson, Ecol. Eng. **36**, 197 (2010)
10. M. J. S. Roth, L. F. Caslake, and M. P. MacGuire, in *Geo-Congress 2022* (2022), pp. 472–484
11. M. G. Gomez, C. M. R. Graddy, J. T. DeJong, D. C. Nelson, and M. Tsesarsky, J. Geotech. Geoenvironmental Eng. **144**, 1 (2018)
12. M. T. Islam, B. C. S. Chittoori, and M. Burbank, J. Mater. Civ. Eng. **32**, (2020)
13. H. Chu, G.-F. Gao, Y. Ma, K. Fan, and M. Delgado- Baquerizo, Ecol. Evol. Sci. **5**, 1 (2020)
14. J. B. H. Martiny, B. J. M. Bohannan, J. H. Brown, R. K. Colwell, J. A. Fuhrman, J. L. Green, M. C. Horner-Devine, M. Kane, J. A. Krumins, C. R. Kuske, P. J. Morin, S. Naeem, L. Øvreås, A. L. Reysenbach, V. H. Smith, and J. T. Staley, Nat. Rev. Microbiol. **4**, 102 (2006)
15. N. Fierer and R. B. Jackson, Proc. Natl. Acad. Sci. U. S. A. **103**, 626 (2006)
16. Y. V. Gonzalez, Influência Da Biomineralização Nas Propriedades Físico-Mecânicas de Um Perfil de Solo Tropical Afetado Por Processos Erosivos, Universidade de Brasilia, 2009
17. P. Tiano, L. Biagiotti, and G. Mastromei, J. Microbiol. Methods **36**, 139 (1999)
18. S. Baskar, R. Baskar, L. Mauclaire, and J. A. McKenzie, Curr. Sci. **90**, 58 (2006)
19. INMET, Tabela Dados Das Estações Gama Ponte

Alta (A046) (2022)

20. J. K. Mitchell and K. Soga, *Fundamentals of Soil Behavior*, Third Edit (John Wiley & Sons, INC, 2005)
21. D. G. Fredlund, N. R. Morgenstern, and R. A. Widger, Can. Geotech. J. **15**, 313 (1978)
22. E. E. Alonso, A. Gens, and A. Josa, Géotechnique **40**, 405 (1990)
23. N. Khalili and M. H. Khabbaz, Geotechnique **48**, 681 (1998)
24. D. G. Toll, Géotechnique **40**, 31 (1990)
25. S. K. Vanapalli, D. G. Fredlund, D. E. Pufahl, and A. W. Clifton, Can. Geotech. J. **33**, 379 (1996)
26. A. L. Öberg and G. Sällfors, Geotech. Test. J. **20**, 40 (1997)
27. A. Tarantino and G. El Mountassir, Eng. Geol. **165**, 89 (2013)
28. N. R. Morgenstern and V. E. Price, Géotechnique **15**, 79 (1965)