

Experimental and numerical approaches of the hydro-mechanical behaviour of a quasi-saturated compacted clayey soil

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Abstract: The present research is funded by the French National Project « TerreDurable », which is dedicated to the study of soils in quasi-saturated conditions (close to saturation) for the analysis of stability and settlement of earth structures such as embankment, dams. A global presentation of the drying-wetting test shows the volume change, air entry and soil-water characteristics of the soil at slurry and oven-dried conditions. Unsaturated undrained triaxial test was carried out in order to investigate the variation of pore-water pressure from quasi-saturated domain to saturation. The experimental results of the triaxial test are then modeled using a two-dimensional explicit finite difference program (Flac 2D). A constitutive law developed in the TerreDurable project allows better understanding the behaviour of quasi-saturated soils using the water retention curve of quasi-saturated domain proposed by Boutonnier (2007, 2010). A simple effective stress model is used (Cam Clay) by taking into account both the suction and the compressibility of equivalent fluid (water + air). The results from numerical calculation and experimental measurements are compared.

1 Introduction

1.1 Problem

In practice, due to the complexity of microstructure, heterogeneity and soil suction, it is usually difficult for the engineers to measure and control effectively the parameters that affect the engineering behaviour of compacted clayey soils. Consequently, experimental studies of these soils in laboratory are useful to a better understanding of their hydro-mechanical behaviour and then to guide the practice.

1.2 Related work

Compacted soils are unsaturated soils, for which the Proctor optimum water content and maximum density correspond to a degree of saturation comprised between 70 and 90%. During their life cycle, under the combined effects of suction and stresses, they may be subjected either to wetting up to saturation or to drying. This domain, between 70 and 90% of degree of saturation, has been the subject of numerous studies.

Since 1950s, much attention was paid, both experimentally and numerically, to the study of the variation of volume and pore-water pressure in the framework of dam constructions (Hilf, 1948; Skempton, 1954; Bishop, 1954). As regard to the laboratory

experiments of compacted soils, the difficulty was to measure or control the pore water pressure, which is negative and cannot be measured directly by a traditional pressure transducer when the suction is below -80 kPa. In 1956, Hilf firstly proposed the axis-translation method to increase the pore-water pressure (u_w) from negative to positive by applying an external air pressure (u_a). This method made it possible to measure and control the soil suction (s), which is equal to the difference between the pore-air and pore-water pressures ($s = u_w - u_a$). Application of axis-translation method has made much progress in the unsaturated soil mechanics, especially for the study of pore-water variation (Bishop et Donald, 1961; Gibbs and Coffey, 1969; Fredlund et al., 1976; Taibi, 1994).

With the development of theory and testing device, Soil Water Characteristic Curve (SWCC, also called Soil Water Retention Curve, SWRC) was proposed to describe the relationship between the hydro-mechanical parameters and suction. A complete description of SWCC in four diagrams (w - e , w - S_r , s - w , s - S_r) was firstly presented by Biarez et al. (1987), and then developed into five diagrams (w - e , w - S_r , s - e , s - S_r , s - w) by Fleureau et al. (1993, 2002). In the meantime, many researchers began to correlate the main parameters of SWCC with the intrinsic parameter of soils such as liquid limit (Fleureau et al., 2002), and special attention

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was paid recently to the study of SWCC under mechanical loading (Lu and Likos, 2006).

More recently, works have highlighted the specific behaviour of soils close to saturation (Boutonnier 2007), with a high compressibility of the interstitial fluid due to the presence of occluded air bubbles.

1.3 Attributions

In this paper, we attempt to present 1) some experimental results such as the SWCC, unsaturated undrained triaxial test of a compacted clayey soil whose degree of saturation is close to unit; 2) a numerical approach based on the Cambridge-model to model the experimental results; 3) a comparison of the experimental results and the numerical model.

2 Material and methods

2.1 Material

The material of this study was taken from a site on the Tours - Bordeaux High-speed Railway Line in the south-west of France at a depth of 1.5 - 7.8 meters. The material is made mainly of clayey soil but also with some sharp gravel with diameters of several centimetres, which were eliminated manually before the laboratory tests. Its initial water content was equal to 39%.

The main geotechnical properties of the material are presented in Table 1. The material can be classified as A3 in the French classification (AFNOR, 1992) and A-7-5 in the American Association of State Highway and Transport Officials (AASHTO) classification (ASTM, 2004).

Table 1. Main properties of the material

Material	Châtaignier Clay	G_s [kN/m ³]	28.3
w_L [%]	70.5	γ_{dmax} [kN/m ³]	13.3
w_p [%]	37	u_{copt} [kPa]	1100
I_p [%]	33.5	< 80 μm [%]	88
w_{opt} [%]	37.5	< 2 μm [%]	70

2.2 Experimental Methods

2.2.1 Preparation of test specimen

The material was dried under laboratory condition (20 ± 1 °C) for several weeks, and then sieved at 2 mm. The passing particles were dried in an oven at 105 °C for about 48 hours, and mixed afterwards with the required quantity of distilled water. Then, the mixed soil was kept in a sealed plastic bag for more than 48 hours. Experiments with a similar soil showed that this time was sufficient to reach equilibrium. The moist soil was compacted, according to the French standard (AFNOR, 2014), in a standard Proctor mold. The compaction was

carried out in 3 layers with 25 blows per layer, which corresponds to energy of 0.6 MJ/m³.

Concerning the saturated oedometer test, the well mixed slurry was carefully poured into a 60-mm-diameter oedometer cell, where the circulation of water from the bottom to the top was possible. Loading was applied by step from 1 to 80 kg, with each load lasted more than 2 days. The slurry with water content of 1.5 times of liquid limit was prepared for the drying-wetting test. As regard to the triaxial test, the prepared compacted sample at water content of 47.5% ($w_{SPO} + 10\%$) was cut into 35 mm in diameter and about 30 mm in height.

2.2.2 Unsaturated undrained triaxial test

The experimental device for the unsaturated triaxial test by axis-translation method is presented in Figure 1, which contains mainly 1) a loading system; 2) three Pressure/Volume controllers, which control the confining pressure, pore-water pressure and the external pore-air pressure of the sample; 3) several transducers, two of them measure the pore-air and pore-water pressures, the other transducers which are not shown in the figure to measure the axis displacement, axis force, etc.; 4) a triaxial cell, a small standard cell for the specimen of 35 mm in diameter was modified by equipping the base with a high air-entry value (HAEV) ceramic disk, whose air-entry pressure was 1.5 MPa.

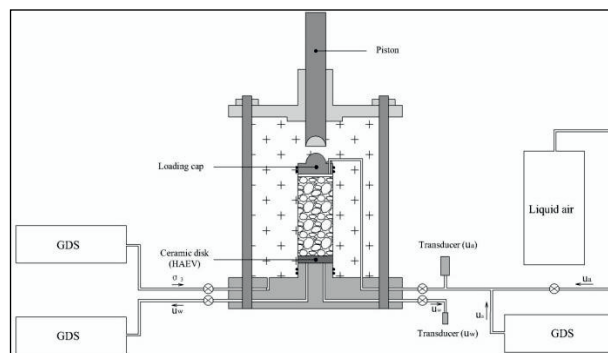


Figure 1. Experimental device for the unsaturated triaxial test by axis-translation method

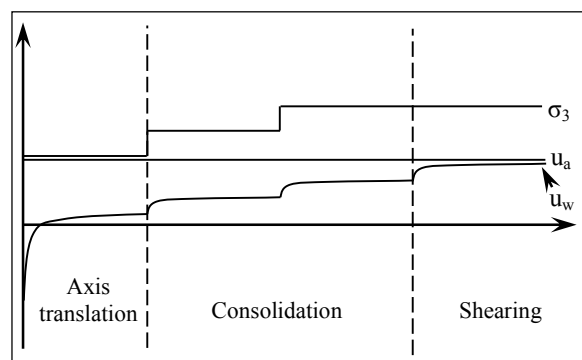


Figure 2. Schematic diagram of the axis translation method

To carry out the unsaturated triaxial test, a non-standard procedure is used and described as follows:

- Saturation of ceramic disk;

- Installation of the specimen and acquisition system;
- Axis translation and consolidation: During the axis translation process, an external air pressure (u_a) was applied by liquid air and pressure/volume controller from the circuit at the top, followed by an increase of confining water pressure ($\sigma_3 = u_a + 20$) simultaneously until the pore-water pressure became positive. After that, the air pressure was constant, while the confining pressure was increased by steps (Figure 2);
- Shearing: the confining pressure and the air pressure was hold and the sample was sheared at a speed of 0.5 %/h.

2.2.3 Drying-wetting test

During drying-wetting test, suction was controlled by the sintered tensiometric plates, osmotic technique and salt desiccator for low, medium and high suctions, respectively. More details of these methods can be found in the work of Fleureau et al. (2001).

2.3 Numerical Methods

2.3.1 Model used

The model reported by Boutonnier (2007) is adopted in this work. More details are available in the works of Mahmutovic et al. (2014), Boutonnier et al. (2015) and Andrianatrehina et al. (2015). In this model, as shown in Figure 3, the soil can be divided into 4 domains of saturation (D1 to D4 - unsaturated to saturation).

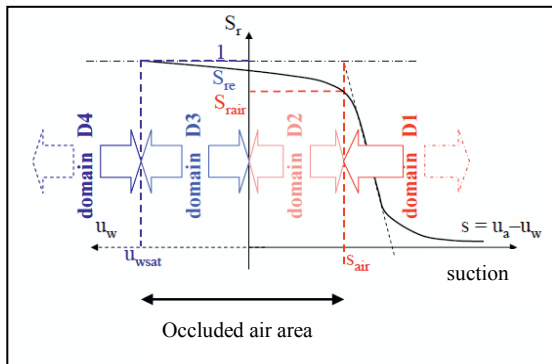


Figure 3. Division of retention curve in 4 domains of saturation (Boutonnier 2007)

In the quasi-saturated areas, the model is based on the compressibility coefficient of the interstitial fluid c_f (Equation (1) for domain D2 and Equation (2) for domain D3). A particular attention is paid to these areas as they are the domains concerned in most of earthworks like motorway, railway, embankments and earth dams.

$$c_f = \frac{1}{S_r} \cdot \frac{1}{s_{air}} (S_{re} - S_{rair}) + c_w \quad (1)$$

$$c_f = \frac{1 - S_r + h \cdot S_r}{u_w + r_{bm} + P_a - u_{wg}} + c_w \quad (2)$$

Quasi-saturated domains can be modeled using the Cam Clay constitutive relational law with an assigned compressibility coefficient (c_f) for air/water phases. The c_f value depends on the degree of saturation, which itself depends upon the pore pressure.

2.3.2 Geometry and boundaries condition

The Flac 2D software was chosen for the numerical simulation due to its wide use both in academic and professional practice. This software includes many pre-existing constitutive laws and enables new theoretical models to be defined.

An axisymmetric calculation is used because of the axial symmetry of the triaxial test. The geometry of the numerical model is drawn with the dimensions of 70 mm in height and 35 mm in diameter which corresponds to the size of the triaxial sample ($D = 35$, $H = 30$ in this study). No displacement is allowed in x-y directions at the base of the model. A stress condition is applied on the top and at the lateral boundary of the model.

2.3.3 Simulation parameters

Cam Clay parameters

Figure 4 presents the results of two oedometer tests for the slurry under saturated drained condition. The main parameters are listed in Table 2. For the reason of heterogeneity of the samples, only the average value of the two tests was taken for the later simulation.

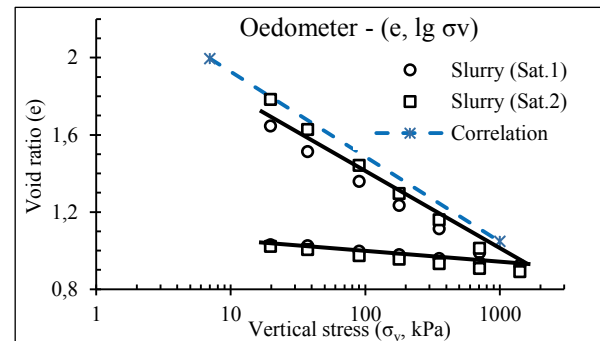


Figure 4. Results of oedometer test for the slurry sample under saturated drained condition

Values of s_{air} change with void ratio (Vanapolli 1998). The chosen value corresponds to the value of suction at the Optimum Proctor: 1200 kPa (Boutonnier 2007).

Table 2. Mechanical parameters of the material

Test	λ	κ	ϕ	M	S_{air} desat [kPa]	S_{air} resat [kPa]
Oedo.	0.191	0.026	-	-	-	-
Triaxial	-	-	22.3°	0.87	-	-
Drying-wetting	-	-	-	-	5000	1700

Quasi-saturated parameters

The proposed model contains 5 parameters: the degree of saturation for a null suction S_{re} , the degree of saturation at air entry S_{rair} , the air entry suction s_{air} , the mean radius of air bubbles r_{bm} , and the Henry's constant h (Table 3).

The value of air entry suction coincides with the value of suction at the optimum Proctor (Boutonnier 2007), and S_{rair} the value of the degree of saturation at the optimum Proctor. h is neglected because of its low influence in the calculus. S_{re} is deduced thanks to the Equation (3) and the understanding of the degree of saturation at 48% of water content (Sample tested in the triaxial test).

$$S_r = S_{re} - u_w \frac{(S_{re} - S_{rair})}{u_{wair}} \quad (3)$$

Table 3. Parameters of the proposed model

Test	S_{re}	S_{rair}	S_{air} [kPa]	r_{bm} [m]	h
Oedo	0.92	0.90	1200	$2 \cdot 10^{-6}$	0

2.3.4 Aim of the simulation

The main goal of the numerical simulation is to reproduce the response of the soil sample in terms of pore pressure. The standard triaxial test is modeled, and not the axis-translation triaxial test because of the leakage into the air circuit when the pore-water pressure exceeds the applied air-pressure.

3 Results and comparison

3.1 Experimental results

Figure 5 presents the drying-wetting path for the slurry at $1.5 w_L$ and oven-dried slurry, the main parameters are listed in Table 2. For the SWCC, the drying path and wetting path are reversible in the (w, e) plan, whereas an obvious hysteresis can be observed in the other four plans. This general observation is coincident with the previous works by Taibi (1994), Fleureau et al. (1993, 2002) for the soils under slurry condition.

Figure 6 and Figure 7 present the results of the unsaturated triaxial test under undrained condition.

The saturation step (Figure 6 - A) shows that the ceramic disk with a diameter of 33 mm and depth of 7 mm can arrive at saturation in six hours for the applied water pressure of 1500 kPa.

Figure 6 - B shows that the initial suction of the sample ($w = 49.25\%$) is about 20 kPa, where the net confining pressure ($\sigma_3 - u_a$) is 20 kPa. The pore-water pressure (u_w) in the sample stabilised in about 2 days after the application of the pore-air pressure (u_a) for the compacted sample with a diameter of 35 mm and depth of 30 mm. The measured suction decreased slightly

from 25 to 100 kPa by increasing simultaneously the pore-air pressure (u_a) from 50 to 200 kPa and confining pressure (σ_3) from 70 to 220 kPa. This means that, by increasing simultaneously the pore-air (u_a) and confining pressure (σ_3).

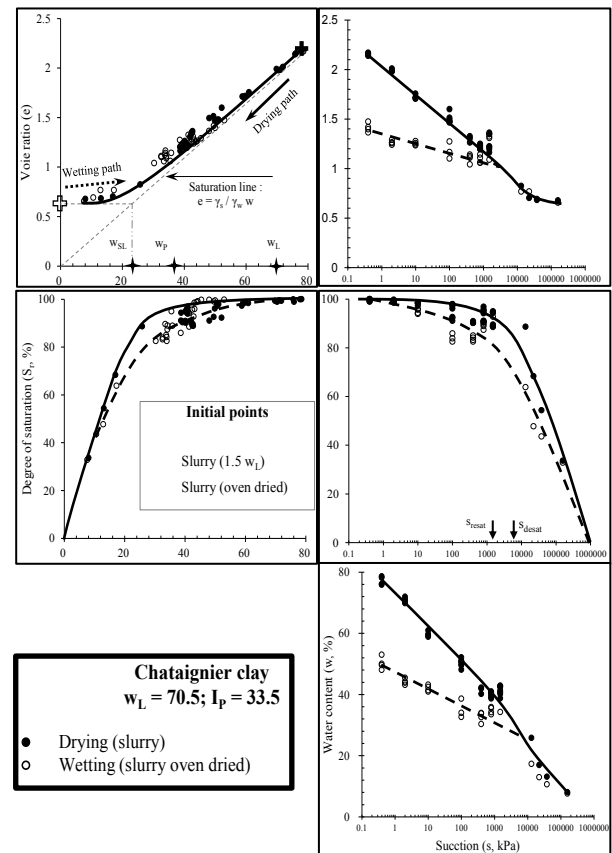


Figure 5. Drying-wetting path of the Chataignier clay

Figure 6 - C presents the results of the consolidation step for the specimen N.1, where axis translation method is applied. Confining pressure was increased from 250 to 400 kPa, whereas the pore-air pressure was constant (200 kPa). The pore-water pressure in the sample increased and exceeded the applied pore-air pressure, where the water began to drain into the pore-air circuit, which means the test was no longer under undrained condition.

Figure 6 - D presents the consolidation results of the specimen N.2, who has the same initial water content and size. But instead of applying a pore-air pressure, the specimen was submitted a relative high confining pressure (300 kPa) so that the pore-water pressure can increase from negative to positive pressure. Then, the confining pressure was continued to increase by 100 kPa each step from 300 to 1000 kPa. As it is noted in the figure, the temperature had an influence on the measurement of the pore-water pressure, and it is necessary to take into account the effect of the temperature for some loading steps in order to calculate the B parameter.

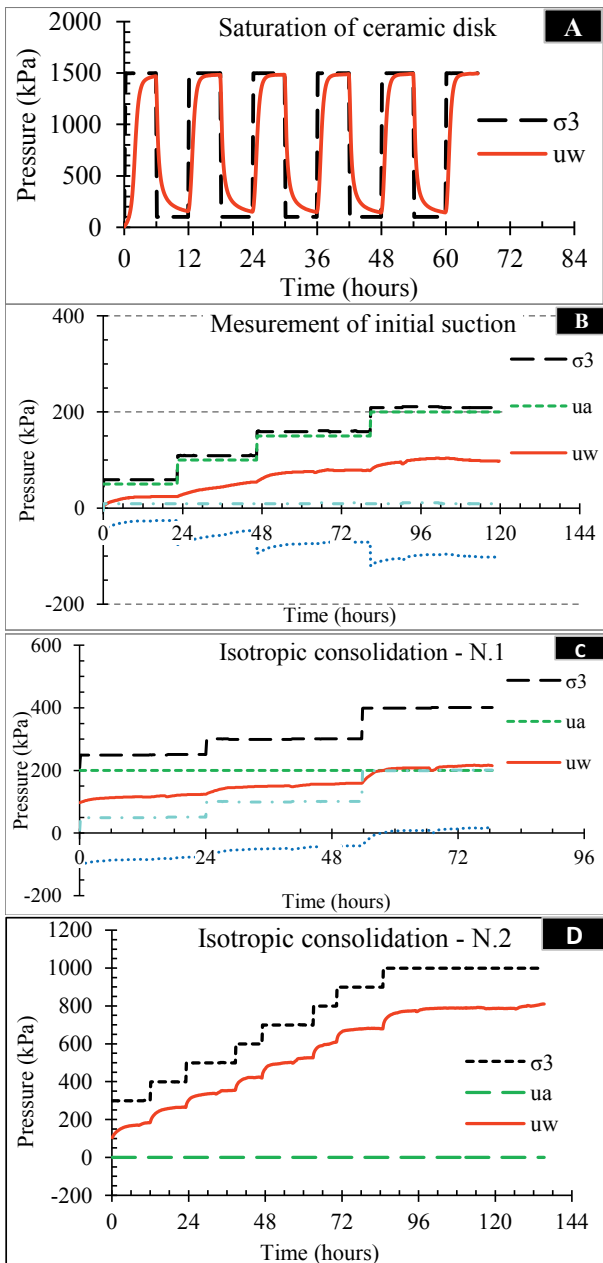


Figure 6. Results of undrained unsaturated triaxial test by axis-translation method (figures A, B, C and D).

By integrating the previous results (Figure 6), the relationship between the variation of suction, B and the net confining pressure is presented in the Table 4 and Figure 7. For the net confining pressure smaller than 200 kPa, it seems that the suction increases with the net confining pressure, but more and more slowly. This observation is consistent with that of Taibi (1994) for the compacted Vieuxpré Clay whose suction is lower than 80 kPa. The B is about 0.75 when the net confining pressure was increased from 300 to 900 kPa, and then B goes up to 0.91 for the net confining pressure at 1000 kPa which means that the specimen was close to saturation under the loading condition.

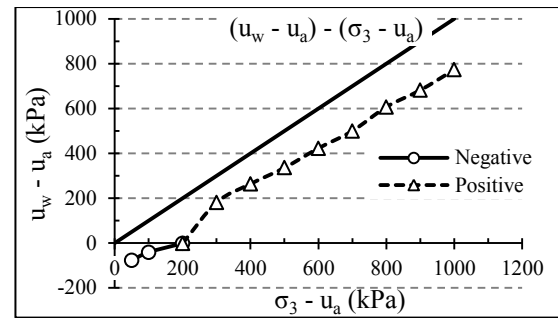


Figure 7. Relationship between net confining pressure ($\sigma_3 - u_a$) and suction ($u_w - u_a$)

Table 4. Variation of $(u_w - u_a)$ and B in terms of net confining pressure ($\sigma_3 - u_a$) - comparison between experimental results and numerical simulations

$(\sigma_3 - u_a)$ (kPa)	B	$(u_w - u_a)$ Experimental (kPa)	$(u_w - u_a)$ Simulation (kPa)	Remarque
50	x	-77	-	$(u_w - u_a)$ is negative
100	0.54	-41	-	
200	0.4	-1	-	
300	-	181	200	$(u_w - u_a)$ is positive
400	0.83	264	270	
500	0.72	336	342	
600	0.71	423	427	
700	0.77	500	516	
800	0.81	607	607	
900	0.75	682	706	
1000	0.91	773	800	

3.2 Numerical results and comparison

Results of numerical simulation are plotted in Figure 8 (triaxial test without axis translation). Values of $(u_w - u_a)$ pressure are also reported in the table 4.

Three numerical curves are plotted 1) the curve with the parameters of the table 3; 2) the curve with the parameters of the table 3 less 3%; 3) the curve with the parameters of the table 3 more 3%. The third curve is the closest of the experimental results. Measurement uncertainties of the degree of saturation explain the necessity of this margin of error.

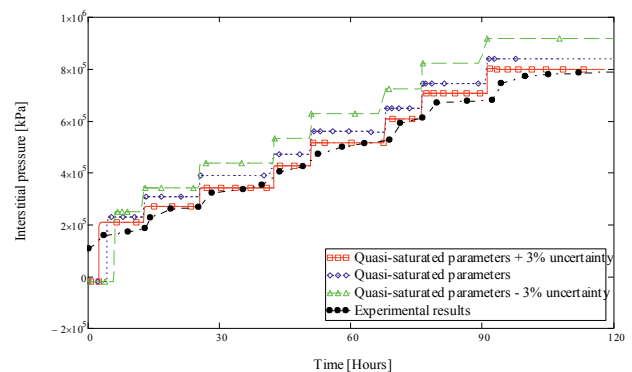


Figure 8. Evolution of pore pressure with net confining pressure in triaxial test – comparison between experimental results and numerical simulation

Conclusion

Evolution of the pore pressure during net confining stress ($\sigma_3 - u_a$) in a triaxial cell is presented. The tested sample is in the quasi-saturated domain and close to saturation. The triaxial test by axis-translation method is complemented by a standard triaxial test for high values of ($\sigma_3 - u_a$) with a null value of u_a . Indeed, in quasi-saturation, with the axis-translation method, water is drained into the air circuit when the pore-water pressure exceeds the applied air-pressure. Results of these experimental study permit to obtain the evolution of the Skempton Coefficient B in terms of net confining pressure and observe the progressive saturation of the sample under mechanical loading.

A numerical simulation was carried out with the model developed in the ANR project TerreDurable for the standard triaxial test. This model use a simple effective stress based on the Cambridge model with the coefficient of compressibility c_f of the interstitial fluid (water + occluded air) which depends on the degree of saturation.

A good agreement is observed between theoretical and experimental results on the triaxial test without axis-translation, which validates the proposed model. The small discrepancies may result from the influence of temperature during the test.

References

- Andriantrehina, R., Mahmutovic, D., Boutonnier, L., Taibi, S., Fleureau, J. M., Fry, J. J., Monnet, J. (2015). Observation of cracking evolution during free desiccation - experimental and numerical approaches. Symposium international SEC 2015. Marne-la-vallée.
- AFNOR (French Association of Standardization). (1992). "Earthworks - Classification of materials for use in the construction of embankments and capping layers of road infrastructures." NF P11-300, France.
- ASTM (American Society for Testing and Materials). (2004). "Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes." D2487-00, West Conshohocken, PA.
- Biarez, J., Fleureau, J. M., Zerhouni, M. I. & Soepandji, B. S. (1987). Variations de volume des sols argileux lors de cycles drainage-humidification. Revue française de Géotechnique. No. 41, Page 63-71.
- Bishop, A. W. (1954). The use of pore-pressure coefficients in practice. Géotechnique, Volume 4, Issue 1, Page 148-152.
- Bishop, A. W. & Donald, I. B. (1961). The experimental study of partly saturated soil in the triaxial apparatus; Proceedings of the 5th International Conference of Soil Mechanics, Paris, Volume 1, Page 13-21.
- Boutonnier, L. (2007). Comportement hydromécanique des sols fins proches de la saturation cas des ouvrages en terre: coefficient B, déformations instantanées et différées, retrait / gonflement. Thèse de doctorat, Institut National Polytechnique de Grenoble, France.
- Boutonnier, L., Mahmutovic, D., Fry, J. J. (2015). Génération de pression interstitielle dans les fondations argileuses des barrages en remblai. Colloque CBR 2015.
- Fleureau, J. M., Kheirbek-Saoud, S., Soemitro, R., & Taibi, S. (1993). Behavior of clayey soils on drying-wetting paths. Canadian geotechnical journal, 30(2), 287-296.
- Fleureau, J. M., & Kheirbek-Saoud, S. (2001). Retrait et Gonflement des sols soumis à un cycle de drainage humidification.
- Fleureau, J. M., Verbrugge, J. C., Huergo, P. J., Correia, A. G., & Kheirbek-Saoud, S. (2002). Aspects of the behaviour of compacted clayey soils on drying and wetting paths. Canadian geotechnical journal, 39(6), 1341-1357.
- Fredlund, D. G & Morgenstern, N. R. (1976). Constitutive relations for volume change in unsaturated soils. Canadian Geotechnical Journal, Volume 13, Issue 3, Page 261-276.
- Gibbs, H. J., Coffey, C. T. (1969). Techniques for pore pressure measurements and shear testing of soil ; Proceedings of the 7th International Conference of Soil Mechanics and Foundation Engineering, Mexico, Volume 1, Page 151-157
- Hilf, J. W. ; 1948 ; Estimating Construction Pore Pressures in Rolled Earth Dams ; Proceedings of the 2nd International Conference of Soil Mechanics and Foundation Engineering, Rotterdam, Volume 3, Page 234-240.
- Lu, N. & Likos, W. (2006). Suction stress characteristic curve for unsaturated soil ; Journal of Geotechnical and Geoenvironmental Engineering, Volume 132, Issue 2, Page 131-142.
- Mahmutovic, D., Monnet, J., Loret, B., Ple, O., Pelizzari, B., Boutonnier, L., Lai, B. (2014). A model for weakly unsaturated soils taking into account the three phases (air, water and soil). Unsat 2014. Sydney.
- Skempton, A. W. (1954). The pore-pressure coefficients A and B. Géotechnique, Volume 4, Issue 1, Page 143-147.
- Taibi, S. (1994). Comportement mécanique et hydraulique des sols soumis à une pression interstitielle négative - Etude expérimentale et modélisation. Thèse de doctorat, Ecole Centrale Paris, France.
- Taibi, S., Fleureau, J. M., Abou-Bekr, N., Zerhouni, M. I., Benchouk, A., Lachgueur, K., & Souli, H. (2011). Some aspects of the behaviour of compacted soils along wetting paths. Géotechnique, 61(5), 431-437.