Suction effects on the compressibility and creep of crushable sands

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ABSTRACT
An experimental laboratory study of the compressibility and creep of two crushable sands is presented, by means of oedometric compression tests in partially saturated samples. The material humidity is controlled by the vapor transfer technique, in order to cover a wide range of total suction up to 340 MPa. The results show that, as suction decreases (i.e. humidity increases), both compressibility and creep deformations increase. The deformation mechanism is characterized by an instantaneous strain that does not depend on suction, and by creep strains which strongly depends on suction. This phenomenon has applications in engineering designs of geotechnical structures, such as rockfill dams, mining rock waste dumps and railway ballast, where granular materials are subjected to significant changes in environmental conditions that could promote hydro-mechanical degradation at long-term.

RÉSUMÉ
Une étude expérimentale en laboratoire de la compressibilité et du fluage de deux sables est présentée à l'aide d'essais de compression uniaxiale sur des échantillons partiellement saturés. L'humidité du matériau est contrôlée par la technique de transfert de vapeur afin de couvrir une large plage de succion totale allant jusqu'à 340 MPa. Les résultats montrent que, lorsque la succion diminue (i.e. l'humidité augmente), la compressibilité et le fluage augmentent, en raison dúne augmentation de la rupture des grains. Le mécanisme de déformation se caractérise par une déformation instantanée ne dépendant pas de la succion et, deuxièmement, par des déformations de fluage fortement dépendantes de la succion. Ce phénomène a des applications dans la conception des ouvrages géotechniques, tels que les barrages en enrochement, les halles de roches stériles minières et le ballast des chemins de fer, où les matériaux granulaires sont soumis à des modifications importantes des conditions environnementales susceptibles de favoriser la dégradation hydro-mécanique à long terme.

1 INTRODUCTION

Several studies have shown that non-linear compressibility of granular materials is mainly due to particle breakage (Vesić & Clough, 1968; Lade et al., 1977; Biarez & Hicher, 1997). In addition, it is well known that the increase in the soil/rock moisture increases the amount of breakage and, consequently, the compressibility (Oldecop & Alonso, 2003; Ovalle, 2018). This behaviour may be explained in terms of the Stress Corrosion Cracking (SCC), which states that part of the existing microcracks in a stressed brittle material sample are exposed to corrosion due to moistening, decreasing crack propagation resistance (Atkinson, 1982). Thus, as stress and/or moisture increases, a granular material experiences a higher degradation due to particle breakage. In addition, SCC might be a slow process and generate creep due to delayed particle breakage (Oldecop & Alonso, 2007; Ovalle et al., 2015). In geotechnical engineering, this phenomenon could explain long term settlements of dams and railway ballast, for example.

Data reported about the influence of relative humidity (i.e. suction) on the compressibility of granular materials are still scarce. The role of each settlement mechanisms (i.e. instantaneous strains and creep) has not been well identified.

In this paper, an experimental laboratory study is presented in order to evaluate the compressibility of two partially saturated crushable sands tested under uniaxial compression with vertical stress levels up to 1.6 MPa. The aim of the study is to investigate the compressibility and the mechanisms of instantaneous and delayed deformation and their dependence on suction.

2 MATERIALS

Two uniform sands of different mineralogical origin and composition were selected (both are SP type according to U.S.C.S.):

- Colina: crushed rock from Colina in the Metropolitan Region (Chile), extracted from a small artisan quarry. The material corresponds to Andesite, an intrusive rock belonging to the Volcanic Group of the Oligo-Miocene era, mainly composed by quartz.
- Pilbara: crushed rock coming from the Pilbara region in Western Australia (Australia), obtained

from waste rock of an iron mine. The material consists in eroded and transported particles (colluvium) derived from a sedimentary Pre-Cambrian banded iron formation in Pilbara, Australia (Linero et al., 2017), consisting essentially of alternating beds and laminae of hematite or magnetite and chert.

The grain size distribution (GSD) of the tested materials are presented in Figure 1.

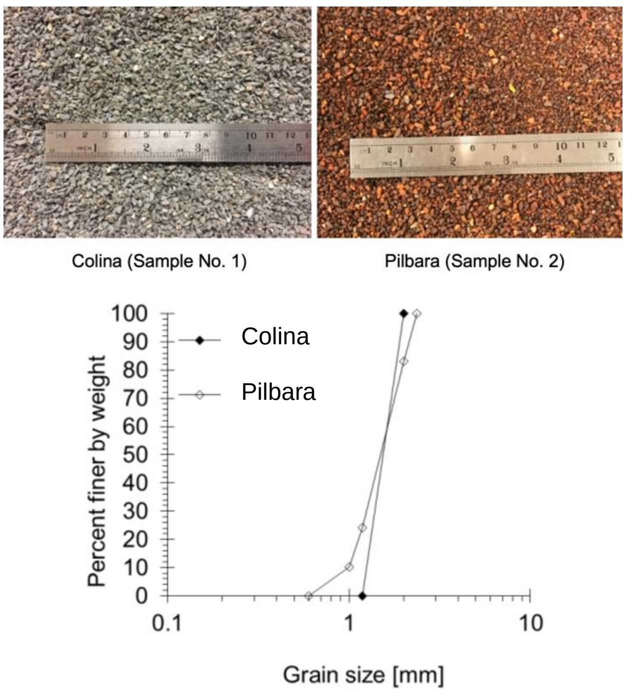

Figure 1. Tested sands

3 TESTING METHODOLOGY

Oedometric compression tests on samples of 68 mm in diameter and 20 mm in height were performed by applying 24 hours loading increments, under controlled relative humidity (suction) conditions.
The following vertical stresses levels were applied:
10→25→49→98→196→392→785→1569 kPa.
Some specimens were saturated by flooding at the maximum stress level applied using demineralized water. Collapse was evaluated via measuring instantaneous settlements (at 0.1 min) and delayed creep strains. Thus, for each load increment, strains were recorded from 0.1 min up to 24 hours (1440 min).

The partial saturation was imposed by the vapor transfer technique, through a closed air-flow circuit that integrates the sample in an oedometric test. The relative humidity was controlled within the circuit and, once equilibrium was reached, suction was kept constant (Fredlund & Rahardjo, 1993). Suction was obtained by Kelvin's law by knowing the temperature (*T*) and the relative humidity (*RH*) of the air in the pores:

$$\psi = -\frac{RT}{v_{w0}\omega_v}\ln(RH) \quad [1]$$

Where ψ is total suction, R is the universal gas constant (8.31432 J/[mol K]), v_{w0} is the specific volume of water, or the inverse of the water mass density ($1/\rho_w$ [m^3/kg]) and ω_v is the molecular mass of the water vapor (18.016 [kg/mol]).

The closed vapor circuit consists in an air pump that generates a circulating flow between the sample and a saline solution (see Figure 2). The system includes a pressure controller so as not to affect the total stresses in the test (air pressure <2 kPa), and two hygrometers for monitoring temperature and relative humidity of the air before and after passing through the sample. Table 1 shows the measured values and the total suction calculated by Eq. 1.

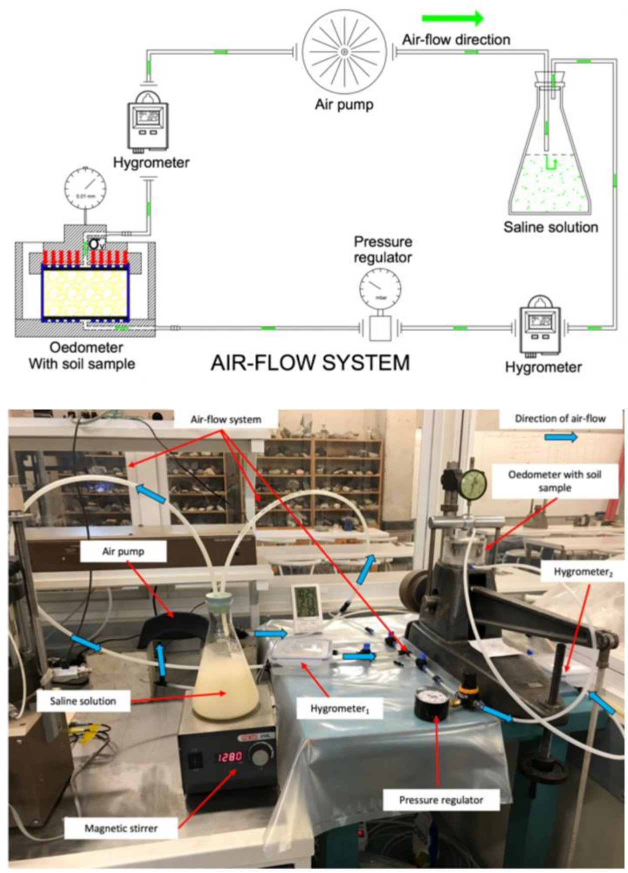

Figure 2. Vapor control technique: (above) Scheme of hermetic circuit and (below) actual circuit

The moisture of the samples was estimated from the water retention curves of each material (Figure 3), obtained by means of a chilled-mirror dewpoint psycrometer (WP4C, Decagon®, USA) (Osses et al., 2019).

The results show that for the lower total suction imposed in the vapor control system, moisture content of tested samples ranged around 1.0 - 2.0% for Colina and Pilbara materials, respectively.

Table 1. Temperature, relative humidity and total suction on each test

Sample	Saline solution	Average T °C	Average RH %	Total suction, ψ MPa
Colina	NaOH	18.0	9	338
Colina	KOH	26.5	15	258
Colina	$MgCl_2$	20.9	39	129
Colina	NaOH	24.9	66	66
Colina[1]	NaBr	24.9	66	66
Colina	K_2SO_4	20.5	93	10
Pilbara	NaOH	23.9	9	324
Pilbara	$MgCl_2$	25.5	45	109
Pilbara[2]	H_2O	–	–	0

[1] repetition test
[2] saturated with demineralized water

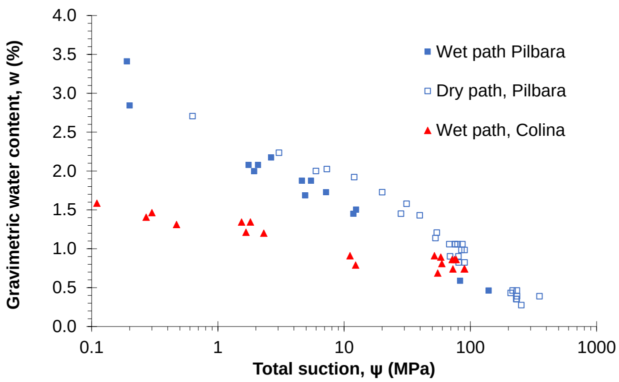

Figure 3. Water retention curves

4 RESULTS AND ANALYSIS

Figure 4 presents oedometric compression curves obtained for Colina and Pilbara materials. Samples tested at suctions of 10 MPa and 66 MPa (Colina) and 109 MPa (Pilbara), were saturated with demineralized water at the maximum stress applied via flooding. Saturated samples showed the highest strain values: 8.2% and 3.8% for Colina and Pilbara, respectively. In contrast, when exposed to a suction around 300 MPa showed strains of 4.6% and 3.1% were recorded in Colina and Pilbara materials, respectively.

Figure 5 presents the GSD at the end of each test, including the initial GSD selected for each soil sample.

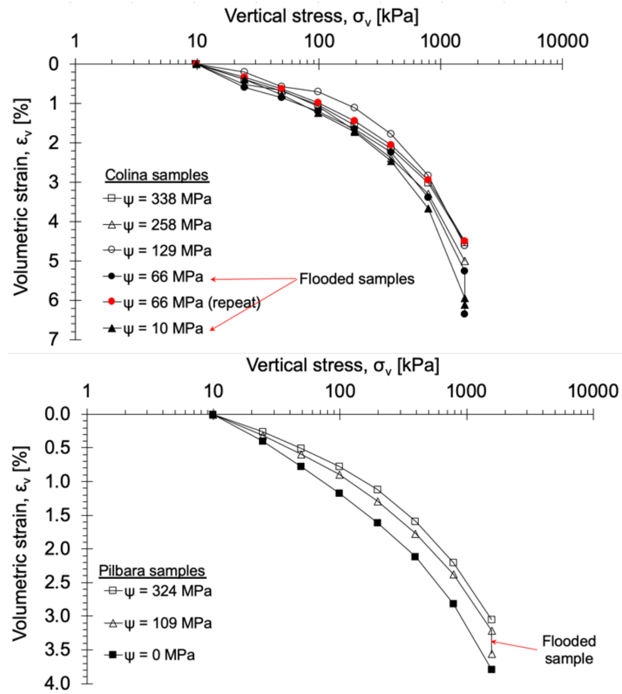

Figure 4. Compression curves: (above) Colina, (below) Pilbara

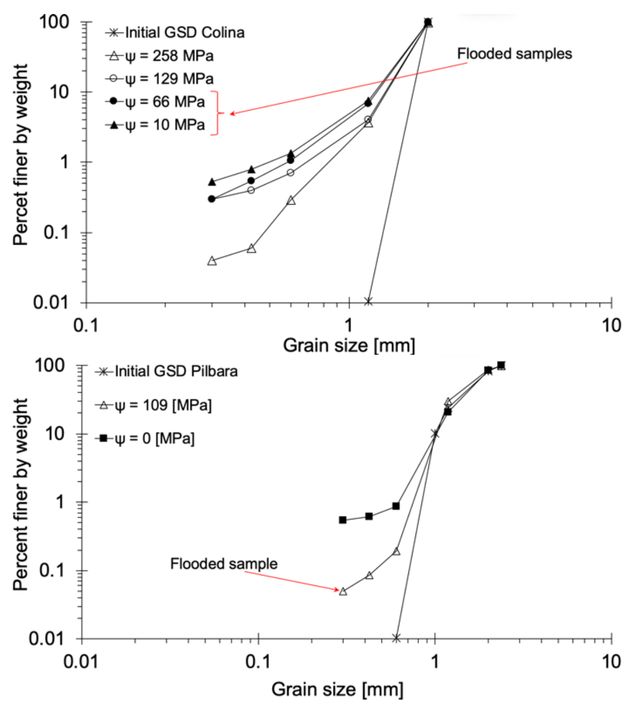

Figure 5. GDSs curves: (above) Colina, (below) Pilbara

Figure 6 shows an example of strain curves against time obtained for a Colina sample with ψ = 334 MPa.

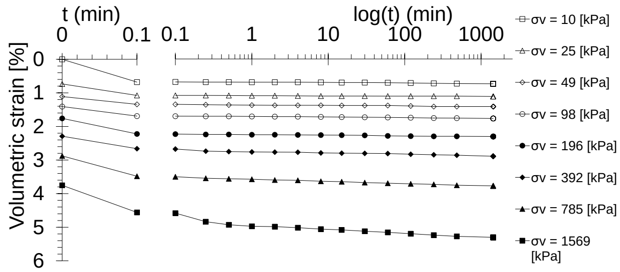

Figure 6. Time–dependent curves on Colina sand, ψ = 334 MPa

As outlined in Figure 7, compressibility can be characterized by the compression index C_c*=Δe/Δlog(σ*$_v$*)*, and the secondary compression coefficient C_α*=Δe/Δlog(t)* (Mesri & Vardhanabhuti, 2009). Figures 8 and 9 present the coefficients C_c and C_α obtained for each stress level in all tests. The results show that compressibility indexes (total and secondary) increases with both applied stress and humidity, and at high suction the curves are close to each other.

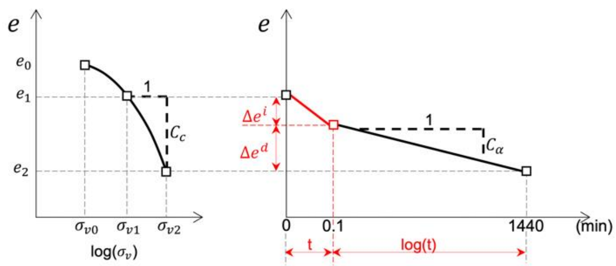

Figure 7. Calculation scheme of C_c and C_α coefficients

According to Figures 6 and 7, at each stress increment two deformation mechanisms are generated: instantaneous strain and time dependent strain (*creep*). Thus, deformation can be decoupled as ε^i (here measured at 0.1 min in this study) and ε^d (here measured –but not stopped– up to 1440 min). Based on this concept, Oldecop and Alonso (2001) proposed a constitutive model for granular materials including creep, where the compressibility index (λ^d) depends on suction, while the instantaneous compressibility index (λ^i) does not:

$$d\varepsilon = d\varepsilon^i + d\varepsilon^d = \lambda^i d\sigma + \lambda^d(\psi)d\sigma \qquad [2]$$

Figures 10 and 11 show the values of ε^i and ε^d, respectively, for Colina and Pilbara. In agreement with the hypothesis of Oldecop and Alonso (2001), both materials present a relation ε^d *vs* σ_v that depends on suction, while ε^i does not. Nevertheless, variations of ε^d are not significant at high suction.

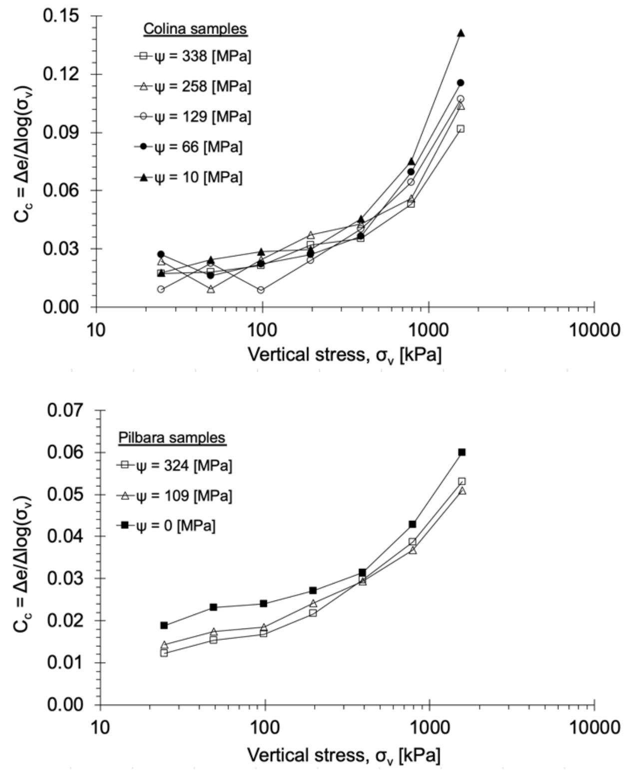

Figure 8. C_C *= Δe/Δlog(σ*$_v$*)*: (above) Colina, (below) Pilbara

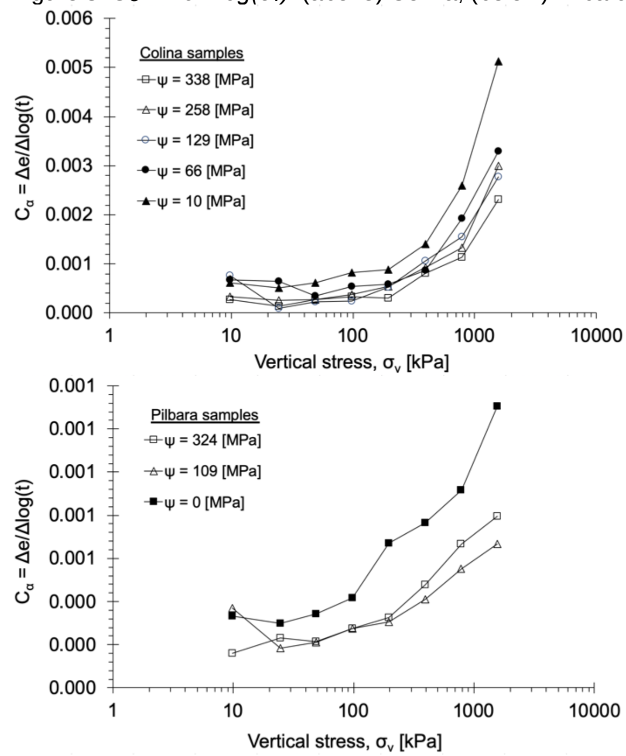

Figure 9. C_α *= Δe/Δlog(t)*: (above) Colina, (below) Pilbara

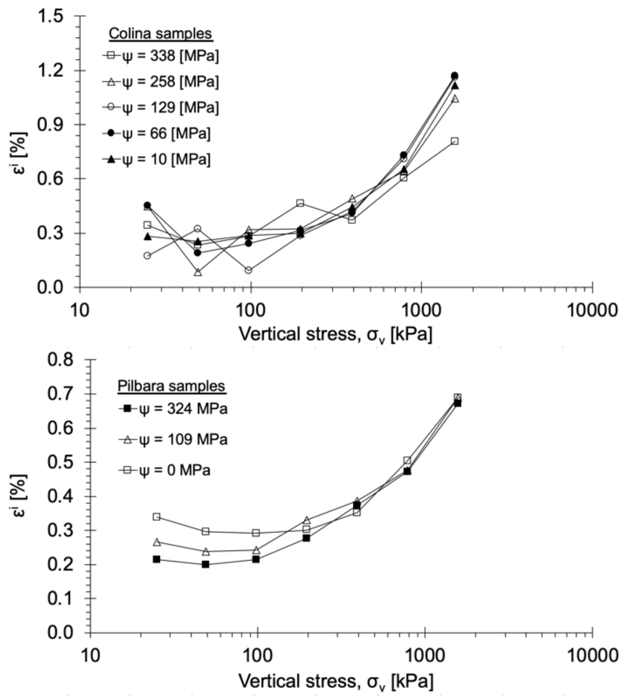

Figure 10. ε^i: (above) Colina, (below) Pilbara

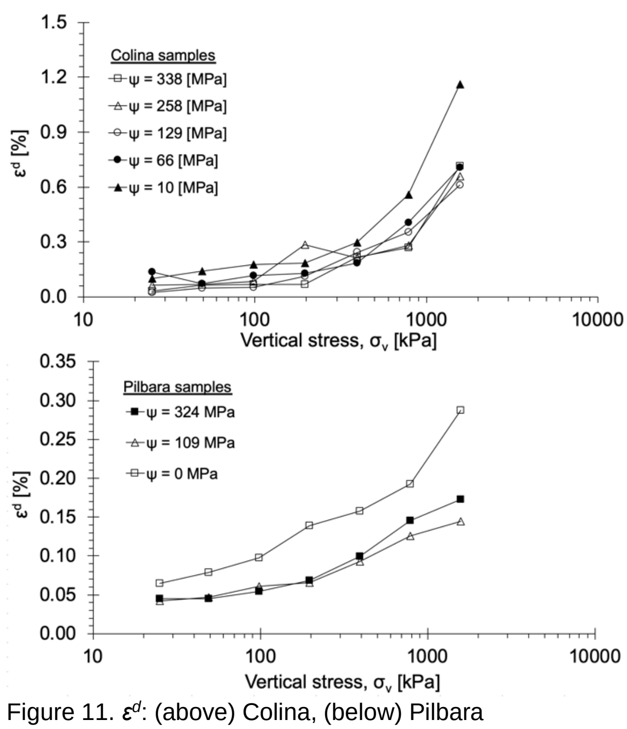

Figure 11. ε^d: (above) Colina, (below) Pilbara

5 CONCLUSIONS

An experimental laboratory study of the effect of suction in compressibility and creep of two crushable sands is presented, by means of oedometric compression tests on partially saturated samples. The main conclusions of the study are the following:

- Compressibility increases with relative humidity (suction).
- The lower the suction, the higher the creep strains.
- The deformation mechanism due to stress increase can be decoupled in instantaneous and delayed (creep) deformation.
- The lower the suction, the higher the creep strains.
- Instantaneous strains does not depend on suction.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Atkinson B. 1982. Subcritical crack propagation in rocks: experimental results an applications, *Journal of Structural Geology*, 4(1): 41–56.

Biarez J., Hicher P.Y. 1997. Influence de la granulométrie et de son évolution par ruptures de grains sur le comportement mécanique de matériaux granulaires, *Revue Française de Génie Civil*, 1(4): 607–631.

Fredlund D.G., Rahardjo H. 1993. *Soil mechanics for unsaturated soils*, John Wiley & Sons, Inc. New York, NY, USA.

Lade P., Yamamuro J., Bopp P. 1996. Significance of particle crushing in granular materials, *Journal of Geotechnical Engineering*, 122(4): 309–316.

Linero S., Fityus S., Simmons J., Lizcano A., Cassidy J. 2017. Trends in the evolution of particle morphology with size in colluvial deposits overlying channel iron deposits, *EPJ Web of Conferences*, 140, pp. 14005.

Mesri G., Vardhanabhuti B. 2009. Secondary compression, *Canadian Geotechnical Journal*, 49(4): 369–392.

Oldecop L., Alonso E. 2001. A model for rockfill compressibility, *Géotechnique*, 51(2): 127–139.

Oldecop L., Alonso E. 2003. Suction effects on rockfill compressibility, *Géotechnique*, 53(2): 289–292.

Oldecop L., Alonso E. 2007. Theoretical investigation of the time-dependent behaviour of rockfill, *Géotechnique*, 7(3): 289–301.

Osses, R., Pineda, J., Ovalle, C., Linero, S., Fityus, S. 2019. Particle size effects on the water retention properties of colluvial sediments. *Submitted to* 7th Asia-Pacific Conference on Unsaturated Soils. August 23~25, 2019, Nagoya, Japan.

Ovalle C. 2018. Role of particle breakage in primary and secondary compression of wet and dry sand, *Géotechnique Letters*, 8(2): 161–164.

Ovalle C., Dano C., Hicher P.Y., Cisternas M. 2015. Experimental framework for evaluation the mechanical behavior of dry and wet crushable granular materials based on the particle breakage ratio, *Canadian Geotechnical Journal*, 52(5): 587–598.

Vesić A., Clough G. 1968. Behavior of granular materials under high stresses, *Proceedings of the American Society of Civil Engineers*, 94(3): 661–688.