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Contribution to the experimental and theoretical study of the behavior of soil-structure interfaces

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Saliha Benalia
ORCID: https://orcid.org/0000-0003-0446-0963
Department of civil engineering, University of Djelfa, Djelfa 17000, Algeria
E-mail: s.benalia@univ-djelfa.dz
Boubaker Benchiekh
ORCID: https://orcid.org/0009-0007-8641-7526
Department of civil engineering, University of Djelfa, Djelfa 17000, Algeria
E-mail: dr.benchiekhboubaker@gmail.com
Leila Zeghichi
ORCID: https://orcid.org/0000-0003-2886-0339
Department of civil engineering, University of Biskra, Biskra 07000, Algeria
E-mail: leila.zeghichi@univ-biskra.dz

Abstract
Designing civil engineering works often requires taking into consideration the contact and interface conditions between the soil and structure. These may refer to the discontinuity surfaces between the soil and a structure such as foundations, geotechnical works, and others. Current research aims to improve the calculation methods for structures through a better understanding of the behavior of materials and interfaces. The present work falls into this context. It involves two parts. The main purpose of the first part is to present the results of the monotonic and cyclic soil-structure interface tests which were carried out using a modified direct shear box apparatus. The tests were conducted using a local material, namely the sand from the town of Messâad in the Wilaya of Djelfa (Algeria), in accordance with a constant normal stress path. In addition, a parametric study, dealing with the effect of density, interface roughness, and type of adhesive used on the behavior of the interfaces, was carried out as well. As for the second part, it primarily aims to validate the Modjoin interface model, which was developed at the Lille Mechanical Laboratory, based on the tests that were carried out in the first part. It is important to know that this model includes the main concepts used in soil modeling, such as isotropic hardening, characteristic state, critical state, softening, and others. Moreover, several validation tests are also presented in this work in order to describe the behavior of the soil-structure interface under monotonic loading to assess the performance of the model.
Keywords: Shear. Interface. Hardening. Softening. Contractance/dilatancy. Elastoplastic model. Validation.

1. Introduction

In the field of Civil Engineering constructions, most structures can be regarded as an assembly of deformable solids in contact. The stability of all these structures depends significantly on the behavior of the contact surfaces or interfaces. In this context, Plytas (1985) defines the interface as that thin zone of soil where large structure changes and grain ruptures may take place due to localized shear occurring in contact with an inclusion in the soil under the action of an axial stress. It was revealed that most of the ruptures observed in these structures occur along the discontinuity surfaces or interfaces.

It is important to note that a lot of problems related to interfaces between the soil and civil engineering structures have been reported in the past. The interface may in fact refer to a contact surface between two or more layers of soil, such as the interface between an embankment and the foundation soil, to a contact surface between the soil and a rocky bedrock, cracks and joints in the rock masses (soil-piles or soil-underground structures, for example), or between the soil and reinforced earth or reinforced concrete. It is worth indicating that various experimental methods have been employed to investigate these soil-structure interfaces. In this regard, it is worth mentioning the studies that were carried out by Potyondy (1961), Wernik (1979), Yoshimi and Kishida (1981), Kishida and Uesugi (1987), Boulon (1989), Boulon and Nova (1990), Evgin and Fakharian (1996), Chambon (2003), Corfdir *et al*. (2004). Their main purpose was to study the behavior of interfaces under monotonic and cyclic loading.

Furthermore, some other aspects, such as smoothing, were also taken into account when developing and validating models for the mechanical behavior of interfaces. It is noteworthy to cite a number of elastoplasticity-based models, such as the model of Desai and Fishman (1991), the model of Shahrour and Ousta (1998), the model of Mortara *et al.* (2001), the model of Wang *et al*. (1998), the model of Hu and Pu (2004), and the model of De Gennaro and Frank (2005). The findings from mentioned studies have provided researchers in the field with a better understanding of the behavior of soil-structure interfaces. The results obtained have often been employed in the calculation and design of a large number of civil engineering works (Tallah 2005; Said 2006).

The primary purpose of this work is to make a contribution to the modeling of the behavior of soil-structure interfaces under monotonic loading. An important part of this paper is devoted to the experimental study of the behavior of interfaces, using a direct shear box apparatus and a local material which, in the present case, is the sand from the town of Messaâd (Djelfa, Algeria).

During this research, several factors, such as the interface surface condition, were studied. The tests carried out in this work were subsequently used to validate the Modjoin model that was used to better understand the behavior of interfaces under monotonic loading.

2. Experimental modeling of the soil-structure interface

2.1 Presentation of the material and the experimental device used

Geotechnical tests were carried out on some sand samples that were collected from Wadi Messaâd, in the Wilaya of Djelfa. This type of sand is widely used in construction in the Wilaya of Djelfa which located 300 km south of Algiers (Algeria). Figure 1 illustrates the town of Djelfa. The identification tests were carried out to show that the sand from Messaâd is clean, coarse, gravelly, and stony.

In order to successfully carry out this work, it was deemed necessary to use a shearing machine and a circular Casagrande box, 6 cm in diameter, to realize the soil-structure shearing tests, using soil with thickness equal to 1cm, as shown in Figure 2. A circular steel or concrete plate, representing the structure, was then introduced into the lower half-box. The plate had a diameter slightly smaller than that of the half-box, with a thickness of 1cm. In addition, the shear force was then measured using a load ring placed between the lower half-box and the base of the machine (Benalia (2011)).

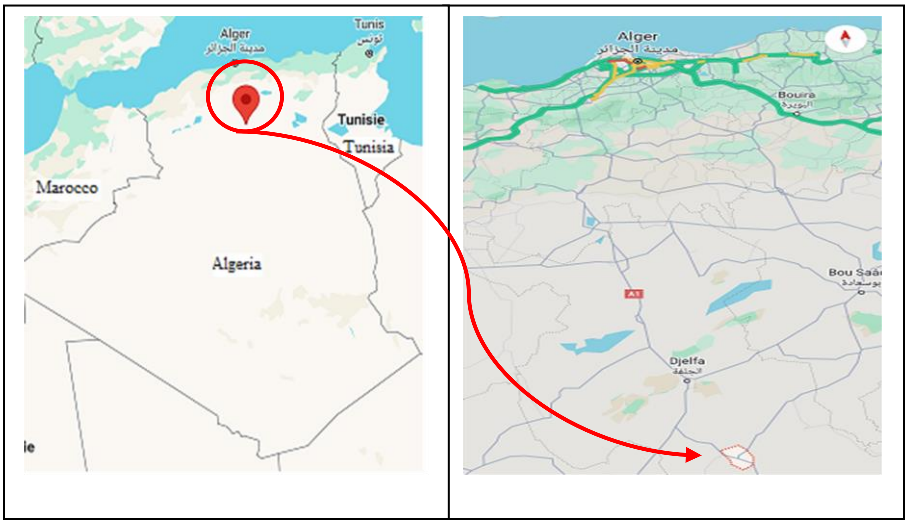


Figure 1 - Position of Messaâd in Djelfa (Algeria).

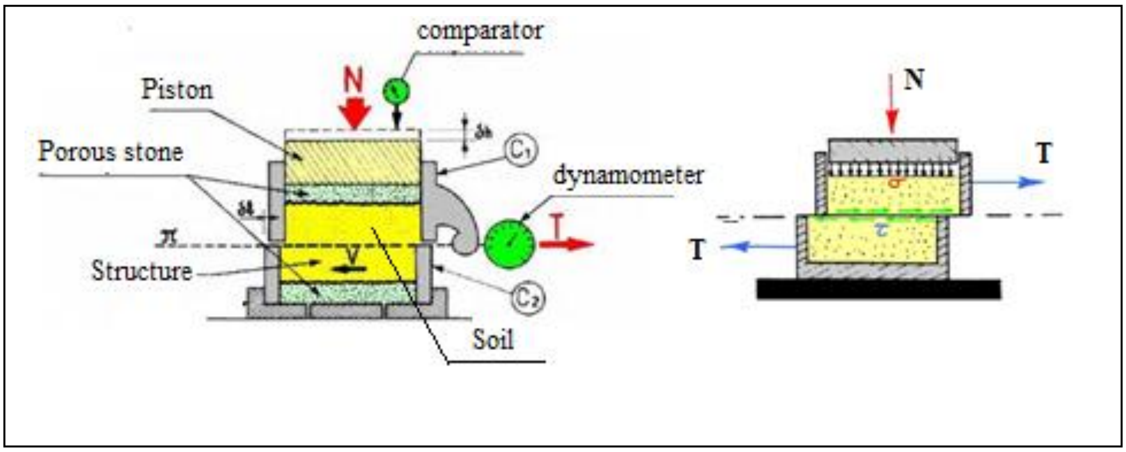


Figure 2 - The modified direct shear box experiment.

2.2 Presentation of the results obtained

A series of shear tests was conducted in order to study the influence of different parameters, such as the structure surface roughness (smooth or rough), the density of sand (loose or dense), the type of structure (steel or concrete), and the type of adhesive used, on the behavior of the interface. For this, two types of sand with different densities were then considered, i.e. a 15% loose sand and a 90% dense sand. The roughness was achieved by gluing the grains of sand onto the plates that represent the structures, using two types of glue, i.e. ARALDITE and BECTA, which can be found on the market. Figure 3 shows the shear test for the rough steel surface with 90% dense sand. Figure 4 shows the shear test for the smooth steel surface with 90% dense sand, while Figure 5 shows the shear test for the rough steel surface with 15% loose sand.

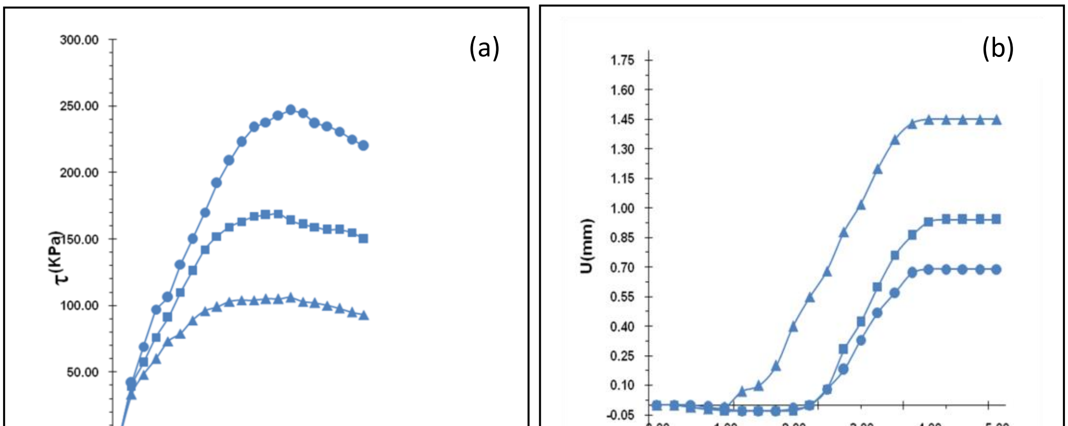


Figure 3 - Shear tests at constant normal stress (Rough steel surface/90% dense sand), (a): Evolution of the tangential stress, (b): Evolution of the normal displacement.

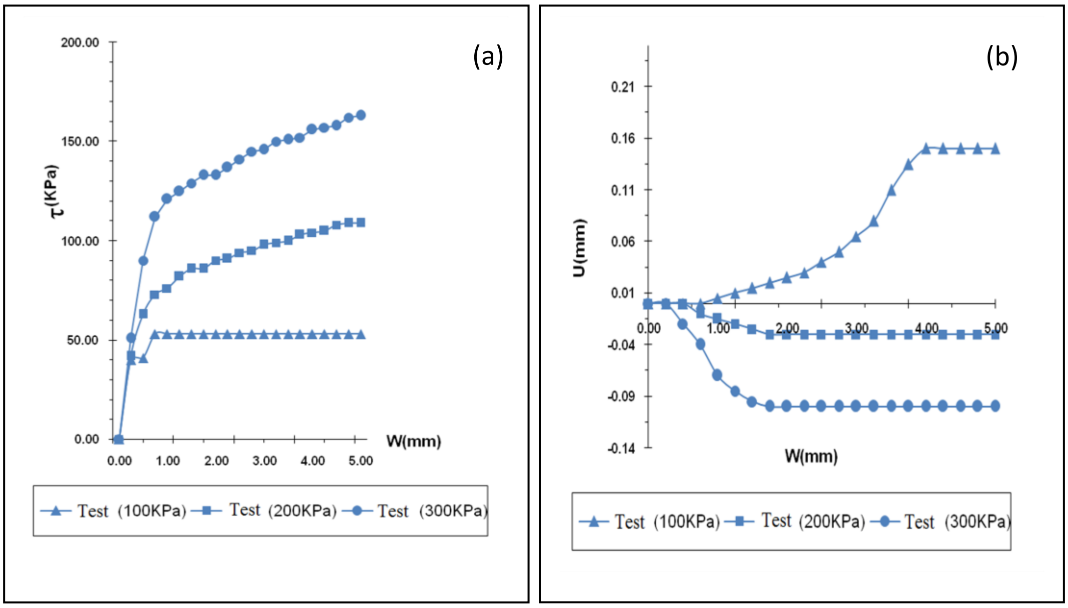


Figure 4 - Shear tests at constant normal stress (Smooth steel surface/90% dense sand), (a): Evolution of the tangential stress, (b): Evolution of the normal displacement.

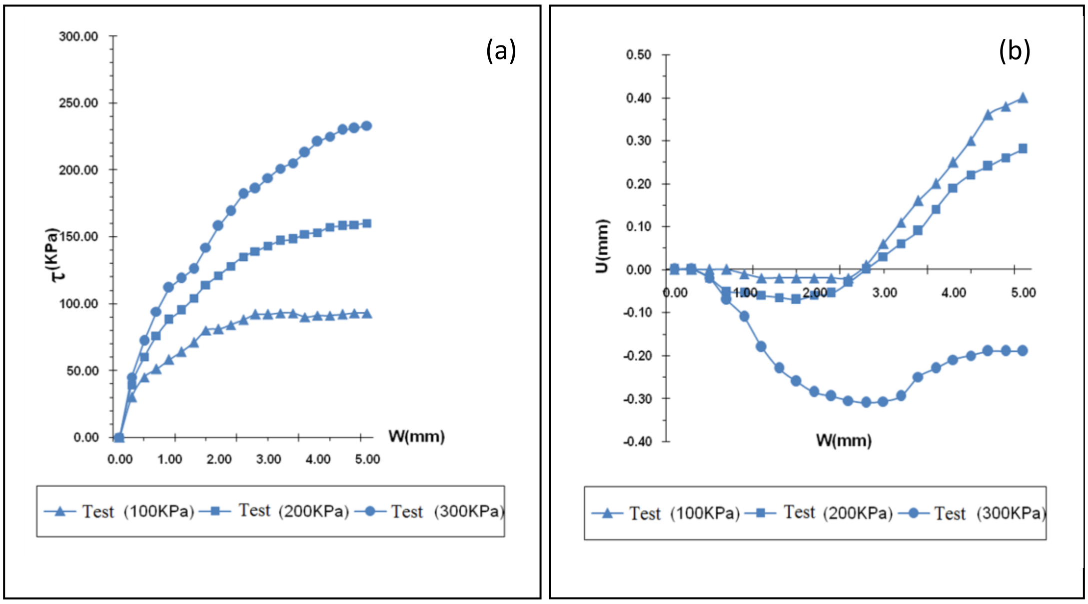


Figure 5 - Shear tests at constant normal stress (Rough steel surface/15% loose sand), (a): Evolution of the tangential stress, (b): Evolution of the normal displacement.

Interpretation of results: The interface can contract or expand freely in the case of the constant normal stress interface tests. Therefore, typical curves for shear tests are, on the one hand, the evolution of the shear stress as a function of the relative tangential displacement (w, τ) and, on the other hand, the evolution of the normal displacement as a function of the relative tangential displacement (w, U). A progressive friction increase is thus observed until reaching the rupture condition (peak or plateau). It is useful to specify that the presence of a shear resistance peak occurs for dense sands. This peak is generally followed by a softening phase, and then the friction stabilizes. In addition, from a volume point of view, the contractance-dilatancy phenomenon results in a decrease in normal displacement (contracting phase) then an increase in this displacement (dilating phase) until stabilization. It should also be noted that the constant normal stress condition is the most frequent and the simplest condition that can be reproduced when considering the boundary conditions.

2.3 Effect of roughness

The shear curve, in the case of high density, allows observing a significant difference in behavior at the qualitative and quantitative level (presence of a shear peak with a higher level of stress in the case of a rough plate), as shown in Figure 6 (a). Likewise, a very significant difference is then observed on the curve representing the evolution of the normal displacement. Here, the dilatancy phase is completely absent in the case of the smooth surface, as depicted in Figure 6 (b).

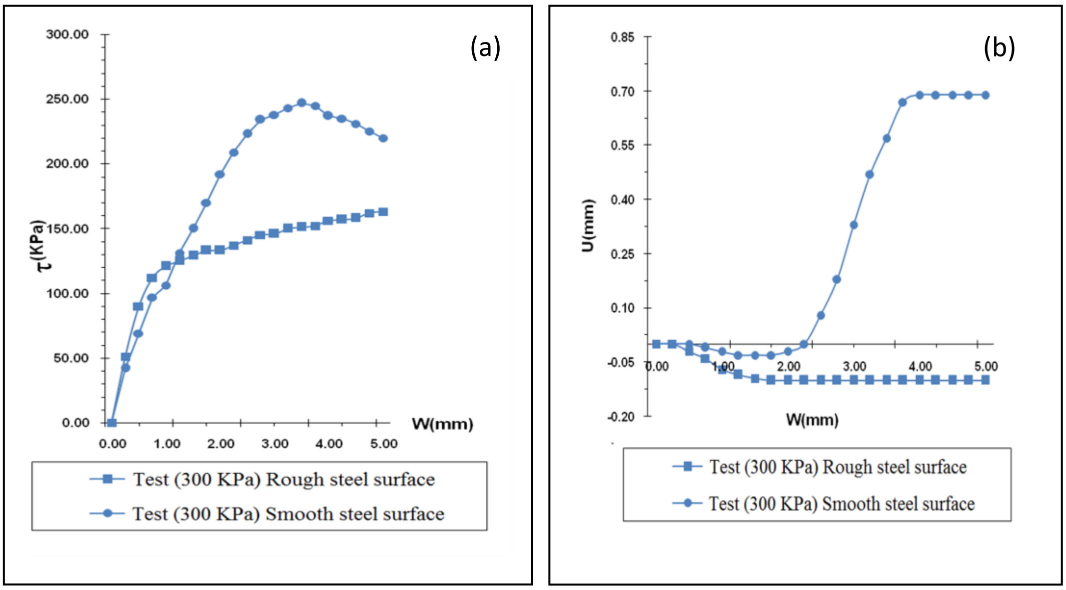


Figure 6 - Effect of roughness (90% dense sand).

2.4 Effect of initial density

The results of the tests carried out here show that the behavior of the interface is highly influenced by the initial density.

In the case of a rough surface, the presence of a shear peak is noted when using dense sand, with the presence of a dilatancy phase that is accompanied by a softening for the evolution of the normal displacement. However, Figure 7 shows that the shear curve for loose sand continues to increase for large displacements and the normal behavior remains contracting throughout the test.

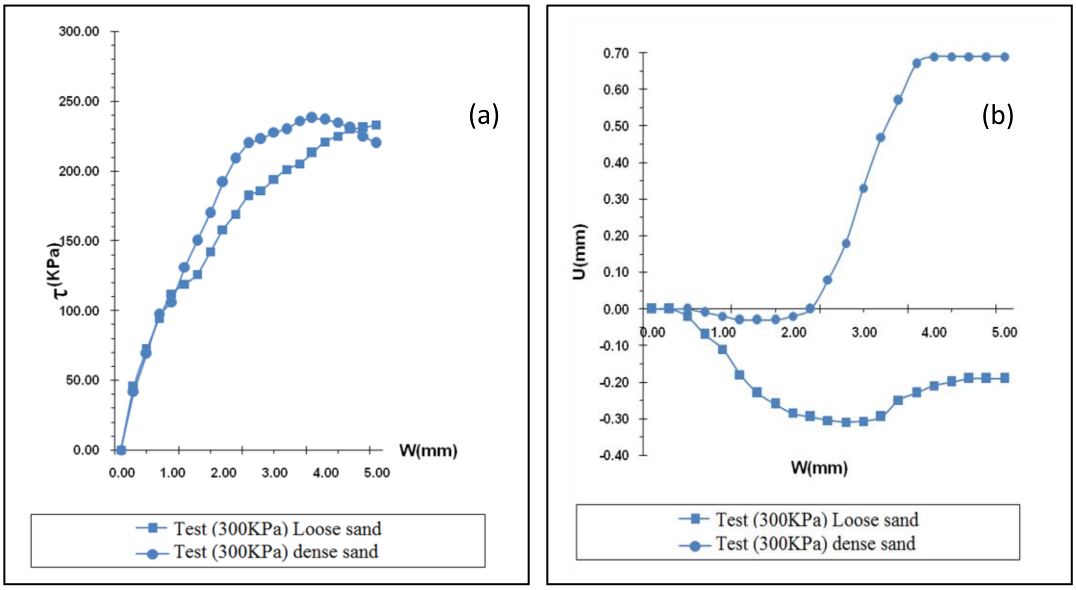


Figure 7 - Effect of density (rough steel surface).

2.5 Effect of adhesive type

It is important to know that two types of adhesives were used in this study, i.e. ARALDITE and BECTA, for the purpose of studying the effect of the type of glue on the normal stress (σ_{n0} = 100, 200 and 300 KPa). Figures 8 depict the results obtained. It was observed that the type of glue used does not have a significant influence on the shear and normal displacement. In addition, a very slight quantitative difference was observed on the shear curves. This may be due to the operating mode, such as the reading on comparators during the test, the grain breakage during the test, etc.

Furthermore, the calculation of the friction angles, when using the two types of glue, shows that the values obtained are very close. Indeed, it was found that for high densities, the angle of friction is φ = 40.29° for the first type of glue (ARALDITE) and φ = 40.56° for the second type of glue (BECTA). However, for low densities, φ = 37.61° for the first type of glue and φ = 37.99° for the second type of glue.

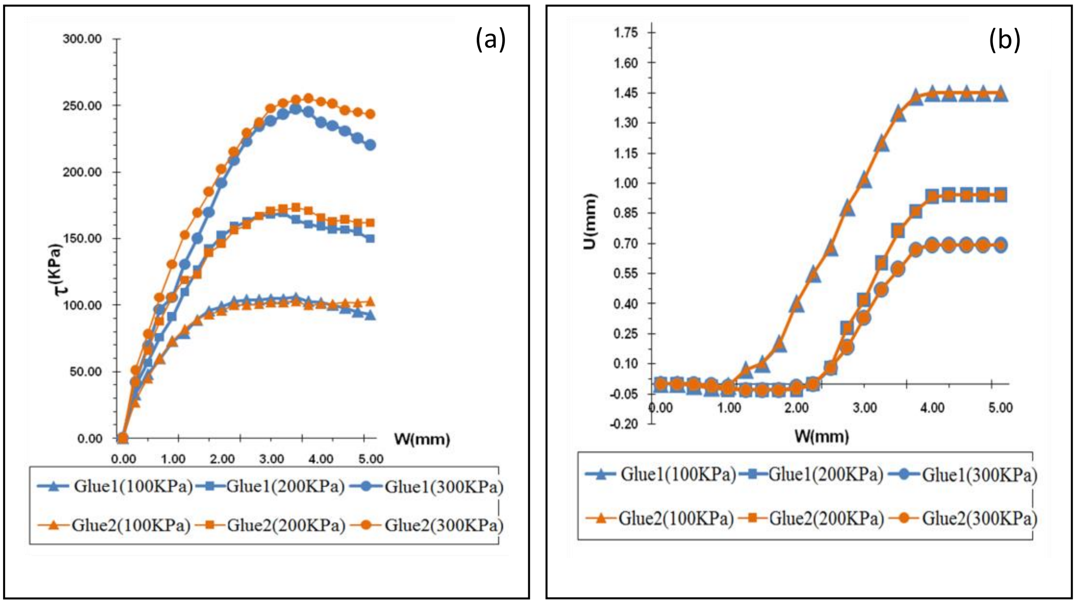


Figure 8 - Effect of adhesive type (rough steel surface/90% dense sand).

It is noticed in Figure 9 that, after each test, the rough surface remains unchanged, i.e. no separation of the grains.

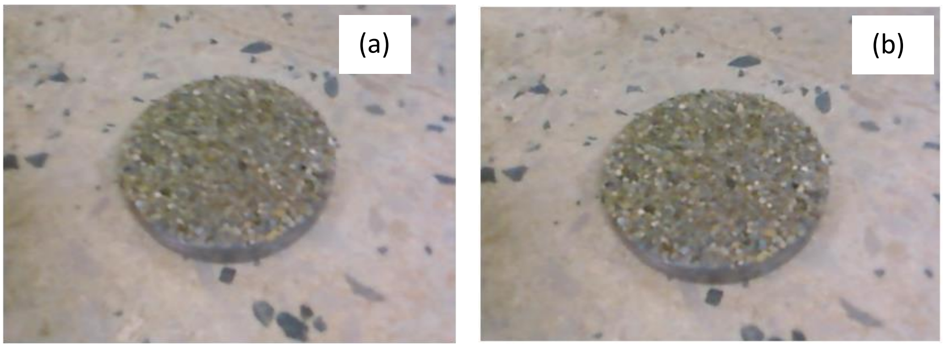


Figure 9 - Surface condition before the tests (a), and after the tests (b).

3. Theoretical modeling of the behavior of ground-structure interfaces

3.1 Equations of the Modjoin model

The Modjoin interface model (Bencheikh 1991) which is based on the elastoplasticity phenomenon was used to model the behavior of interfaces. It should be emphasized that according to this theory the increment of displacement with respect to the interface can be decomposed into an elastic contribution $\Delta\varepsilon_e$ and a plastic contribution $\Delta\varepsilon_p$. The displacement increment may therefore be expressed as:

$$\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p \quad (1)$$

The development of an elastoplastic constitutive law requires the formulation of expressions for the elastic behavior, the failure criterion, the load surface, the work hardening rule, and the plastic flow rule.

<u>Elastic behavior:</u> The nonlinear elastic constitutive law can be used for soils. This law is expressed using the following relationships:

$$\begin{cases} K = K_0 \left(\frac{\sigma_n}{P_a}\right)^{0.5} \\ G = G_0 \left(\frac{\sigma_n}{P_a}\right)^{0.5} \end{cases} \quad (2)$$

Where K and G are the elastic moduli of compressibility and shear, respectively, K_0 and G_0 are constants that characterize the interface, and P_a is the atmospheric pressure.

<u>Failure criterion and load surface:</u> The rupture criterion adopted in the present study is the Mohr-Coulomb criterion. The load surface equation is obtained by introducing a work hardening function R_m as follows:

$$f_m(\sigma_n, \tau, \varepsilon_t^P) = |\tau| - tg\phi.(\sigma_n + C).R_m \quad (3)$$

Where C and φ are two parameters representing, respectively, the cohesion and friction angle at the interface of the model.

<u>Work hardening rule:</u> Here, the plastic distortion is chosen as the hardening parameter. In order to simulate the stress peak and the softening phase, it was deemed appropriate to associate with the plastic distortion a function Rm which passes through a maximum and then decreases. Afterwards, R_m becomes stable for large distortions. The following expression is then adopted for R_m:

$$R_m\left(\varepsilon_t^p\right) = \frac{\alpha \varepsilon_t^p}{\beta\left(\frac{\sigma_{n0}}{P_a}\right)+\varepsilon_t^p} + A\left(\varepsilon_t^p\right)^2 e^{-B\varepsilon_t^p} \quad (4)$$

Here α, β, A and B are model constants, and σ_{n0} is the initial normal stress.

Plastic flow rule: The increment of the relative plastic displacement derives from a plastic potential g. For the sake of taking into account the concept of characteristic state, it seemed more appropriate to consider the following:

$$\frac{\partial g}{\partial \sigma_n} = \left[M_g - \frac{|\tau|}{\sigma_n}\right].A_g \quad (5)$$

With Mg = tg ψ and Ag are two parameters of the model.

Thus, eleven parameters ought to be determined from the experimental curves, namely:

- Two elastic parameters (K_0 and G_0),
- Nine plastic parameters (φ, c, R0, α, β, A, B, ψ, and ag).

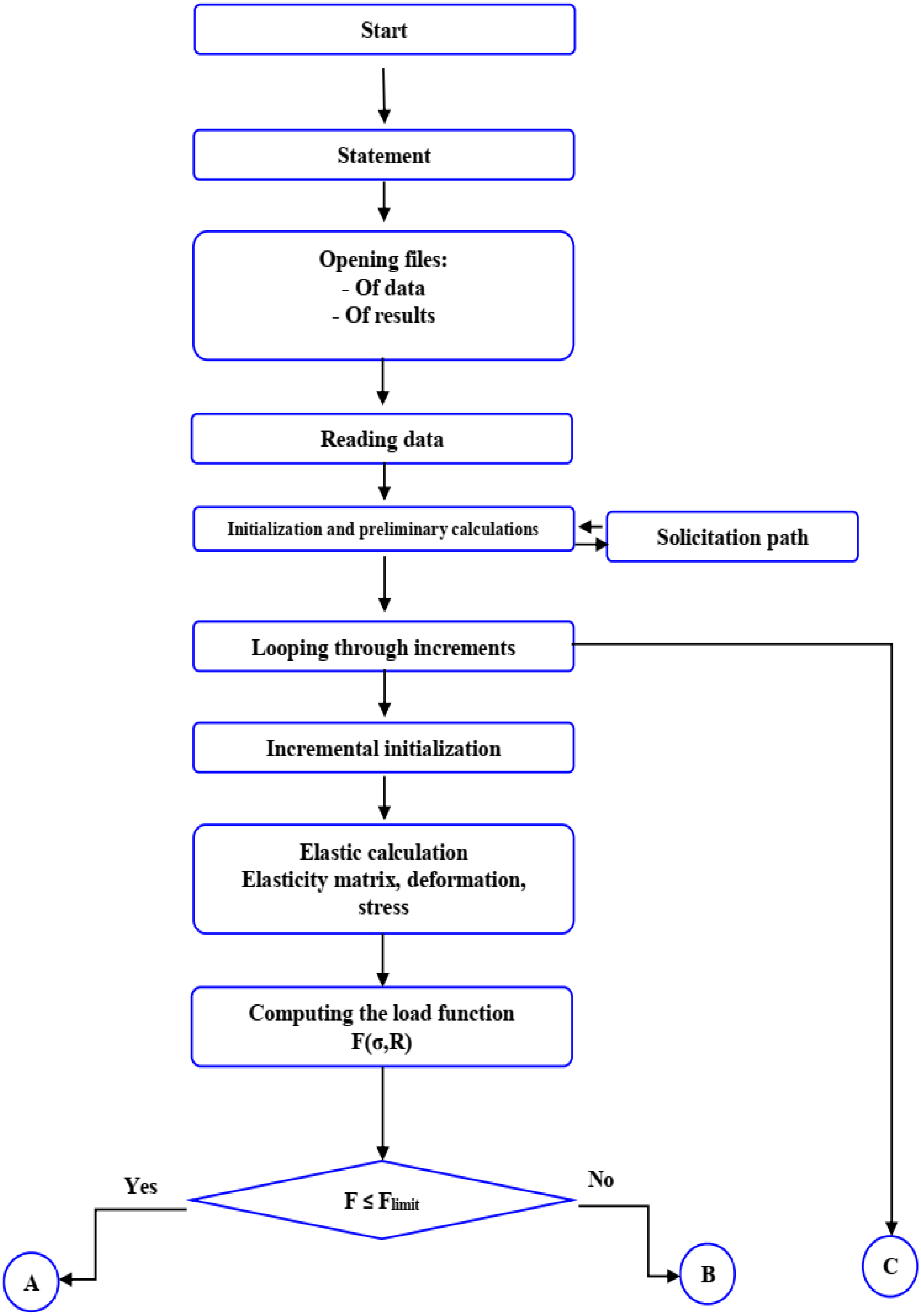
3.2 Validation of the model using experimental tests

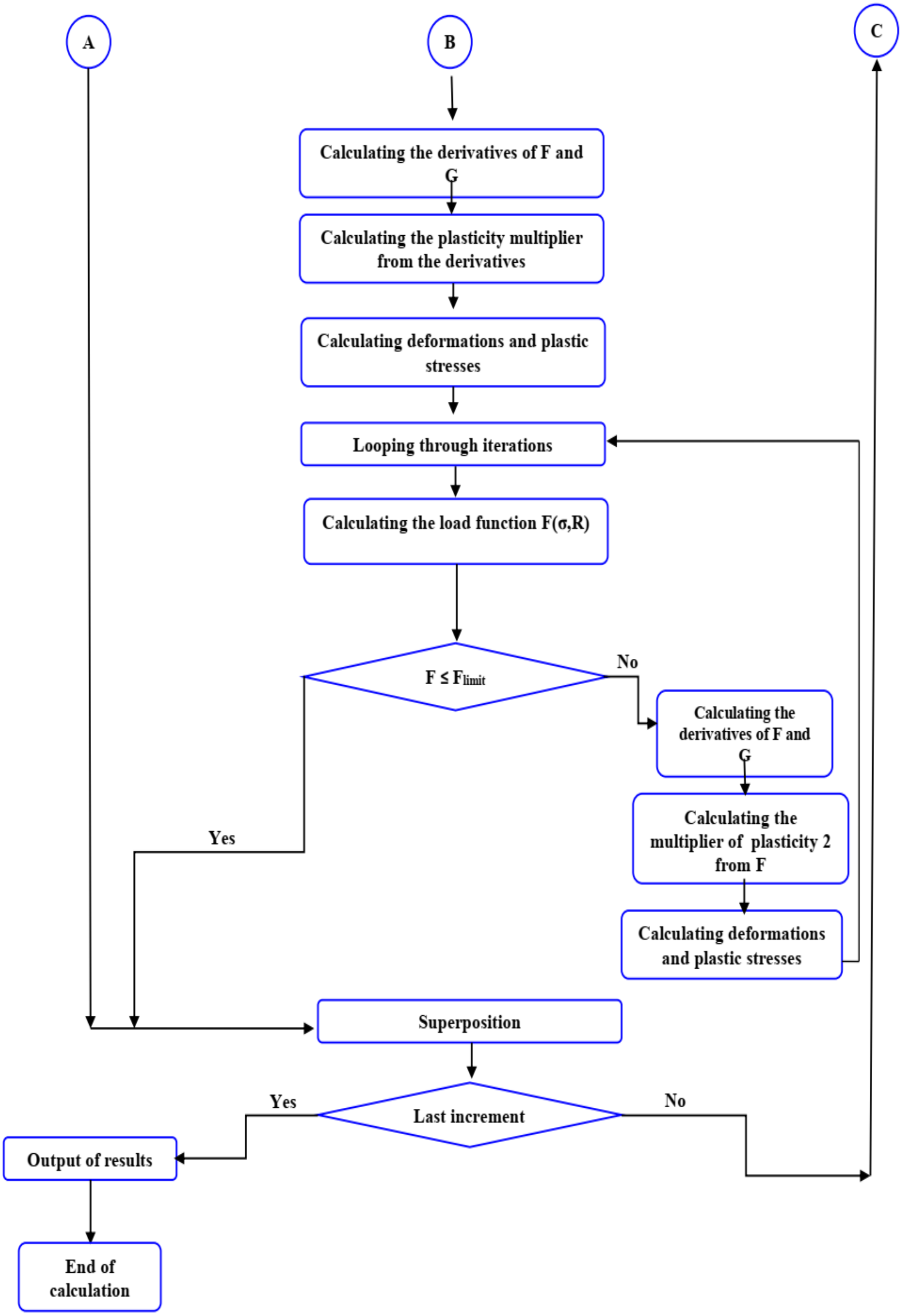
Once the model parameters have been determined (Table 1), the simulation results are then presented, using the Modjoin model and following the flowchart that is depicted in Figure 10. The tests were carried out with the sand from Messaâd, in dense and loose states, and steel structures with rough and smooth surfaces.

Table 1 - Different parameters for each type of test.

Tests	Ko/ (100 KPa/mm)	Go/ (100 KPa/mm)	φ/°	c	R0	α	β	A	B	ψ/°	ag
Smooth steel surface /15% loose sand	4	2.00	21.24	0	0.2	1	0.08	0	0	12.14	0.5
smooth steel surface/ 90% dense sand	4	2.00	29.06	0	0.2	1	0.08	0	0	20.85	0.5
Rough steel surface /15% loose sand	3	1.50	37.61	0	0.2	1	0.3	0.2	0.6	19.07	0.5
Rough steel surface /90% dense sand	3	1.50	40.29	0	0.2	0.89	0.2	0.36	0.8	17.36	0.5

Figure 10 - Flowchart for calculating the model under monotonic loading.




A
B
C
Calculating the derivatives of F and G
Calculating the plasticity multiplier from the derivatives
Calculating deformations and plastic stresses
Looping through iterations
Calculating the load function F(σ,R)
F ≤ Flimit
No
Yes
Calculating the derivatives of F and G
Calculating the multiplier of plasticity 2 from F
Calculating deformations and plastic stresses
Superposition
Last increment
Yes
No
Output of results
End of calculation

Dense sand/rough steel test: Figures 11 (a) and 11(b) present the simulation results of three tests at constant normal stress. It can be seen that the model describes quite well the evolution of the shear stress. It also reproduces the peak and softening properly. Regarding the evolution of the normal displacement, it is observed that the model correctly reproduces the contractance and dilatancy phases. However, these phases do not correspond exactly to those of the experimental curves, particularly at the end of the test. This is certainly due to grain breakage during the test.

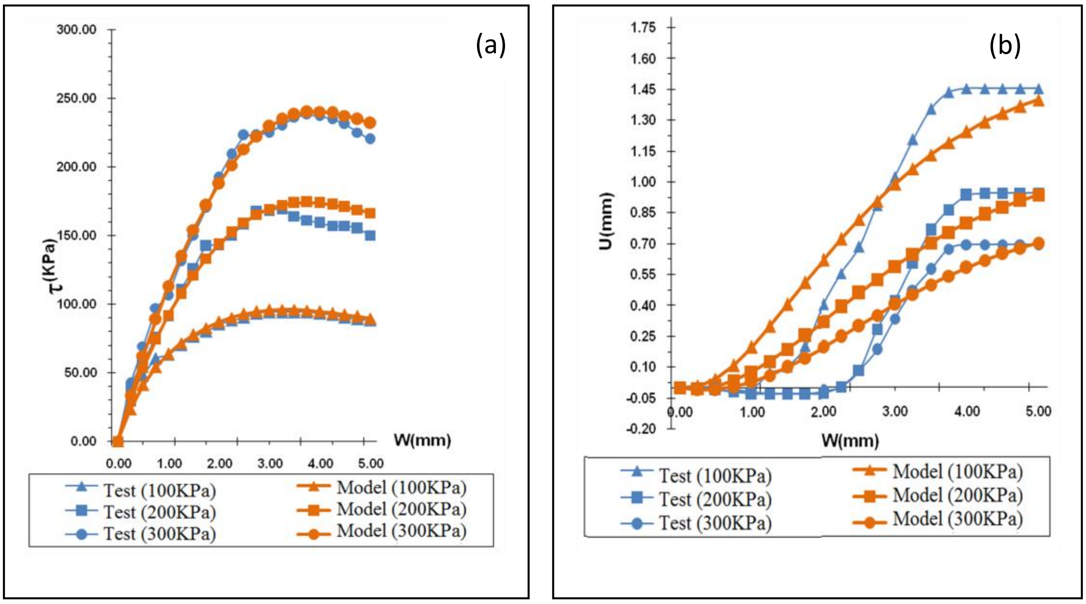


Figure 11 - Simulation of tests at constant normal stress (Rough steel surface/90% dense sand).

Dense sand/smooth steel test: Figures 12 (a) and 12 (b) indicate that the model describes quite accurately the evolution of the shear stress and normal displacement.

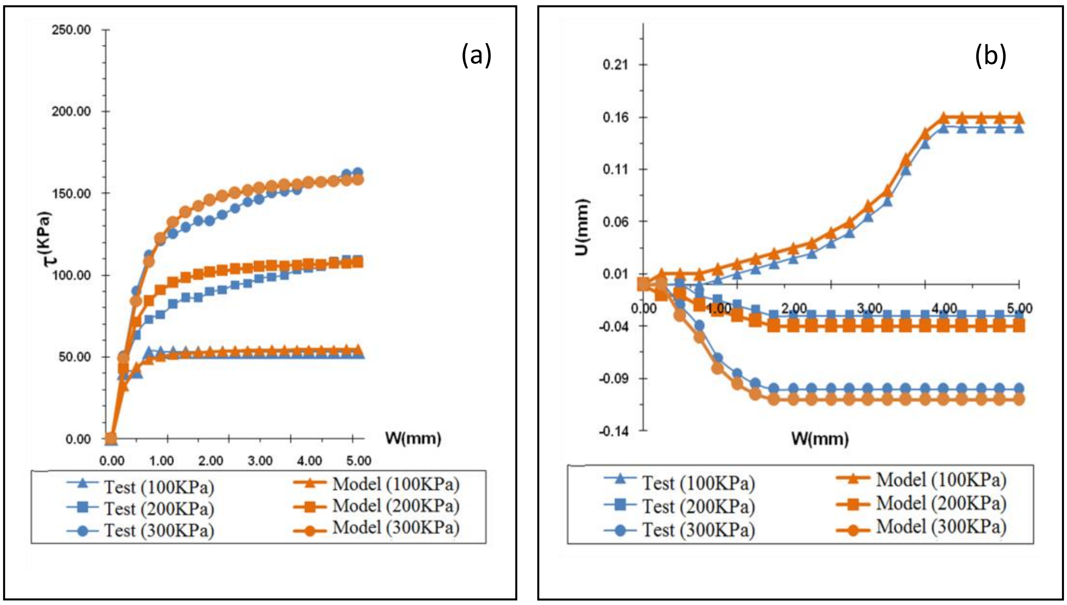


Figure 12 - Simulation of tests at constant normal stress (Smooth steel surface/ 90% dense sand).

3.3 Study of the effect of various parameters on the model response

This section aims to present a study whose findings can be used to better understand the functioning of the model and to show that it is highly important to determine the different parameters used here. The method adopted consists of studying the effect of the disturbance of each parameter on the response of the model.

<u>Effect of parameter φ:</u> Figure 13 (a) shows explicitly that the disturbance of the parameter φ has a significant effect on the peak and limit shear stress values. Likewise, Figure 13 (b) shows that this same parameter has a significant impact on the evolution of W. It has indeed been found that an increase in φ expands the dilatancy domain.

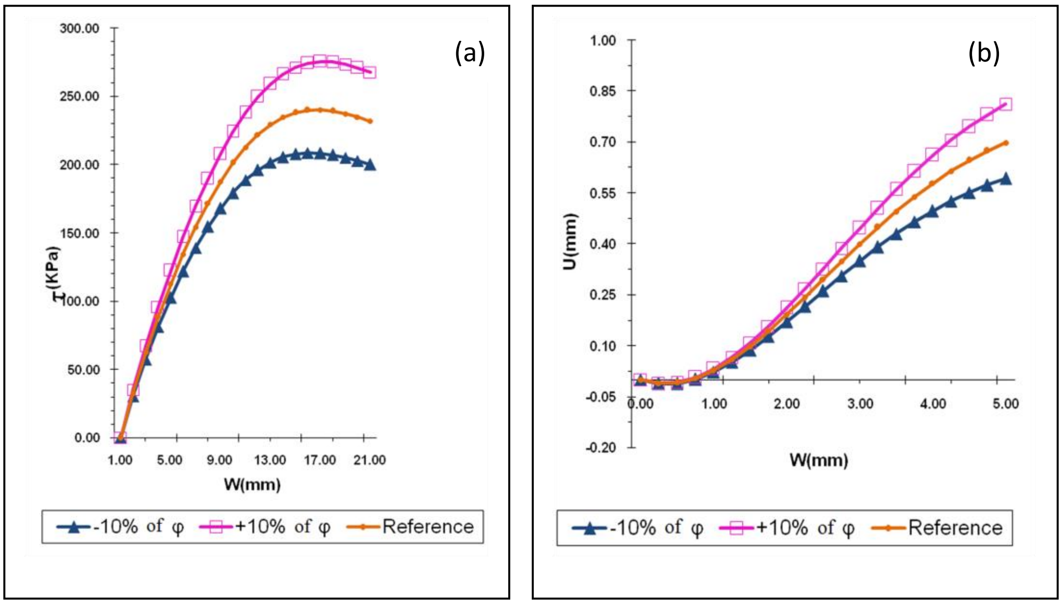


Figure 13 - Effect of parameter φ.

<u>Effect of the parameter ψ:</u> Figure 14 shows that the effect of ψ on the shear curve is practically zero. This parameter essentially influences the evolution of W. It has in fact been noticed that an increase in ψ enlarges the contractance but reduces the dilatancy, as illustrated in Figure 14(b).

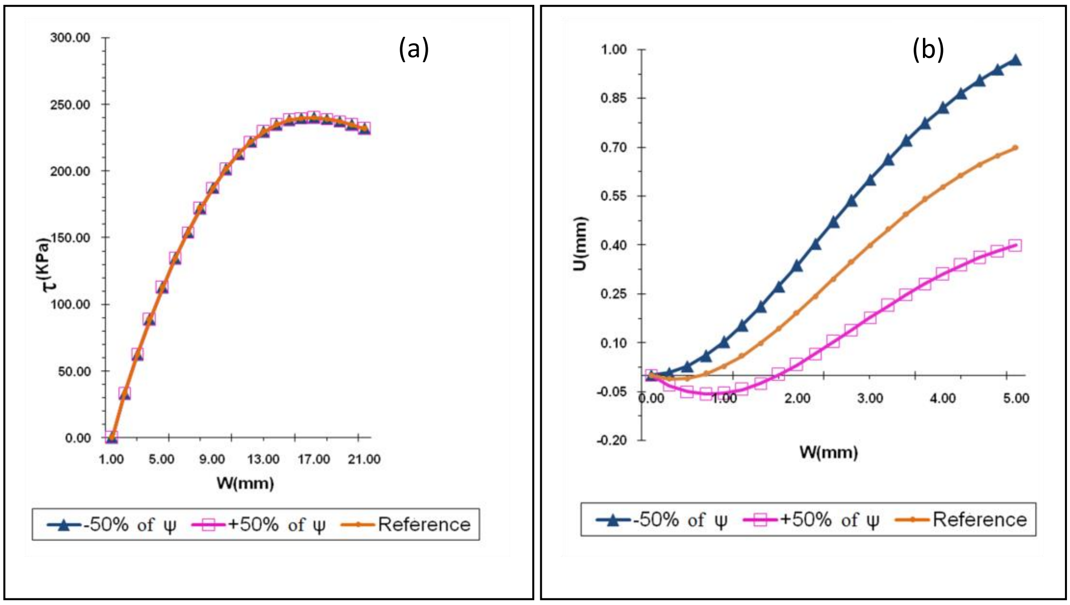


Figure 14 - Effect of parameter ψ.

4. Conclusion

Numerical simulation in geotechnics requires sufficient knowledge about the behavior of the soil mass and about the soil-structure interface zones. The development of laboratory tests can greatly contribute to the experimental study of soil-structure interfaces. In addition, the validation of behavioral models can help to reproduce the behavior of interfaces that are observed in the laboratory. The results of these tests show that there is an analogy between the behavior of powdery soils and that of soil-structure interfaces, and in particular with respect to the main aspects such as progressive plasticization, softening and the critical state in large displacements. Moreover, the behavior of the interface is highly influenced by some parameters such as the roughness of the structural surface and the density of sand. On the other hand, the type of adhesive used for grain bonding has practically no effect on the behavior of the soil-structure interfaces. Furthermore, the simulation of constant normal stress shear tests using the Modjoin model turned out to be quite satisfactory. It was indeed found that the model describes quite well the main aspects of the interface behavior, such as the stress peak, softening, characteristic states, and critical state in large displacements. Finally, the study of the sensitivity of the model to its parameters made it possible to better understand the role of each parameter and to identify the uncertainties in the determination of parameters.

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