Modelling of the Soil-Structure Interface Behavior by Direct Shear Tests under Monotonous Loading

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Abstract

This paper presents and analyzes the experimental and numerical results of a series of direct shear tests performed under monotonous loading on a dune sand, both loose and dense, in contact with a rigid steel plate, both smooth and rough. The direct shear tests were conducted by means of a modified Casagrande shear box. The calculations carried out using a finite elements computer program. Obtained results made it possible to determine the shear strength parameters characteristics of the sand-plate interface, and show a good agreement between experimental and predicted data. They show in addition that, for all considered levels of normal stress, the rough interface is more advantageous than the smooth interface, and more with a dense sand that with a loose sand of same type.

Keywords: *Sand-plate interface, Direct shear test, Experimental study, Numerical simulation, Plaxis.*

1 Introduction

Behavior of the geotechnical structures (reinforced slopes, retaining walls, shallow and deep foundations, tunnels and other underground excavations) is a problem of soil-structure interaction. Resolution of this problem requires knowledge of the soil-structure interface behavior under monotonous (dead and live loads) or cyclic (seism, wind and vibrations of machines) loadings in order to conclude the design of geotechnical structures. Various experimental techniques and numerical simulations were developed during these thirty last years (Uesugi and Kishida, 1986; Boulon, 1989; Shahrour and Bencheikh, 1992; Shahrour and Rezaie, 1993; Evgin and Fakharian, 1996; Hu and Pu, 2004; Khemissa et al., 2004 and 2015). However, some aspects of soil-structure interface behavior remain not elucidated.

This paper aims to present the experimental and numerical results of a series of direct shear tests under monotonous loading. The experimental tests were performed on a dune sand presenting two forms of compactness, one loose and the other dense, in contact with a rigid steel plate presenting two forms of roughness, one smooth and the other rough. The calculations include a numerical simulation of the experimental tests using the Plaxis finite elements code. It aims to study the sand-plate interface's behavior and to determine its principal properties according to proposed sand compactness and roughness shape of the chosen rigid steel plate. Followed experimental approach and carried out numerical simulation are initially described. Obtained principal experimental and numerical results are also analyzed.

2 Experimental Approach

Experimental data presented hereafter are based on a series of direct shear tests performed under monotonous loading by means of a modified Casagrande shear box. This device consist of two half-boxes: upper mobile half box filled with sand and lower fixed half box filled with the same sand (for the "sand-sand" shear tests) or with a rigid steel plate (for the "sand-plate" shear tests). Applied normal stresses were σ_v=100, 200 and 300 kPa. For each of these three considered normal stresses, the shear force is continuously applied until total demobilization of the interface friction ("sand-sand" or "sand-plate" interface).

Used dune sand is clean and uniformly graded. Its geotechnical characteristics are as follows:
- specific unit weight: γ_s=26.5 kN/m^3;
- minimum dry density: $\gamma_{d\text{-}min}$=1.50;
- maximum dry density: $\gamma_{d\text{-}max}$=1.73;
- coefficient of uniformity: C_u=2.33;
- coefficient of curvature: C_c=1.19.

Used plate consists of a galvanized steel of yield stress σ_e=240 MPa. Its interior surface can be smooth to simulate the smooth soil-structure interaction (Figure 1a), or rough by joining of sand grains on this one to simulate the rough soil-structure interaction (Figure 1b).

a/ Smooth steel plate *b/ Rough steel plate*

Figure 1. Photographs of the used smooth (a) and rough (b) steel plates placed in the lower fixed half box

3 Numerical Simulation

For understanding the interaction mechanism between the sand and the steel plate used in the experimental study and to highlight the influence of their parameters, direct shear test simulations were carried out using the classic Mohr-Coulomb model. Carried out simulations aim to determine the sand-plate interface properties starting from the experimental data described above. Calculation model simulates a shear box comparable to that used in the experimental study (Figure 2).

Dune sand is modelled as a Mohr-Coulomb elastoplastic behavior material characterized by its five parameters (E, ν, c, φ and ψ). The sand-plate interface is modelled as an elastoplastic material with the following reduced characteristics:

$$c_{int} = R_{int}\, c_{sand}$$
$$\tan(\varphi_{int}) = R_{int} \tan(\varphi_{sand})$$

where c_{sand} and φ_{sand} represent the sand shear parameters and R_{int}=0.1 to 1 the interaction coefficient characterizing the interface form (i.e. factor of form). Table 1 gives the material properties fixed for the sand, the steel plate and their interface.

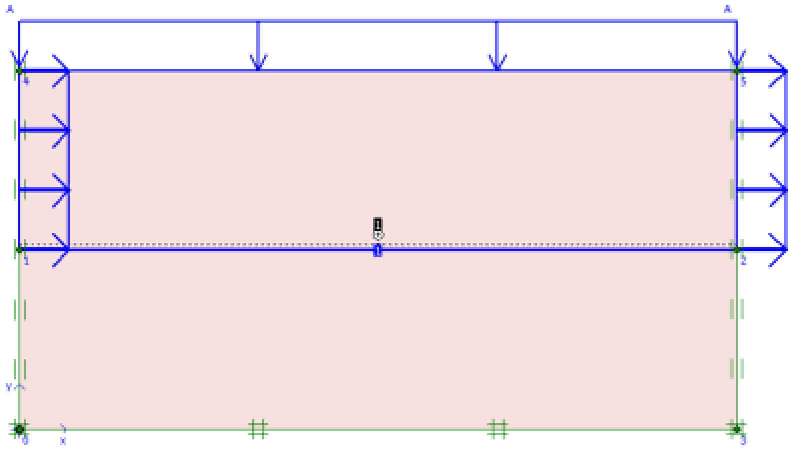


Figure 2. Geometry model adopted for the direct shear box

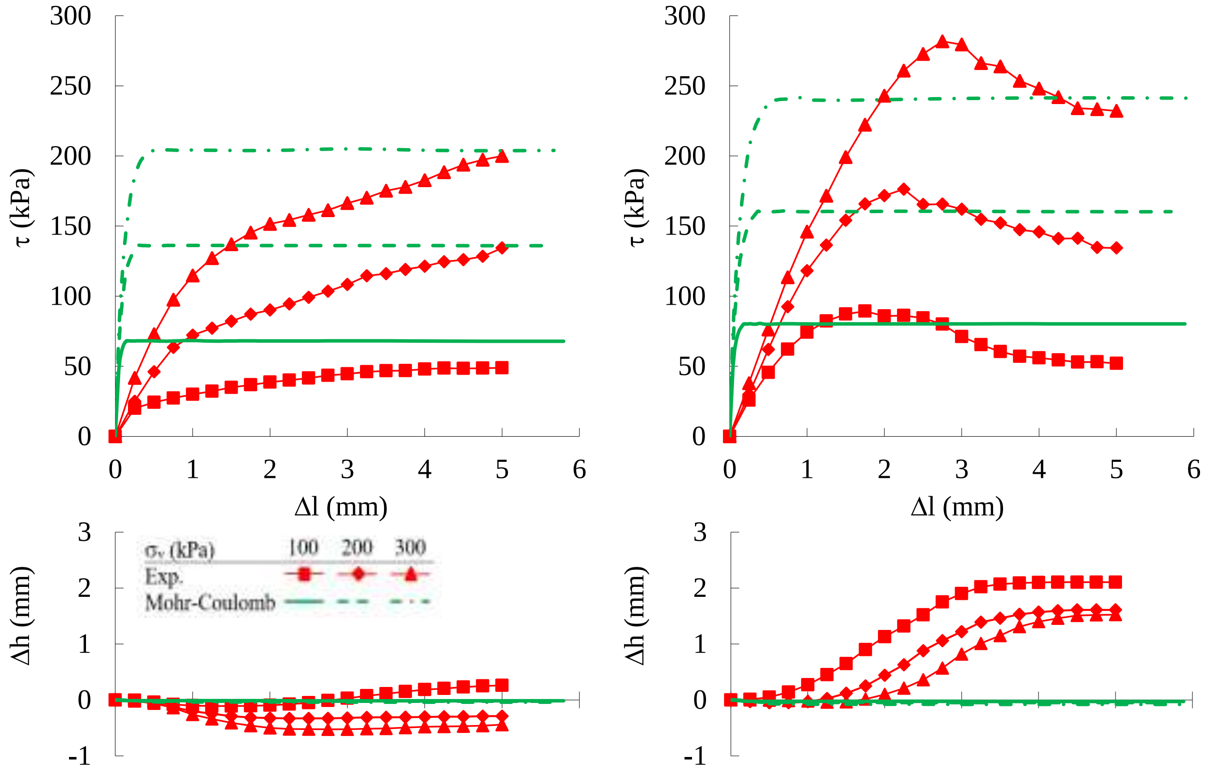
Table 1. Material properties fixed

	Sand	
Compactness State	**loose**	**dense**
Dry unit weight γ_d (kN/m^3)	15	17
Young's modulus E_{ref} (kN/m^2)	$3x10^5$	$5x10^5$
Poisson's ratio ν	0.3	0.3
Cohesion c_{ref} (kN/m^2)	0.1	0.1
Interne friction angle φ' (°)	38	43
Dilatancy angle ψ (°)	8	13
Factor of form R_{int}	0.9	0.9
	Plate	
Normal rigidity EA (kN/m)	$1.26x10^{10}$	
Bending rigidity EI (kNm^2/m)	236.25	
Poisson's ratio ν	0.2	
	Sand-plate interface	
Interface form	**smooth**	**rough**
Interface cohesion c_{int} (kN/m^2)	0.1	0.1
Interface friction angle φ_{int} (°)	38	43
Interface dilatancy angle ψ_{int} (°)	8	13
Factor of form R_{int}	0.3	0.9

After generation of the mesh and initial stresses initiation (K_o-procedure), the calculation comprised an application phase of the considered normal stress followed by a shear phase by application of a prescribed displacement of the upper mobile half box. The prescribed displacement is maintained increasing until total demobilization of the friction interface. In addition to the shearing properties of used sand, the calculations make it possible to determine the interface properties corresponding to the two types of roughness retained (smooth and rough) according to compactness state of used sand (loose and dense).

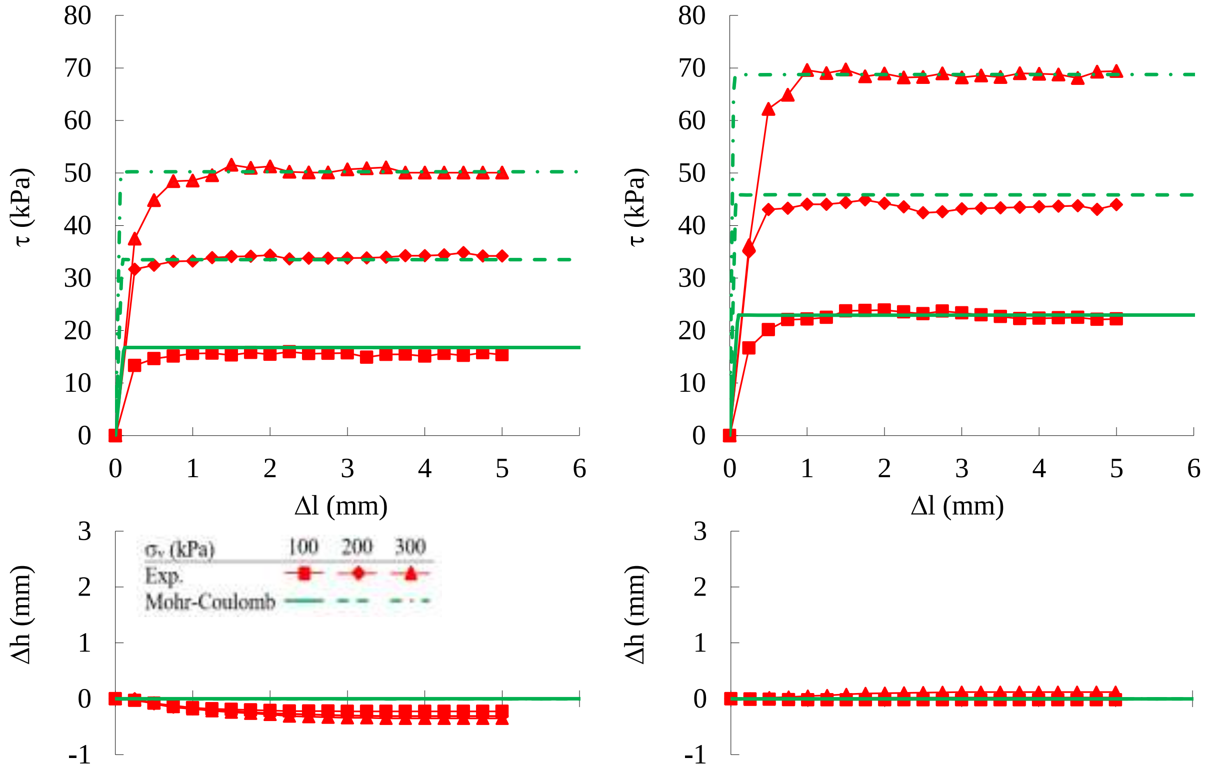
4. Discussion of the Experimental and Numerical Results

Figures 3a, 3b and 3c show the experimental and predicted shear curves, respectively, for the sand alone, the smooth sand-plate interface and the rough sand-plate interface. These curves take quasi-similar forms for each state of sand compactness. They describe a behavior characterized by an increase of the interface shear strength (highlighted of the friction mobilization by adherence between the sand and plate) followed by a peak more or less delivery for dense sand (corresponding to the shear strength at rupture) and of a stage corresponding to ultimate shear strength for loose sand (failure load by adherence defect). One can also note that, when the normal stress increases, the shear rate decreases but the failure strength increases. This explains that the normal stress increasing agrees with a better adherence between the sand and plate. In addition, one can note a good agreement between the experimental and predicted data.



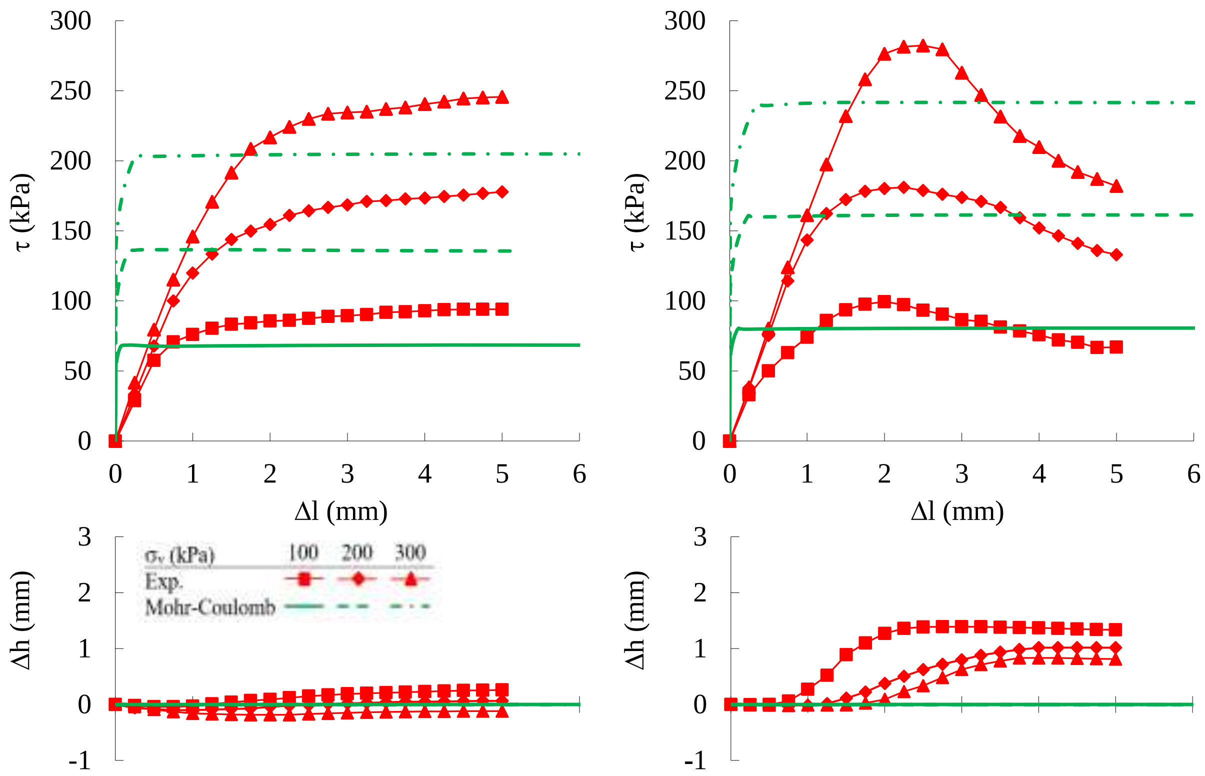
a/ Loose sand *b/ Dense sand*

Figure 3a. Comparison of the experimental and predicted direct shear curves for the sand alone



a/ Loose sand *b/ Dense sand*

Figure 3b. Comparison of the experimental and predicted shear curves for the smooth sand-plate interface



a/ Loose sand *b/ Dense sand*

Figure 3c. Comparison of the experimental and predicted shear curves for the rough sand-plate interface

Qualitative analysis of the experimental and numerical results calls the following remarks:

- the ultimate shear strength increases with normal stress. It is higher for rough interface than for smooth interface, and more with dense sand than with loose sand;
- the ultimate shear strength can be defined by the yield shear stress (corresponding to the shear peak value) for dense sand and by the residual stress (corresponding to the asymptote) for loose sand, as well for smooth interface as for rough interface;
- the interface's roughness influences positively the composite material behavior and appears by mobilization of the friction between the sand and plate (i.e. improvement of their adherence);
- the factor of form R_{int} is higher for rough interface than for smooth interface, and more with dense sand that with loose sand (Figure 4).
- the sand-plate interface friction angle φ_{int} is higher for rough plate than for smooth plate, and more with dense sand that with loose sand (Figure 5).

The values of $R_{int}>1$ show that the rough plate provide a supplement of resistance, as well for loose sand (where $\varphi_{int}> \varphi_{sand}=38°$) as for dense sand (where $\varphi_{int}> \varphi_{sand}=43°$). One can conclude that the rough interface is more advantageous than the smooth interface, and more with dense sand that with loose sand of same type.

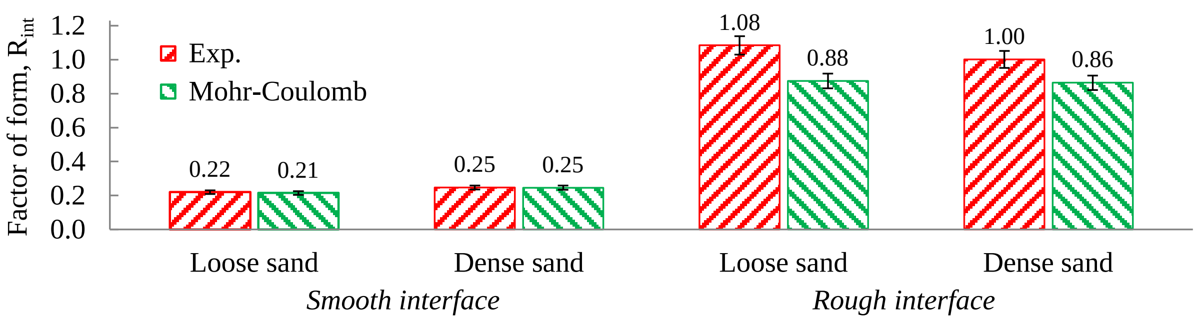


Figure 4. Comparison of the experimental and predicted factor of form values for the sand-plate interface

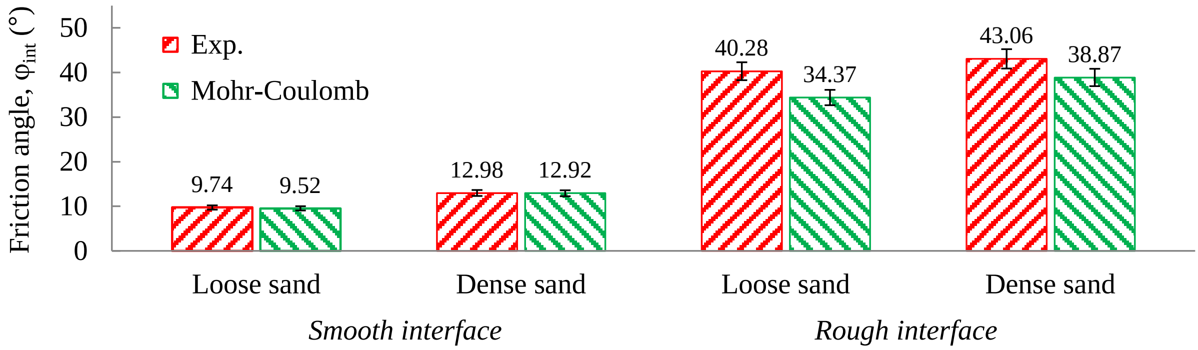


Figure 5. Comparison of the experimental and predicted sand-plate interface friction angles values

5. Conclusion

Experimental and numerical direct shear test results presented in this paper constitute an additional proof of roughness's influence of the soil-structure interface and their interaction with the geotechnical structures. The operation mechanism of composite material depends on the geotechnical characteristics of material constituting the structure to reinforcing and on the geometrical and mechanical characteristics of used reinforcement systems.

Comparative study made on adherence and on shear strength of the sand-plate interface makes it possible to conclude that the rough interface is more advantageous than the smooth plate, and more with dense sand that with loose sand of same type. However, the performance of a given rough interface is a function of the abutment mobilized by the considered roughness’s form.

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