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Scale effect in shaft friction from the interface direct shear tests

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The thickness of the shear band mobilised on the pile shaft subjected to loading is practically the same for a small model and a large diameter prototype. At the same normal stress to the shaft of the model and of the prototype pile, the normal stiffness of the interface and so the shear conditions are however different for the both cases. Lateral friction measured on the model and the prototype will differ. This scale effect in shaft friction related to the ratio diameter of the model to mean grain size is studied with the interface direct shear tests, where the pile diameter is modelled with a constant normal stiffness applied to the shear box. The scale effect larger than 1 is obtained for the dilative soil behavior within the interface. The value of the scale effect smaller than 1 is deduced from the interface direct shear tests with the soil contractancy.

Keywords: model tests, direct shear box, constant normal stiffness

1. Introduction

In physical modelling some distortions with respect to the prototype conditions, related to the grain size, can occur in granular soils. They are not taken into account by the general similitude equations. These distortions are due to formation of shear bands at the interface between the soil and structure as for pile foundations, anchors and nailing or to localization of the deformation in shear bands within the soil mass for retaining walls or shallow foundations. Observations of the sheared zone in the interface direct shear box together with a research on localization has shown that the thickness of the shear bands depends mainly on the average size of grains, and is typically about ten grain diameters, Desrues (1990). As the same soil is generally used in the model and the prototype, a distortion in physical modelling of foundations will be observed. When the behavior of the foundation is governed by the mechanism of localization of the deformations in shear bands within the soil mass or by a formation of sheared zone at the interface between soil and structure, then a scale effect related to the ratio size of the model to mean size of grains will appear. When the shear mechanism in the pile-soil interface is approximated with direct shear test, the different boundary conditions (i.e. the normal stiffness) will be applied for a small diameter model and a large diameter prototype pile.

The development of new apparatus in physical modelling, like centrifuge, where the miniaturization of models is imposed by the limited size of the container, demands the possible scale effect to be verified and quantified. One should note that if this scale effect can produce some problems in physical modelling interpretation in granular material, it could be practically used and explored in the design of anchores and nails in granular material, Wernick (1978), Schlosser and Guilloux (1981), Lehan et al. (1993).

The scale effect in the case of shallow foundations has been studied by Habib (1985), Kimura et al. (1985) Tatsuoka (1991). They presented some requirements concerning the minimal size of the foundation with respect to the grain size in order to avoid the scale effect related to localization of deformations within the soil mass.

Two distinct types of the soil behavior within the interface can be distinguished. The first one corresponding to the soil-pile interface presenting dilative behavior, and the second one, in which the soil within the interface tends to contract during shearing. Analysis of the interface mechanisms has shown, Boulon and Foray (1986), Boulon (1988), that a significant scale effect in the shaft friction measured on model piles can be expected due to formation of shear bands along the pile shaft. The scale effect on the shaft friction for rough model piles of different diameter (from 16 mm to 55 mm) embedded in dense quartz Hostun sand was studied in the centrifuge, Bałachowski (1995), for the dilative interface. These results were compared to the prediction given by the analysis of the interface mechanisms and the results of the interface direct shear tests using different normal stiffness, Foray et al. (1998). Garnier and König (1998) performed a series of centrifuge tests with rough surface inclusions of different diameter (from 4 mm to 36 mm) embedded in dense Fontainebleau sand and the evaluated scale effect was similar to the previous results. For completely smooth shafts, the skin friction in pull-out tests, Reddy et al. (2000), was practically the same regardless the diameter of inclusion, and any scale effect due to shear band formation along the pile shaft was not observed.

In this paper a complementary approach to centrifuge tests is presented and the scale effect in lateral friction due to shear band formation within the interface is evaluated from the interface direct shear tests. It is estimated not only for the dilative interface as it was realized in centrifuge test, Bałachowski (1995), Foray et al. (1998), but for the contractive interface as well. Here, some quartz and carbonated sands are considered.

2. Interface direct shear tests

In a first approximation, the mechanism of the mobilisation of the skin friction along the pile shaft can be considered to be similar to an interface direct shear test with constant normal stiffness (CNS) k, corresponding to the lateral stiffness of the surrounding soil, as suggested in Fig. 1. Volumetric changes of the soil within interface induce the normal displacement in the surrounding soil and changes in the normal stress to the shaft. A simple calculation, Wernick (1978), shows that k can be related to the pressuremeter modulus of the soil E_p (or G) by:

$$k = \frac{\Delta\sigma_n}{\Delta u} = \frac{2E_p}{R} \tag{1}$$

where:
$\Delta\sigma_n$ - the increment of the normal stress to the shaft,
Δu - the increment of the normal displacement,

E_p - the pressuremeter modulus,
R - the pile radius.

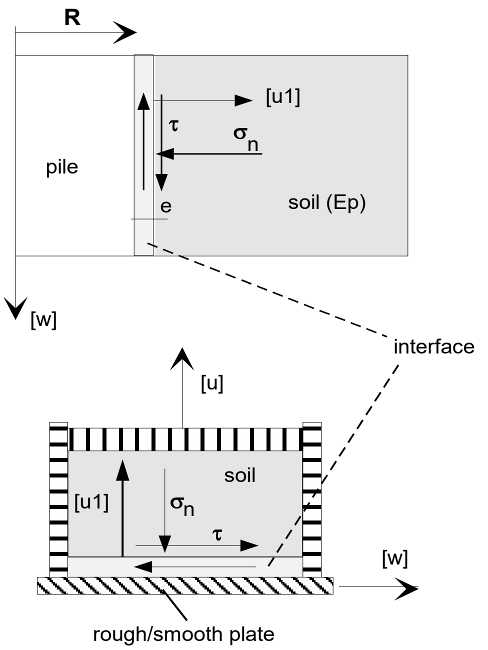

Fig. 1. Analogy between shear mechanism on the pile shaft and the interface direct shear test with constant normal stiffness, Boulon (1986).

The extensive research program on the behavior of the soil-structure interfaces was developed by Plytas (1985), Boulon and Foray (1986), Boulon (1988), Genevois (1989) and Hoteit (1990) for quartz and carbonated sands using the interface direct shear box with CNS and smooth and rough interfaces. Airey et al. (1992) developed cyclic direct shear interface tests with CNS for carbonated sands and studied skin friction degradation due to cyclic shearing.

In the case of contractive behavior of the soil within the interface the normal stress tends to decrease during shearing. For a given interface and an initial normal stress this tendency is more evident at higher normal stiffness imposed to the box. Let us consider the dilative soil behavior within the interface. As the soil tendency to dilate within the interface is restrained by the surrounding soil mass (normal stiffness imposed to the box), a significant increase of the normal stress can be observed during shearing. The higher normal stiffness imposed to the box, the higher normal stress is mobilized in the interface direct shear test. The maximal dilatancy within the interface will be observed for dense sand, rough plate, small normal stress and high normal stiffness. The maximal soil contractancy is expected for loose sand, smooth plate, high normal stress and high normal stiffness imposed to the box. Carbonated sand will contract more than quartz sand during shearing.

One should note that the normal stiffness is applied to the upper part of the shear box and no to the interface itself. Normal displacement u_1 at the boundary of the interface (Fig.1) is larger than the displacement u applied to the upper plate of the shear box. The normal stiffness applied to the shear box and the measured shear stress should be theoretically corrected for the compressibility of the soil sample in the upper part of the shear box. This correction could be realised taking into account unload-reload modulus measured either in oedometric conditions or in pressuremeter test. The influence of the soil compressibility in the upper part of the box can be however considered negligible, as the unload-reload modulus is even several times higher than the initial tangent one at given stress level.

3. Definition of scale effect

A schematic presentation of the maximum shear stress as a function of CNS k is given in Fig. 2 for the interface presenting dilative behavior. As the normal stiffness applied to the box is inversely proportional to the pile radius, it should be higher for a model pile than for a large diameter prototype. Thus, at a given depth represented by a given initial normal stress, and for a given sand density and interface roughness, a higher shear stress should be obtained in the case of a small diameter model pile ($\tau_{k\ model}$) than along the large prototype pile ($\tau_{k\ prototype}$).

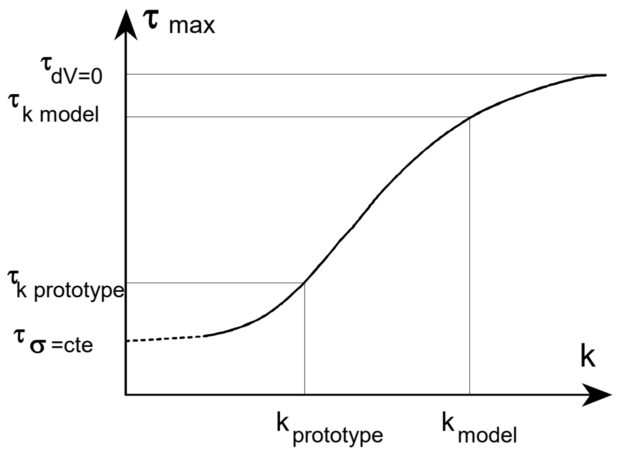

Fig. 2. Maximum shear stress vs. constant normal stiffness - dilative behavior, Genevois (1989).

An analogue schematic presentation of the maximum shear stress with the CNS k is given in Fig. 3 for the contractive interface. In that case, at a given initial normal stress, sand density and interface roughness, a higher shear stress should be measured along the large diameter prototype pile ($\tau_{k\ prototype}$) than for a small diameter model pile ($\tau_{k\ model}$).

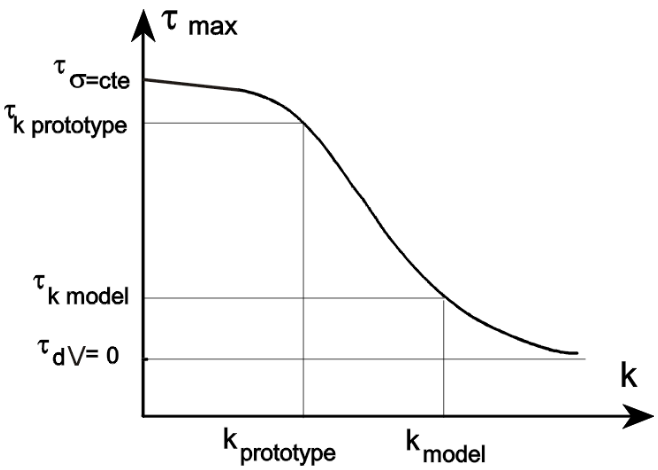

Fig. 3. Maximum shear stress vs. constant normal stiffness - contractive behavior.

The scale effect for shaft friction τ^* can be estimated from the interface CNS tests according to the schemes on Fig. 2 and Fig. 3:

$$\tau^* = \frac{\tau_{k\,model}}{\tau_{k\ prototype}} \tag{2}$$

It will be larger than 1 for the dilative interface or smaller than 1 in case of the contractive behavior of the soil within the interface. For a given interface (soil mineralogy, soil density, initial normal stress, grain size and plate roughness) this scale effect τ^* should be a function of the imposed normal stiffness, and for a given soil it should be related to the pile diameter.

3.1 Maximal scale effect

The extreme range of the normal stiffness will be either for large diameter piles with low volumetric changes within the interface, which corresponds to a classical shear test with constant normal stress conditions (k=0) or for small diameter model piles with strong interface dilatancy/ contactancy, which corresponds to the shear test with a high CNS. The upper boundary of normal stiffness is no volume changes condition (k=∞).

Three different Hostun quartz sands were considered: medium (d_{50}=0.32 mm), coarse (d_{50}=0.7 mm) and gravel (d_{50}=1.2 mm). An analysis of the interface direct shear tests with constant normal stress, Hoteit (1990) and Plytas (1985), shows that the maximum shear stress for sands of the same mineralogy is practically independent of the grain size (Fig. 4 and Fig. 5). This conclusion will not be valid for very large normal stress applied to the box, or for carbonated sands, when a considerable grain crushing occurs, being function of the grain size. On the other hand the shear stress mobilized at CNS test should be related to the dilatancy/ contractancy in the interface.

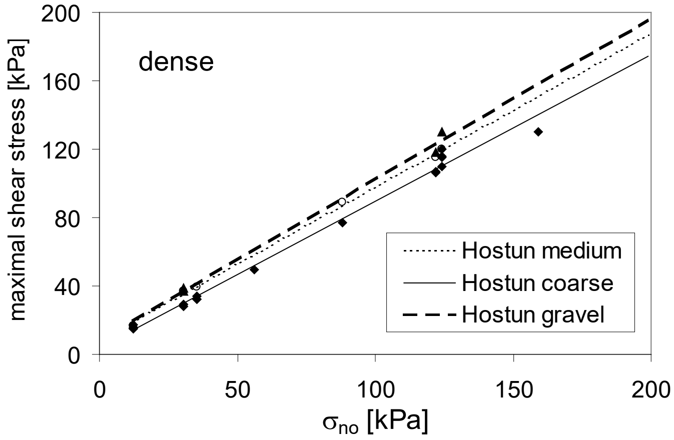

Fig. 4. Maximal shear stress from interface direct shear test at constant normal stress - rough plate - Hostun material (I_D≈0.8).

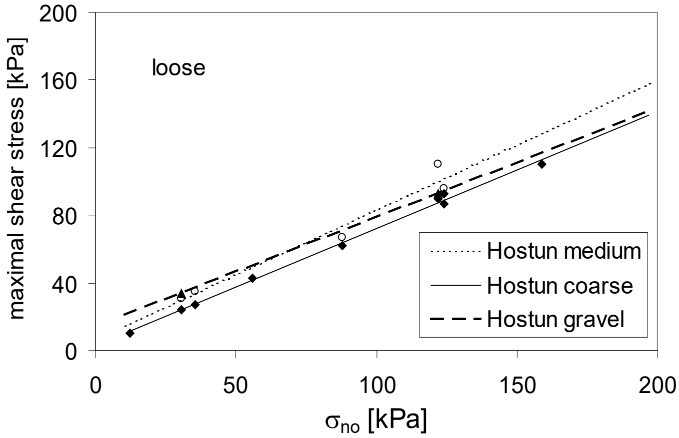

Fig. 5. Maximal shear stress from interface direct shear test at constant normal stress - rough plate - Hostun material (I_D≈0.3).

The maximal scale effect in the given interface direct shear test is determined taking into account two boundary conditions: no volume changes (k=∞) and constant normal stress (k=0):

$$\tau^*_{\max} = \frac{\tau_{(k=\infty)}}{\tau_{(k=0)}} \tag{3}$$

The results of the interface direct shear tests at these two boundary conditions are given on Fig. 6 for Hostun medium sand.

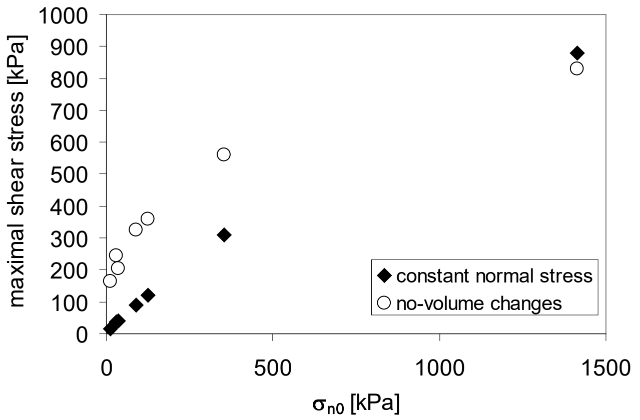

Fig. 6. Maximal shear stress at two extremal boundary conditions – dense Hostun medium sand, rough plate.

The value of the maximal scale effect in friction for the interface presenting highly dilative behavior (high density-rough plate) is given in Fig. 7 for two quartz sands, having the same mineralogy but different grain size. The larger grain size of the sand, the higher maximal scale effect (up to 20) to be observed in the interface direct shear test, specially at low initial normal stress applied to the shear box. The value of the maximal scale effect attenuates with initial normal stress and becomes negligible for very high initial normal stress.

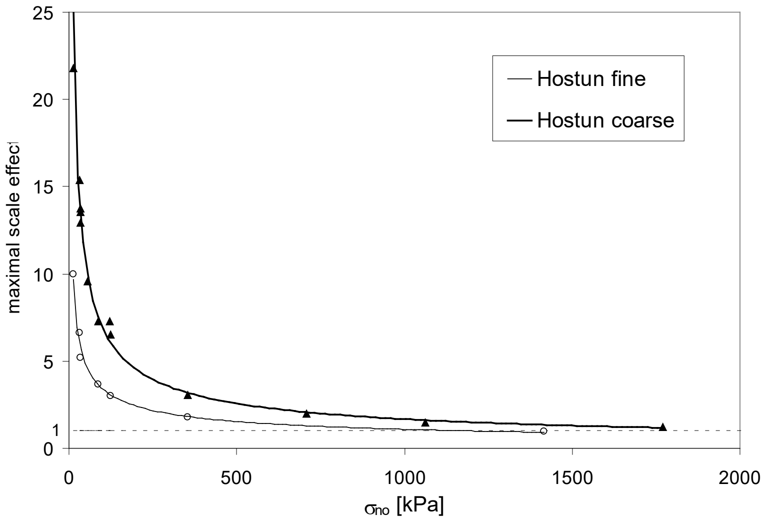

Fig. 7. Maximal scale effect from the interface direct shear box for two quartz sands and rough plate.

Maximal (less than 1) scale effect in friction for the contractive interface is given in Fig. 8 for a smooth plate and two loose sands: quartz Hostun coarse and carbonated Quiou sand, Hoteit (1990) and

Plytas (1985). The highest scale effect is observed at low initial normal stress and steadily increases with initial normal stress applied to the shear box. For quartz sand the difference between the shear stress at constant normal stress and no volume changes shear tests will attenuate at high initial normal stress (about 2000 kPa). Due to important grain crushing in the shear box tests with carbonated sand, the maximal scale effect is lower in carbonated than quartz sand and does not converge to value of 1.

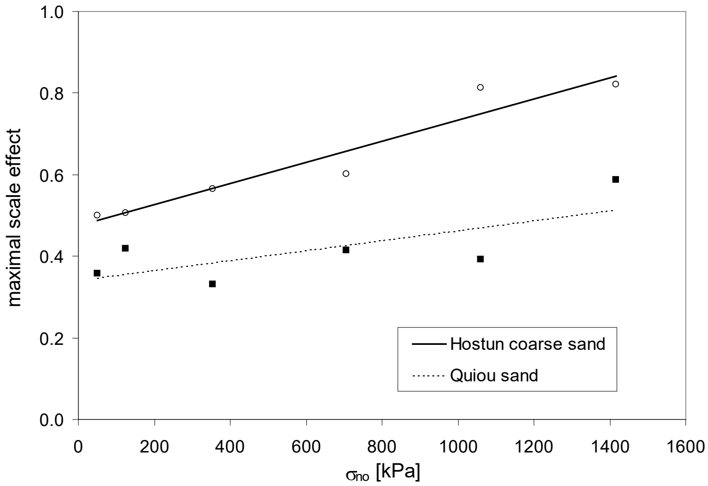

Fig. 8. Maximal scale effect from the interface direct shear box for quartz Hostun sand and carbonated Quiou sand.

3.2 Scale effect for model piles

The scale effect corresponding to the model piles of a given diameter can be estimated from the interface direct shear tests with CNS and shear modulus or pressuremeter modulus determined in calibration chamber according to the following procedure:

- for a given depth or vertical stress, the pressuremeter modulus is estimated,
- earth pressure coefficient at rest K_0 is estimated,
- initial normal stress acting on the pile shaft is calculated according to formula (4),
- the constant normal stiffness k is calculated for each model and the prototype pile according to formula (1)

$$\sigma_{n0} = K_0 \sigma_v^{'} \tag{4}$$

Taking into consideration the pressuremeter modulus data (Fig. 9) determined in the calibration chamber by Mokrani (1991) for two dense quartz sands and the results of the interface direct shear tests with CNS, it is possible to estimate the constant normal stiffness for the model and the prototype piles.

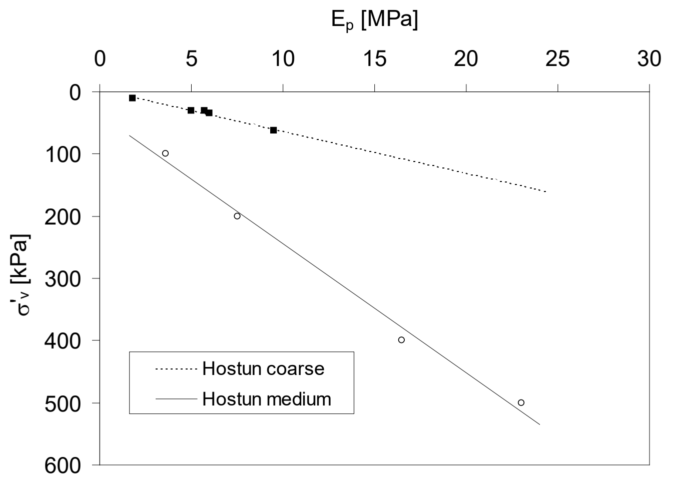

Fig. 9. Pressuremeter tangent modulus in dense sands determined in the calibration chamber in Grenoble.

3.2.1 Dilative interface

The values of maximal shear stress vs. imposed normal stiffness are available for dense Hostun medium (Fig. 10) and dense Hostun coarse sand (Fig. 11) and rough plate, Bałachowski (1995). One can estimate the shear stress corresponding to a given stiffness and initial normal stress for the model and for the prototype. The results of the interface direct shear tests at constant normal stress were applied for the prototype pile 1600 mm in diameter, as its normal stiffness of the interface does not exceed 100 kPa/mm for both Hostun sands. For example, the normal stiffness for a prototype pile embedded in medium sand, calculated with (1) at effective overburden stress σ'_v = 200 kPa will be equal to 20 kPa/mm.

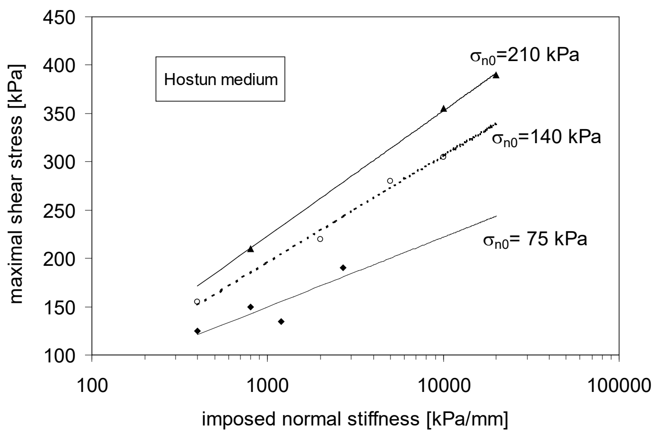

Fig. 10. Interface direct shear tests at CNS for dense Hostun medium sand - rough plate.

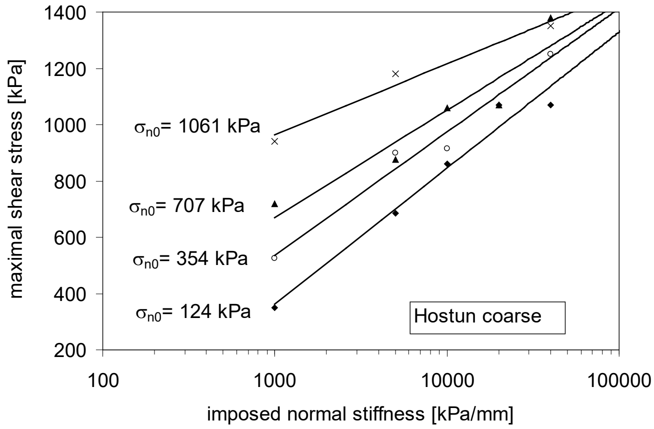

Fig. 11. Interface direct shear tests at CNS for dense Hostun coarse sand - rough plate.

For a given depth (initial normal stress), the scale effect is determined to be the ratio of the maximal shear stress estimated for the model and for the prototype. It is presented in Fig. 12 for Hostun medium sand as a function of the imposed normal stiffness.

The interface analysis showed that the shear band width *e* is a function of mean grain diameter d_{50}. Here, it was assumed that :

$$e \approx 10 \cdot d_{50} \tag{5}$$

For a given initial normal stress σ_{n0}, constant normal stiffness k and the pile diameter D, (D/e) ratio was calculated. Then the maximal shear stress (Fig. 13) and the scale effect (Fig. 14) in lateral friction were presented as a function of (D/e) ratio and the initial normal stress applied to the box.

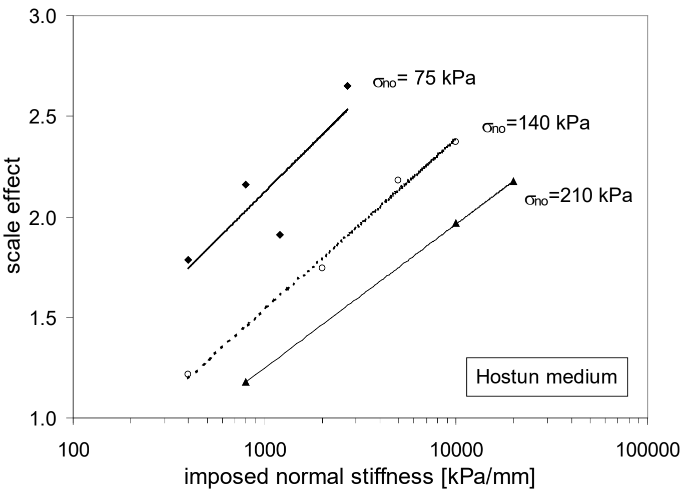

Fig. 12. Scale effect vs. imposed normal stiffness for dense Hostun medium sand - rough plate.

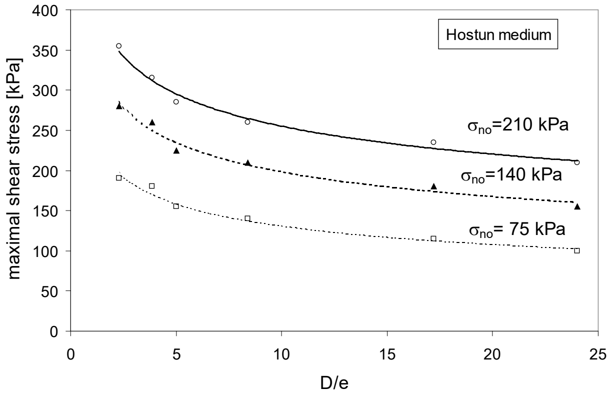

Fig. 13. Maximal shear stress vs. (D/e) ratio for dense Hostun medium sand - rough plate.

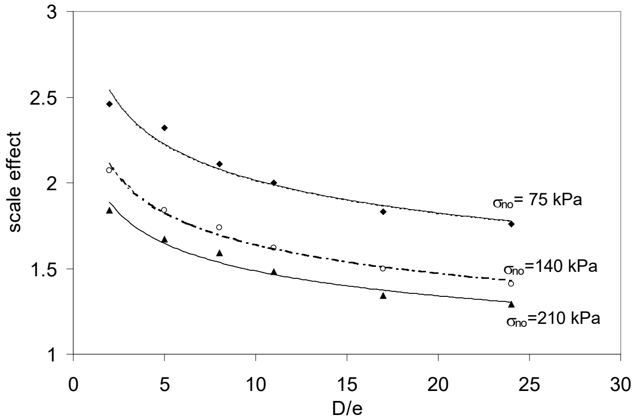

Fig. 14. Scale effect from interface direct shear test with CNS vs. (D/e) ratio - dense sand and rough plate.

3.2.2 Contractive interface

In the case of contractive behavior of the interface, the maximal shear stress decreases steadily with the imposed normal stiffness applied to the shear box (Fig. 15 and Fig. 16), Hoteit (1990). The corresponding scale effect for loose quartz Hostun coarse sand and loose carbonated Quiou sand and smooth plate is given on Fig. 17 and Fig. 18 as a function of the imposed normal stiffness; whereas its maximal value is presented on Fig. 5. As carbonated sands are very sensitive to grain crushing, the scale effect decreases more rapidly and the process starts at lower imposed normal stiffness for Quiou sand (*k* about 400 kPa/mm) than for Hostun one (*k* about 4000 kPa/mm). Using the same approach as for the dilative interface, the scale effect for loose Hostun and Quiou sands and smooth plate was determined (Fig. 19 and Fig. 20) as a function of (*D/e*) ratio. The highest scale effect is observed for small models and high initial normal stress. It is larger for carbonated than for quartz sands. This scale effect attenuates for (*D/e*) ratio exceeding 20.

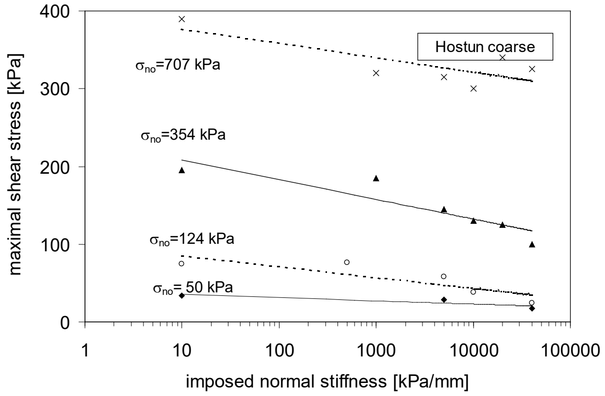

Fig. 15. Maximal shear stress for loose Hostun coarse sand and smooth plate.

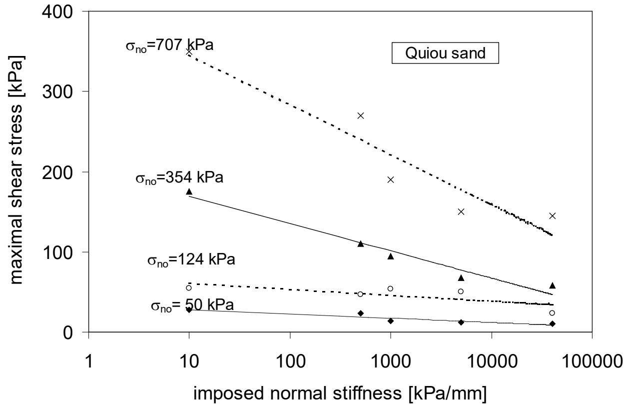

Fig. 16. Maximal shear stress for loose Quiou sand and smooth plate.

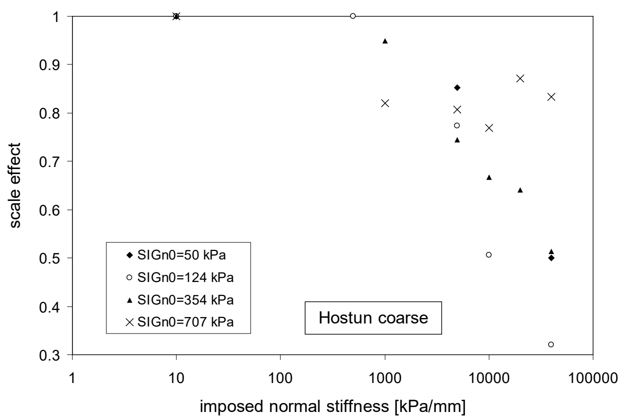

Fig. 17. Scale effect vs. imposed normal stiffness for loose Hostun coarse sand and smooth plate.

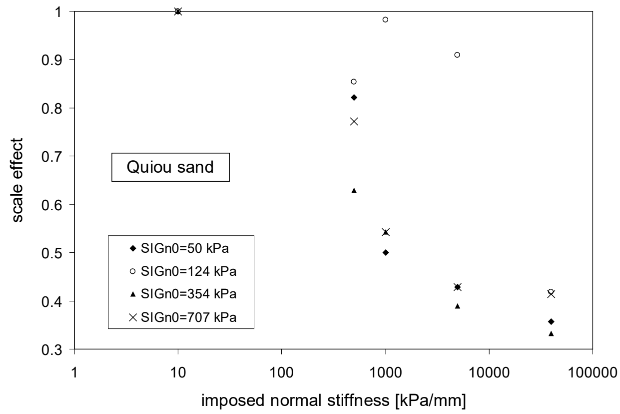

Fig. 18. Scale effect vs. imposed normal stiffness for loose Quiou sand and smooth plate.

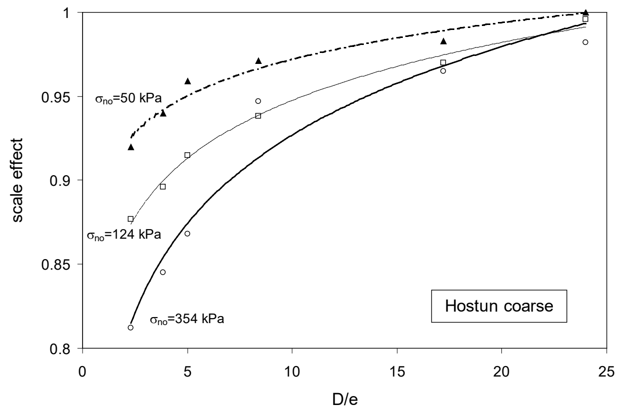

Fig. 19. Scale effect vs. (*D/e*) ratio for loose Hostun coarse sand and smooth plate.

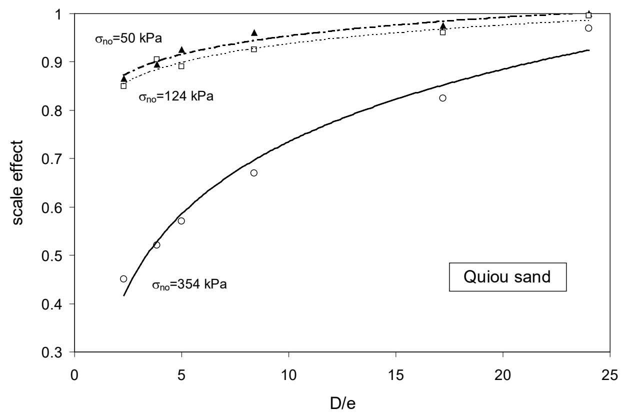

Fig.20. Scale effect vs. (*D/e*) ratio for loose Quiou sand and smooth plate.

4. Conclusions

Scale effect in lateral friction due to shear band formation in the soil-structure interface was determined from interface direct shear tests with constant normal stiffness. This scale effect higher than 1 was obtained for the dilative interface and smaller than 1 for contractive soil behavior within the interface. For the latter, the scale effect will be more pronounced in carbonated sand than in quartz one.

The higher attention should be paid when doing tests with small diameter models. In order to avoid the scale effect the diameter of the model should exceed 200 grains at in highly dilative or contractive soil within the interface.

The interface direct shear test has some limitations to model correctly the lateral friction mobilisation on the pile shaft:

- For the inclusions of a very small diameter, the phenomena is a really axisymetric problem and cannot be reproduced in plane strain conditions in the direct shear test. The circumferential stress influence and its evolution during the shearing can not be reflected in the interface direct shear test.
- In the case of contractive soil behavior within the soil-pile interface, the arching phenomena could appear and the contact between the contracting interface and the surrounding soil mass can be lost. This phenomena will not exist during the shear test in the interface shear box.
- In these cases the scale effect determined with the interface direct shear tests will be underestimated.

Acknowledgements

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References

1. Desrues J., An introduction to strain localisation in granular media. Physics of granular media, Proc. Winter School, Les Houches, February 1990, Nova Sciences Publications, pp.127-142.
2. Wernick E., Stresses and strains on the surface of anchors, Revue Française de Géotechnique, Special number on the anchors, pp. 113-119, 1978.
3. Schlosser, F.; Guilloux, J., Le frottement dans le renforcement des sols, Revue Française de Géotechnique N°16, 1981.
4. Lehane, B.M; Jardine, R.J.; Bond, A.J.; Frank, R., Mechanisms of shaft friction in sand from instrumented pile tests, JGE, Vol.119, No.1, 1993.
5. Habib P., Effet d'échelle et surface de glissement. Revue Française de Géotechnique N°31, 1985.
6. Kimura T., O. Kusakabe & K. Saitoh, Geotechnical model tests of bearing capacity problems in a centrifuge, Géotechnique N 35, 1985.
7. Tatsuoka F. et al. Progressive failure and particle size effect in bearing capacity of a footing on sand, Geotechnical Engineering Congress, Geotechnical Special Publication No.27 of ASCE, 1991.
8. Boulon M. and Foray P. Physical and numerical simulation of lateral shaft friction along offshore piles in sand, 3rd Int. Conference on Numerical Methods in Offshore Piling, Nantes, pp.127-147, 1986.
9. Boulon M. Numerical and physical behavior under monotonous and cyclic loading. In Kolkman et al. (Ed.). Modelling Soil-Water-Structure Interactions: 285-293. Rotterdam, Balkema, 1988.

10. Bałachowski L., Différents aspects de la modélisation physique du comportement des pieux: Chambre d'Etalonnage et Centrifugeuse, Thèse de doctorat à l'INPG, 1995.
11. Foray P., Bałachowski L., Raul G., Scale effect in shaft friction due to localisation of deformations Centrifuge'98. Tokyo, Kimura et al. (Ed.), Balkema, 1, pp. 211-216, 1998.
12. Garnier J. and König D., Scale effects in piles and nails loading tests in sands, Centrifuge'98. Tokyo, Kimura et al. (Ed.), Balkema, 1, pp. 205-210, 1998.
13. Reddy E.S., Chapman D.N. and Sastry V.V.R.N., Direct shear interface test for shaft capacity of piles in sand, Geotechnical Testing Journal, 23 (2), pp. 199-205, 2000.
14. Plytas C., Contribution à l'étude expérimentale et numérique des interface sols granulaire- structure, application à la prévison du frottement latéral des pieux. Thèse à l'Universite J.F. Grenoble, 1985.
15. Genevois J-M., Capacité portante des pieux à grande profondeur. Simulation physique à l'aide d'une chambre de calibration, Thèse de doctorat à l'Université Joseph Fourier - Grenoble I, 1989.
16. Hoteit N., Contribution à l'étude de comportement d'interface sable-inclusion et application au frottement apparent. Thèse à l'Universite J.F. Grenoble, 1990.
17. Airey D.W., Al-Douri, R.H. and Poulos H.G., Estimating of pile friction degradation from shearbox tests, Geotechnical Testing Journal, Vol.15, No.4, pp. 388-392, (1992).
18. Mokrani L., Simulation physique du comportement des pieux à grande profondeur en chambre de calibration, Thèse de doctorat à l'INPG, 1991.

Efekt skali dla tarcia na podstawie badań bezpośredniego ścinania w kontakcie

Przy tym samym naprężeniu normalnym na pobocznicy modelu pala o małej średnicy i prototypu o dużej średnicy zjawisko mobilizacji tarcia przebiega przy innych warunkach brzegowych. Zjawisko to może zostać odzwierciedlone w badaniu bezpośredniego ścinania w kontakcie ze stałą sztywnością normalną, odwrotnie proporcjonalną do rozpatrywanej średnicy pala. Przeanalizowano wartości maksymalne tarcia uzyskane w aparacie bezpośredniego ścinania dla piasków kwarcowych i węglanowych oraz gładkiego i szorstkiego kontaktu, przy różnym zagęszczeniu piasku. Określono efekt skali jako stosunek tarcia mobilizowanego na modelu do tarcia mobilizowanego dla pala o dużej średnicy. Efekt skali pomierzony w aparacie bezpośredniego ścinania w kontakcie przy stałej sztywności normalnej ma wartość większą od 1 w przypadku dylatancji w kontakcie lub wartość mniejszą niż 1 dla kontraktancji na styku konstrukcja-grunt.

Notations

d_{50} - mean grain diameter,
e - shear band width,
k – imposed normal stiffness,
u - displacement applied to the upper plate of the shear box,
u_l - normal displacement at the boundary of the interface,

D - pile diameter,
E_p – pressuremeter modulus,

G – shear modulus,
I_D – density index,
K_0 - earth pressure coefficient at rest,
R – pile radius,

$\Delta\sigma_n$ - the increment of the normal stress to the shaft,
Δu - the increment of the normal displacement,
σ_n - normal stress,
σ_{n0} - initial normal stress,
σ'_v - effective overburden stress,
τ - shear stress,
$\tau_{k\ model}$ - shear stress on model pile,
$\tau_{k\ prototype}$ - shear stress on prototype pile,
$\tau_{(k=0)}$ - shear stress for constant normal stress condition,
$\tau_{(k=\infty)}$ - shear stress for no volume changes condition,
τ^* - scale effect