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Influence of lateral stress on soil-structure interface tests in a hollow cylinder apparatus

Influence de la contrainte latérale sur les expérience d'interface sol-structure dans un appareil à cylindre creux

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ABSTRACT: The contact shear behaviour between the soil and a structure has a significant impact on the load transfer of geotechnical structures. In the past, several different approaches to test and quantify this soil-structure interface behaviour have been conducted using e.g. modified ring-shear, direct-shear or simple-shear devices. In most experimental studies, the lateral deformation is restricted to zero (stiff frames of direct shear and simple shear devices) and the lateral stress is unknown. To gain insights on the influence of an anisotropic stress state on the interface, contact shear tests on ring-shaped samples with various lateral stresses are presented in this work. Therefore, a modified hollow cylinder apparatus with a contact plate and short sample geometries was used. The first results indicate, that neither the anisotropy of the stress state can be neglected, nor the interface behaviour follows straight the soil shearing behaviour for the test setup used here.

RÉSUMÉ: Le comportement de cisaillement de contact entre le sol et une structure a un impact significatif sur le transfert de charge des structures géotechniques. Dans le passé, plusieurs approches différentes pour tester et quantifier le comportement de l'interface sol-structure ont été menées en utilisant, par exemple, des dispositifs de cisaillement annulaire modifié, de cisaillement direct ou de cisaillement simple. Dans la plupart des études expérimentales, la déformation latérale est limitée à zéro (cadres rigides des dispositifs de cisaillement direct et de cisaillement simple) et la contrainte latérale est inconnue. Pour mieux comprendre l'influence d'un état de contrainte anisotrope sur l'interface, des essais de cisaillement par contact sur des échantillons en forme d'anneau avec différentes contraintes latérales sont présentés dans ce travail. Pour ce faire, un appareil à cylindre creux modifié avec une plaque de contact et des géométries d'échantillons courtes a été utilisé. Les premiers résultats indiquent que l'anisotropie de l'état de contrainte ne peut pas être négligée et que le comportement de l'interface ne suit pas directement le comportement de cisaillement du sol pour la configuration d'essai utilisée ici.

Keywords: Interface tests; contact shear behaviour; anisotropic stress state.

1 INTRODUCTION

In many geotechnical projects, interfaces occur, as they include rigid structures such as piles, walls and foundations. The contact shear behaviour between the soil and the structure has a significant impact on the load transfer of geotechnical structures. For instance, the surface roughness of the structural element has a considerable influence on the behaviour of the entire system. This inspired several authors to experimental investigations and modelling approaches for interface shearing behaviour (e.g. Wernick 1978; Uesugi and Kishida 1986; Stutz and Martinez 2021). Some interface models depend only on the normal stress on the interface (e.g. Ghionna and Mortara 2002) while others use existing soil models for derivation and therefore take the whole stress tensor into account. The last-mentioned attempts for contact modelling are based on different assumptions concerning the stress state at the interface: while Arnold and Herle (2006) suppose all normal stresses to be equal ($\sigma_{11} = \sigma_{22} = \sigma_{33}$) for simplicity, Stutz et al. (2017) make another assumption. They assume the in-plane deformation to be negligible and allow the in-plane stress to take other values than the stress normal to the interface ($\sigma_{11} \neq \sigma_{22} = \sigma_{33}$). The approach of Staubach et al. (2022) couples neither the in-plane stresses nor the in-plane deformations directly with each other but with the neighbour soil (in FEM) so all normal stresses can be different ($\sigma_{11} \neq \sigma_{22} \neq \sigma_{33}$). Most previous experimental studies on interfaces have been conducted using modified ring-shear, direct-shear or simple-shear devices. In these cases, the frames restrict the lateral deformation to zero and the lateral stress is unknown. Therefore, important information to characterize interface shear behaviour under different stress conditions is raw (Dumitrescu et al. 2009).

One step towards understanding the influence of the 3D stress state was taken by Dumitrescu et al. (2009). They developed an interface shearing device with one adjustable normal stress on a plane orthogonal to the interface. A cylinder with a contact surface is rotated in a hollow cylinder sample, while the normal stress on the interface is applied through a membrane (radial stress) and the normal stress on one of the planes orthogonal to the interface is applied by a piston (axial stress). The experimental results indicate that the anisotropy of the initial stress state should be considered in the description of contact shear behaviour.

In this work, another device for interface tests with different normal stresses was developed. Therefore, a modified hollow cylinder triaxial device with a contact plate and short samples is used. This allows to control four independent stress or strain components and to take more complex stress states into account. First experiments with Karlsruhe fine sand are presented and compared to simple existing boundary surfaces for soils (section 3.2, Figure 6 and Figure 7).

2 TEST DEVICE AND METHODS

2.1 Test device

In the modified hollow cylinder apparatus (see Figure 1), a hollow cylinder shaped soil sample is tested in a pressure cell. The sample is separated from the cell fluid by membranes on the outer and inner curved surface areas. A plate with glued sand on the bottom of the sample ensures a fully rough contact with a full force transfer. In this modified device, the top plate is a changeable contact plate, so different roughness properties can be tested (see Figure 2). By rotating the bottom plate, torsion can be applied to the sample and shear deformation is induced at the interface.

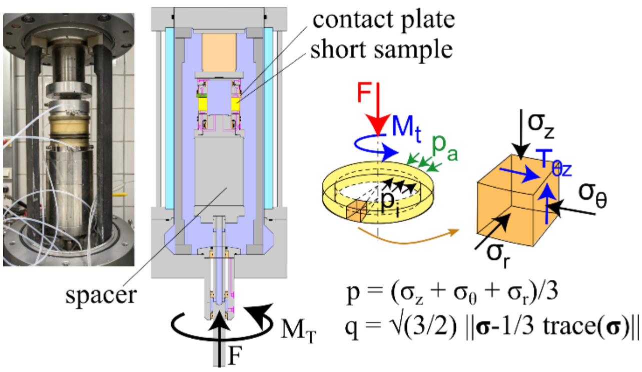

Figure 1. Modified hollow cylinder apparatus to control three independent normal stresses in interface shearing tests (one on shear plane, two on orthogonal planes).

The normal stress at the interface is controlled by an axial load. Additionally, the pressure on the outer cell (p_a) and in the inner cell inside the hollow sample (p_i) can be controlled independently. Thereby, an anisotropic initial stress state can be generated and with different pressures on the outer and the inner membranes, three different normal stresses can be applied (one on the shear plane and two on the planes orthogonal to the shear plane).

Figure 2. Different rough contact plates: with glued sand (left), coarse sandblasted (center), fine sand blasted (right).

2.2 Sample preparation and soil properties

The experiments were conducted on medium dense samples of Karlsruhe fine sand (Figure 3). For preparation, the membranes are placed in a mould and the sand was pluviated between the membranes (Figure 3). The sample has an outer and inner diameter of 100 mm and 60 mm with a height of 20 mm.

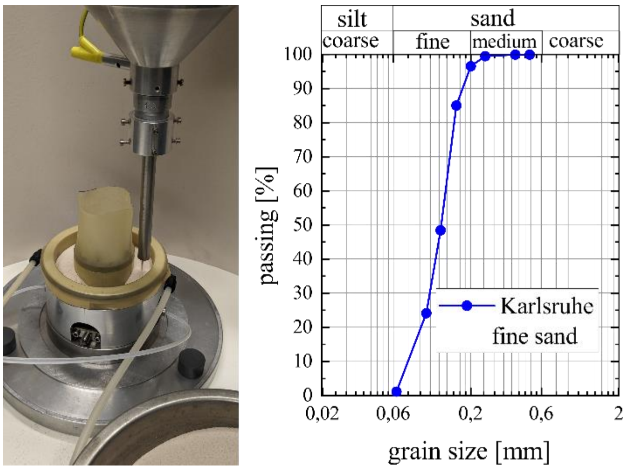

Figure 3. Sample preparation with air pluviation (left) and grain size distribution of Karlsruhe fine sand (right).

2.3 Influence of membrane stiffness

The membranes are fixed at the bottom and top caps hence they are deformed in the same way as the sample and contribute to the measured forces. Especially for the short sample height of 20 mm and a tangential shear deformation up to 30 mm, the influence of the membrane stiffness cannot be neglegted: The measured moment during torsion tests results not only from the mobilised friction on the sample but also from membrane forces. In the literature, dummy tests with water-filled membranes are used to develop correction formulas for the membrane forces in hollow cylinder tests (e.g. Koseki, Yoshida and Sato 2005). In these tests, unrealistic membrane deformations occur when it comes to large rotation angles. For an enhanced correction, in the present work, tests on soil samples with different membranes were used to capture the actual membrane (or sample) deformation and a mathematical correction was developed. Example test data with the membrane correction is shown in Figure 4.

3 RESULTS

3.1 Loading path

All tests were driven with a constant vertical stress σ_z of 100 kPa (normal stress on the shear plane), except the tests in Figure 5. The normal stresses on the planes orthogonal to the shear plane (radial stress σ_r and tangential stress σ_θ, see Figure 1) were 50 kPa, 100 kPa or 150 kPa and identical in the presented tests. After reaching the test specific initial stress state, the drained contact shearing phase was started by rotating the bottom end plate.

For the medium dense samples ($I_D \approx 0.6$), the corrected shear stress (see Figure 4) increases until an asymptotic state is reached. In the test series a rough contact plate with glued grains and less rough contact plates of fine and coarse sandblasted steel were used.

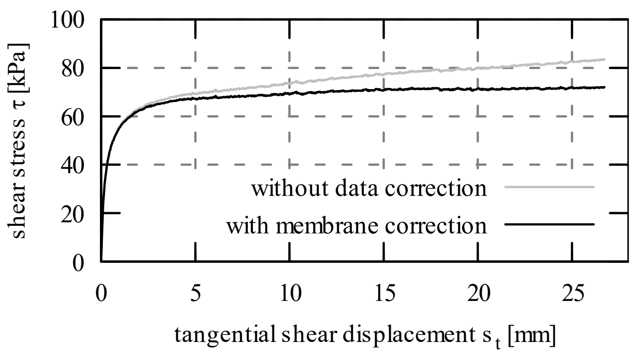

Figure 4. Drained contact shearing phase (torsion) after isotropic initial state (p = 100 kPa) with medium dense Karlsruhe fine sand and a rough contact plate.

3.2 Shear strength

The tests with isotropic initial stress states (Figure 5) show a proportional relation between the shear strength and the mean stress as well as between the shear strength and the normal stress on the shear plane and therefore act in the framework of common yield criteria, e.g. the Mohr-Coulomb criterion.

This behaviour changes for the test series including anisotropic initial states: Figure 6 and Figure 7 show the deviatoric stress in the sample (colored) and the shear stress on the shear plane (grey) during tests with a contact plate with glued grains and one of fine sandblasted steel. Note, that the largest reached deviatoric stress q appears not necessary at the same test as the largest shear stress on the shear plane $\tau_{\theta z}$. The maximum deviatoric stresses do not match with the critical deviatoric stress q_{crit} calculated with the Mohr-Coulomb criterion and the corresponding Lode angle (value at asymptotic state is marked with x). A hypothesis for the explanation is the occurrence of a forced horizontal failure plane. The geometry and

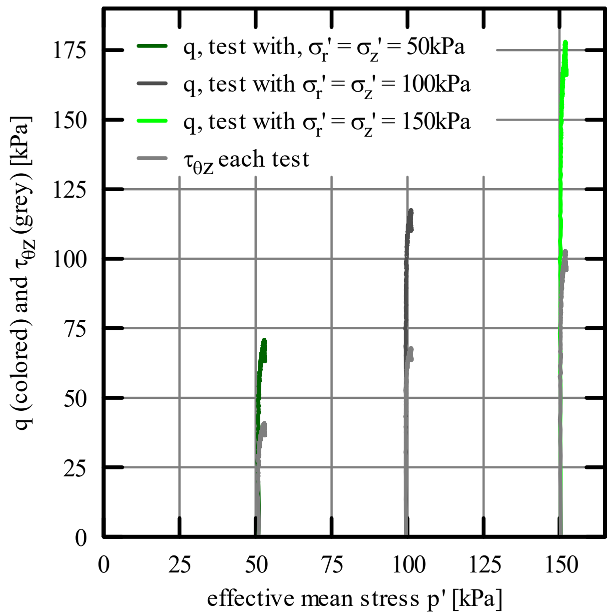

Figure 5. Interface tests with isotropic initial state: $\sigma_z = \sigma_r = \sigma_\theta = p$, rough contact plate of coarse sandblasted steel.

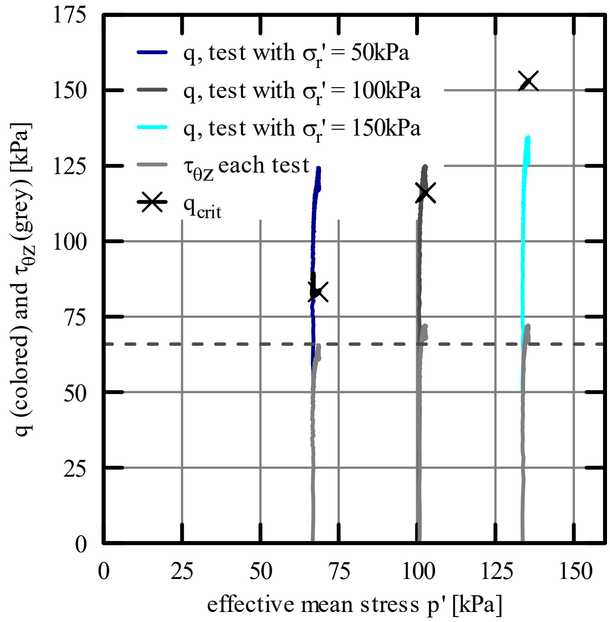

Figure 6. Interface tests with anisotropic confinement and rough contact plate with glued grains.

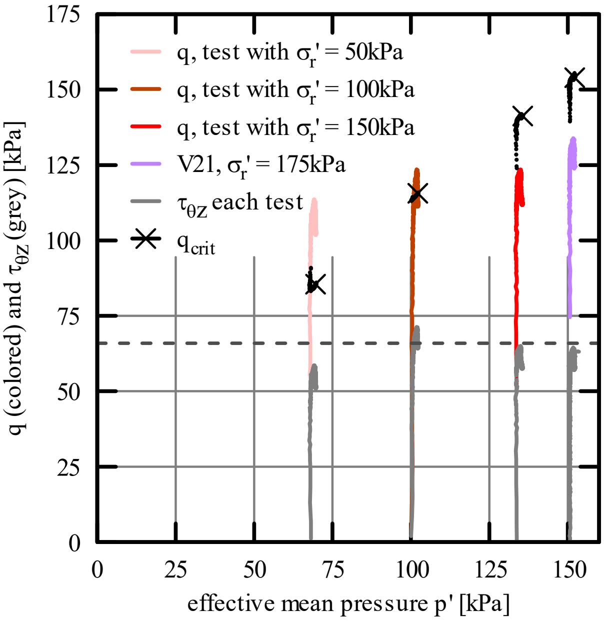

Figure 7. Interface tests with anisotropic confinement and less rough contact plate of fine sandblasted steel.

end plates might constrain the decisive failure plane to be horizontal. Following this assumption and looking at the vector on the shear plane, only the stress components σ_z and $\tau_{\theta z}$ are contributing. As the normal stress is equal in all tests in Figure 6 and Figure 7, the maximum shear stress $\tau_{\theta z}$ should be a constant value (dashed line: calculated with Mohr-Coulomb on horizontal failure plane).

The experimental data diverge from this line and hence indicate, that the anisotropic confining stress influences the shear strength. The different values of lateral stress change the state of the soil above the contact plate and render the shear strength of the interface. These results confirm the findings of Dumitrescu et al. (2009), who reported an influence of the normal stresses on the plane orthogonal to the shear plane (anisotropic confinement).

4 CONCLUSIONS

The presented experiments contribute to the understanding of soil-structure interface behaviour.

- A hollow cylinder apparatus was modified that three independent normal stresses can be controlled during interface shear tests.
- Due to boundary and interface conditions, the maximum deviatoric stress did not match with failure criteria in pure soil shearing. This might result from a predefined failure plane.
- The maximum shear stress on the horizontal (failure) plane is potentially influenced by anisotropic confinement states, as the normal stresses on the planes orthogonal to the shear plane render the state of the soil on the contact and so the shear strength of the interface.
- Further investigations should be conducted on the influence of sample geometry to separate possible effects during monotonic and cyclic shearing.

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