Mechanical characterization of a gravel column in a calibration chamber operating as a triaxial cell

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ABSTRACT: A series of tests considering the behavior of gravel columns was performed. A segment of column with a height of 1 m and a diameter of 0.53 m was modelled in a calibration chamber used as a triaxial cell at three different lateral stress applied. The vertical load transferred on the column head was simulated with steady increase of water pressures in the upper and lower membranes. During the loading the volumetric changes in the column material were measured. The influence of lateral membrane rigidity and the effect of encapsulated column were analyzed. The strength and deformation parameters of gravel material determined in the calibration chamber operating as a triaxial cell are discussed.

1 INTRODUCTION

The gravel columns are often used to reinforce a soft cohesive subsoil. This inclusion can be formed as a typical gravel column or encapsulated one. The behavior of such column depends on the characteristics of the gravel material used, the parameters of the surrounding soft soil and the load distribution between the column head and the soft subsoil, function of the size and shape of the grid. The design is based on the composite cell concept (Priebe, 1995, Ellouze et al. 2010) or homogenization of parameters of the column and the surrounding soft soil (Asiri, 2012, Springmann et al. 2014). Another approach consists on monitoring of field performance of the subsoil reinforced with such column (McCabe et al. 2010). The behavior of gravel column was also investigated in model tests in rigid box. The experiments considered the vertical loading tests on a single column (Sivakumar et al. 2010), on the composite cell or the group of 2÷4 stone columns embedded in cohesive subsoil (Fattah et al. 2011). Sivakumar et al. (2010) investigated the settlement reduction due to column reinforcement in different fills including the influence of wetting process. The load distribution between the column head and the surrounding soil for different group of columns and the reinforcement effect was studied by Fattah et al. 2011. These tests were however performed in a small size rigid box, with soil massif height less than 25 cm (Sivakumar et al. 2010) or 80 cm (Fattah et al. 2011). Such a small embedment of the column is lower than the critical depth, so the experimental results can be only considered qualitatively. The mechanical properties of a gravel material can be tested in large triaxial cell. The diameter of the sample should however exceed at least 5 times the dimension of the largest grain, Lenarta et al. 2014. The triaxial cell sufficiently large to perform such tests was not available. An attempt was made to use medium size calibration chamber operating as a large triaxial cell. In this study the effect of lateral stress level on the behavior of a gravel column segment was investigated.

2 CALIBRATION CHAMBER TESTS

2.1 *Experimental setup*

Calibration chamber constructed at Gdańsk University of Technology (Bałachowski & Dembicki, 2003) enables large soil samples of 53 cm in diameter to be tested in. The general scheme of the set-up with control system is given on Figure 1. The calibration chamber is equipped with two (upper and lower) membranes filled with water. Its double-wall construction (Fig. 2) with inner and outer chambers permits typical boundary conditions to be applied during the tests by the use of pneumatic control system. Volumetric changes within the sample are registered by micropulse transducers BTL2 monitoring water level in air-water columns on the control panel (Fig. 3). It is thus possible to monitor volumetric changes around the sample and in the upper and lower membranes.

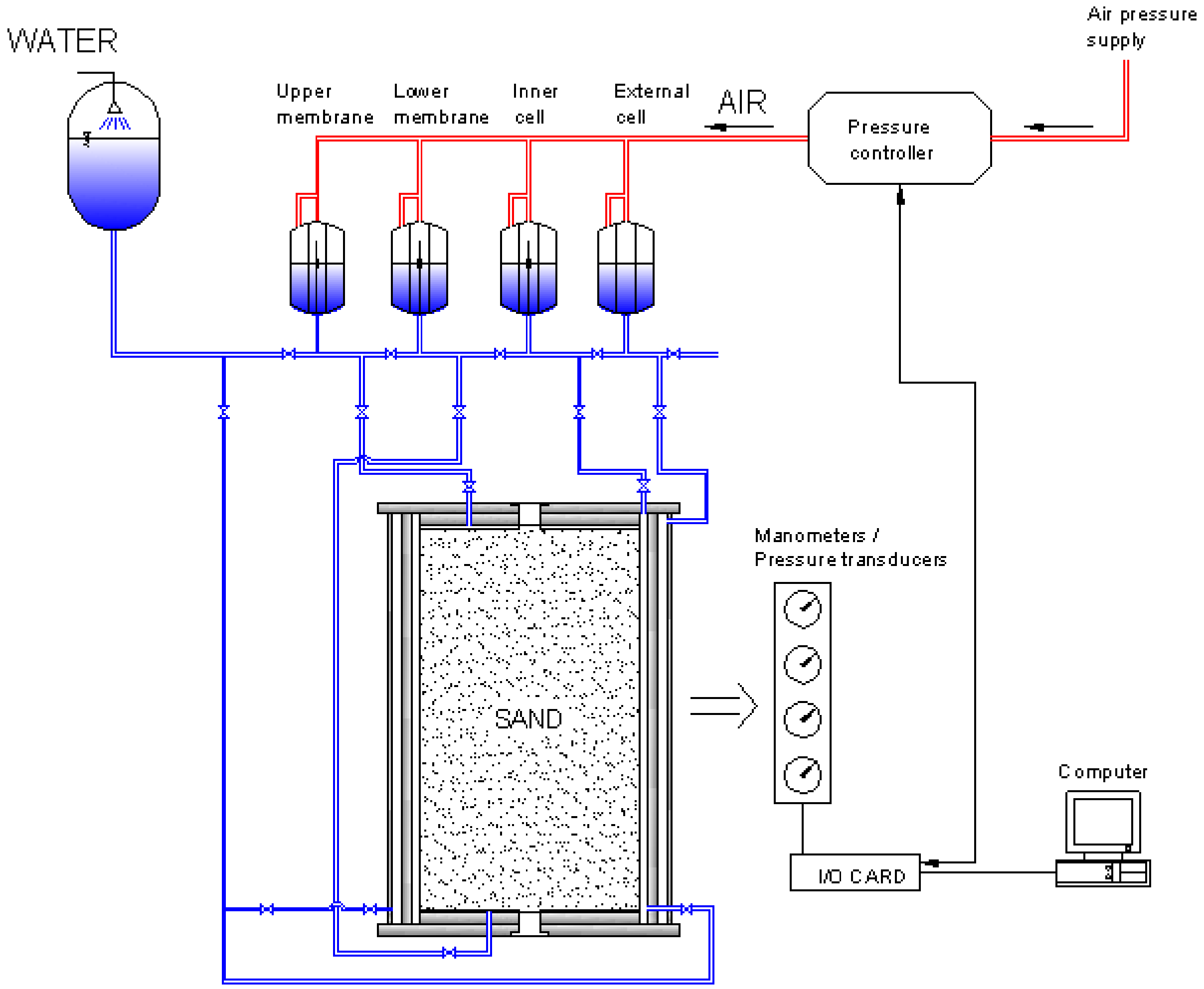

Figure 1. Scheme of calibration chamber device with control system, Bałachowski & Dembicki, 2003.

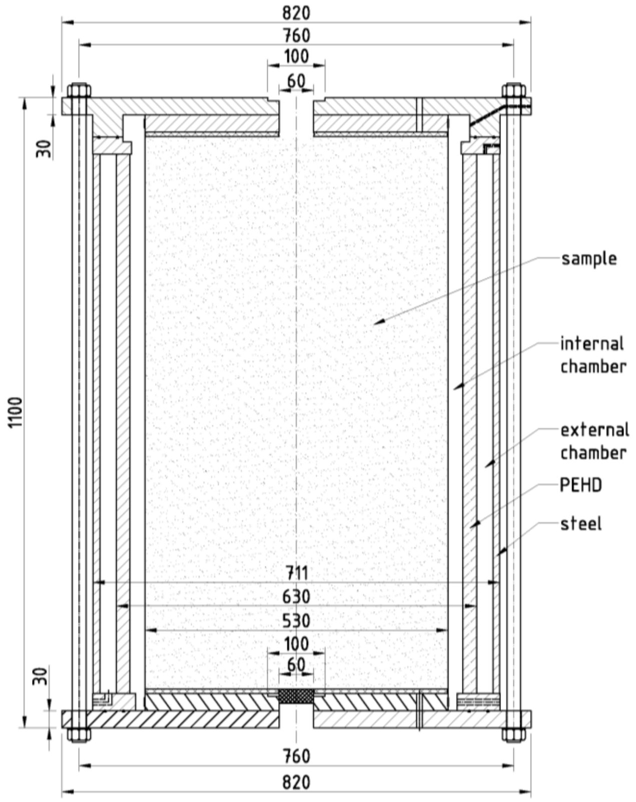

Figure 2. Cross section of calibration chamber, Bałachowski, 2006.

Figure 3 Control panel with volume changes measurements.

2.2 *Sample preparation*

The soil mass in the calibration chamber is generally reconstituted as a large sand sample for the tests of calibration of in-situ probes. In this study well-graded (U_c=11.1) sandstone material containing angular grains was used. The grain size distribution curve of the gravel material is shown on Figure 4. The column was reconstituted in five layers, compacted at natural water content of 3%. Small compaction energy was applied and relative density of the column material was close to 0.6. The grain crushing was not observed during the sample compaction. The rubber membranes were protected against grain penetration and cut by the use of woven geotextile.

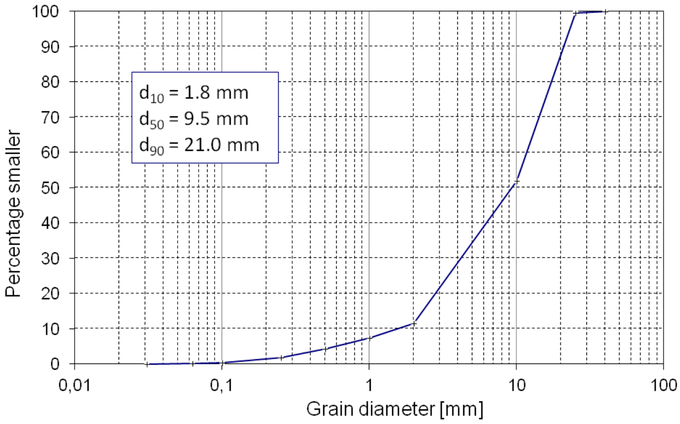

Figure 4. Grain size distribution curve of column material.

2.3 *Test description*

Firstly the sample was consolidated at a given confining stress and then subjected to vertical stress increase. Initial stress state around the specimen subjected to initial vertical stress 30 kPa is given on Figure 5. The initial vertical stress in the lower membrane is equal 48 kPa due to self weight of the gravel. It was assumed that initial vertical stress and horizontal stress applied in the mid-height of the column are equal. It means that the initial earth pressure at rest coefficient is close to 0.8. The assumed initial stress state around the specimen corresponds to that around the segment of the column in the soft soil with low lateral stiffness. The lateral stress was kept constant during the test. The tests with three different initial vertical stress levels – 30 kPa, 50 kPa and 70 kPa - were performed to model the column behavior at different depths. These values of vertical stress were limited due to experimental constrains related to non uniform distribution of displacements in upper and lower membranes at large deformation and high volume changes measured in the consolidation stage.

Vertical stress was applied with equal water pressure increase in upper and lower membranes. For the test performed at horizontal stress 70 kPa additional unloading-reloading loops were done (Fig. 7). The lateral stress was kept constant during the tests in both internal and external chambers (Fig. 2). Volume changes within the column material are observed by the monitoring of floating element position in air-water columns on the control panel (Fig. 3). The axial strain of the column was determined using the sum of volume changes in the upper and lower membranes:

$$\varepsilon_1 = \frac{\Delta V_1 + \Delta V_2}{A} \tag{1}$$

where: ΔV_1 and ΔV_2 are volume increases in the upper and lower membranes and A is the cross-section area of the column. The volumetric strain was calculated using the formula:

$$\varepsilon_v = \frac{\Delta V_1 + \Delta V_2 + \Delta V_3}{V_0} \tag{2}$$

where: ΔV_1, ΔV_2 and ΔV_3 are volume increases in the upper membrane, lower membrane and inner chamber, respectively and V_0 is the initial volume of the specimen.

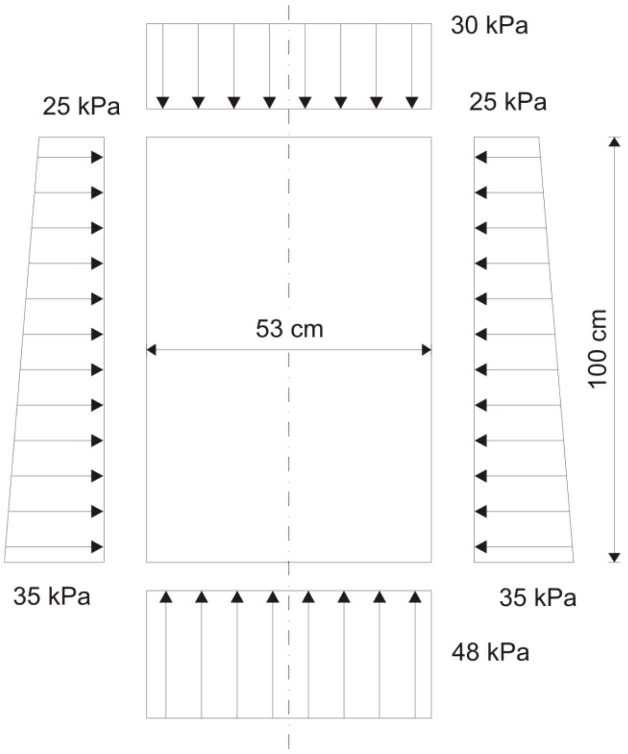

Figure 5. Example of initial stress state around the segment of gravel column in the calibration chamber.

2.4 *Test results*

An example of the model test results for horizontal stress equal 50 kPa is given on Figures 5 and 6. The compression test of the column segment was maintained until relative stabilization of vertical stress was observed (Fig. 6). Due to limited capacity of the membranes to expand the imposed axial strain was constrained to 2%. Changes in the water volume in the upper and lower membranes and in the inner chamber around the specimen are given (Fig. 7) as a function of applied vertical stress. During the loading the specimen is subjected to steady compression on the lower and upper ends of the column. The volumetric changes within the specimen can be precisely determined taking into consideration the measurements in the inner chamber, Bałachowski (2006). At the beginning of the loading the column undergoes compression, at higher stress/strain level applied some dilative behavior appears – see the volume changes registered in the inner chamber.

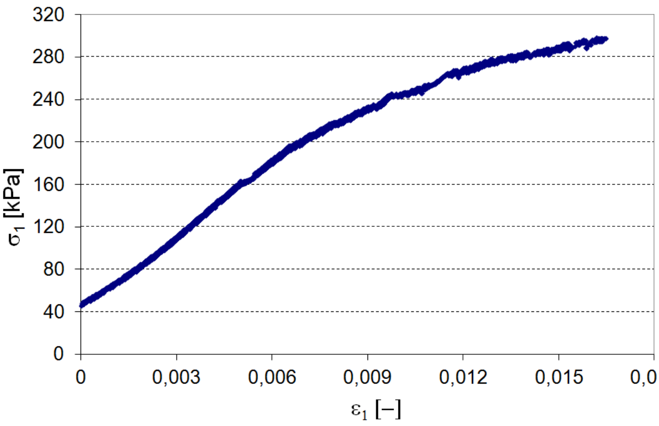

Figure 6. Vertical stress increase during the compression test at σ_3=50 kPa.

The summary of the results for three tests is presented on Figures 8-9. The mobilization of deviator stress at three horizontal stress levels is compared on Figure 8. Volumetric strain evolution for these three tests is given on Figure 9. While the gravel column is steadily contracted at the horizontal stress of 70 kPa, some dilatancy of the material occurs at lower confining pressures.

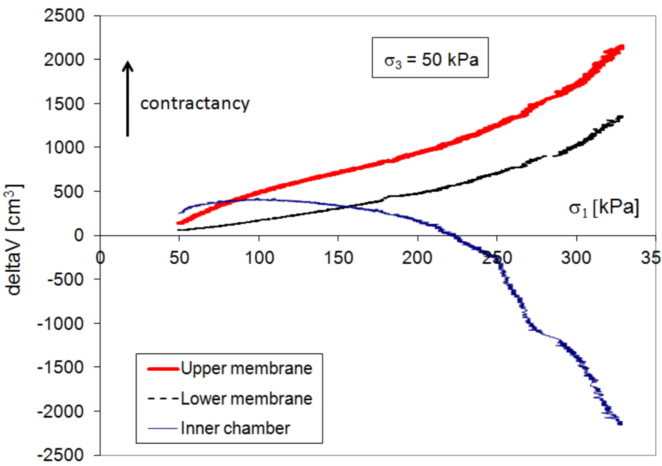

Figure 7. Volume changes in upper and lower membranes and in the inner chamber around the column.

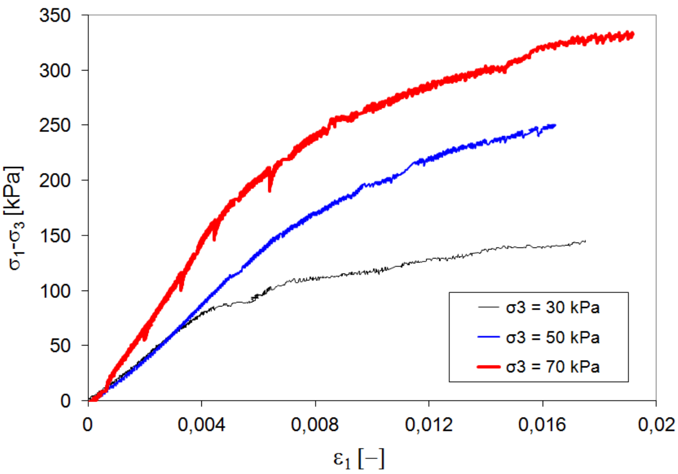

Figure 8. Deviator stress increase at three different lateral stress.

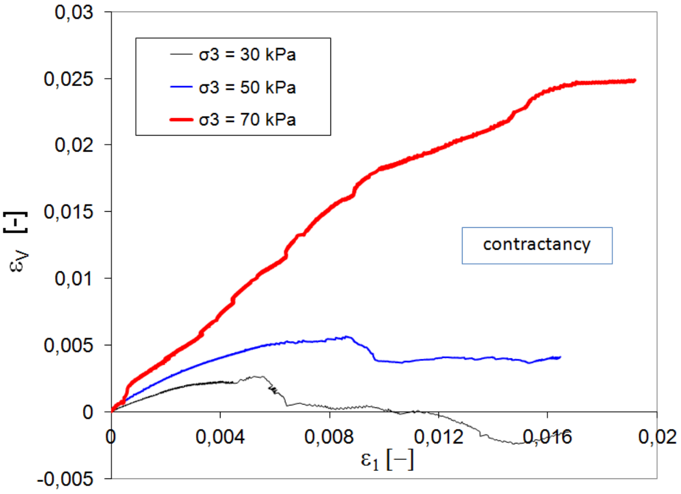

Figure 9. Volumetric strain during the compression.

The angle of internal friction of gravel material was calculated at the maximum axial strain corresponding to the stabilization of deviator stress using the formula:

$$\phi = \arcsin \frac{\sigma_{1\max} - \sigma_3}{\sigma_{1\max} + \sigma_3} \qquad (3)$$

where: σ_{1max} is the maximum vertical stress and σ_3 is the horizontal stress in the mid-height of the column segment. The obtained values of ϕ vary from 44.4° to 45.6°. The Mohr circles are plotted on Figure 10 with angle of internal friction equal 44.8°.

The tangent modulus of deformation of the gravel column calculated at 0.2% of axial strain is given in Figure 11. Additionally, unloading-reloading loops for the test at σ_3= 70 kPa were analyzed and the corresponding unloading-reloading modulus was determined (Fig. 12). It increases linearly with the mean stress and is considerably higher than the tangent modulus.

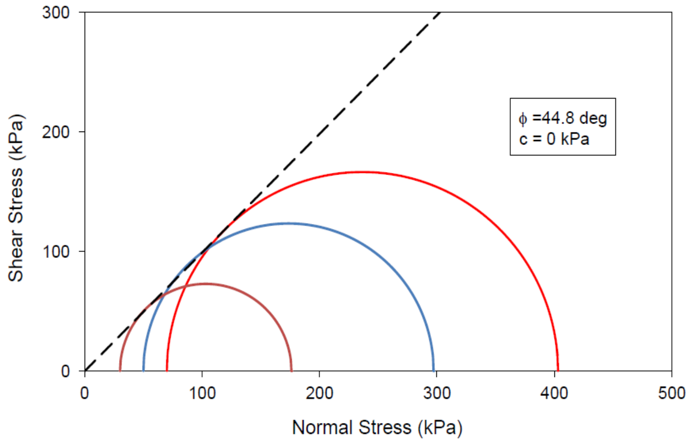

Figure 10. Mohr circles with failure envelope.

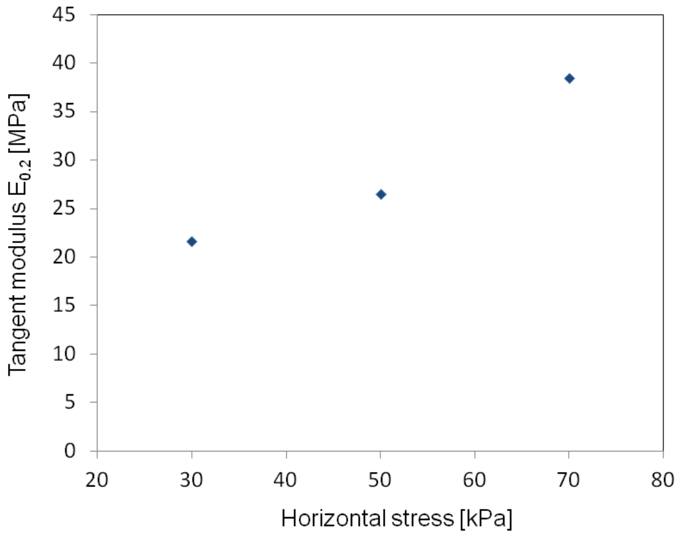

Figure 11. Tangent modulus of deformation at 0.2% of axial strain.

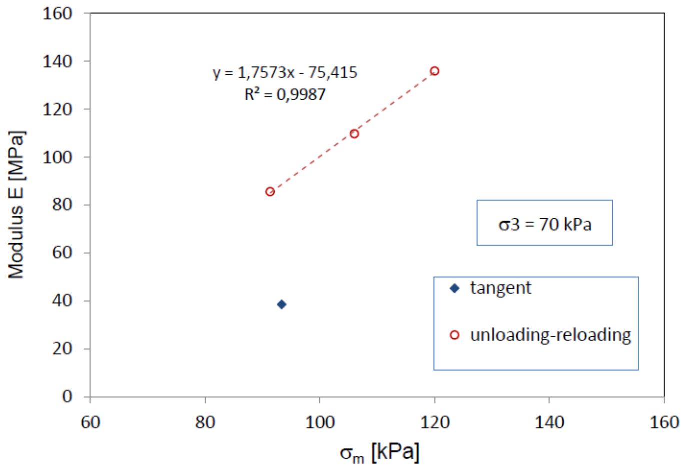

Figure 12. Modulus of deformation of gravel material as a function of mean stress.

3 DISCUSSION

3.1 *Similitude conditions*

The segment of the column in natural scale was tested in the calibration chamber. The stress state around the sample including an increase of horizontal stress with depth enables the correct modeling of such column segment. The applied boundary condition of lateral stress kept constant signifies that lateral stiffness of the surrounding soil is equal zero. The soft soil has however a small lateral stiffness. It was assumed in the laboratory that the load is transferred to the column head only. In a real case the load is transmitted also to the soft soil around the column. This complex transfer mechanism, related to the geometry of improved subsoil and stiffness of the column head and soft soil, is also time dependent and couldn't be modeled in these tests in the calibration chamber. The physical modeling of a smaller gravel column embedded in the soft surrounding soil would be possible with considerable modifications of the sample preparation method and the loading set-up.

The membranes were additionally protected against grain penetration, however such penetration still occurs. Due to this fact the estimated vertical strain is overpredicted and deformation modulus is underestimated. Moreover, the deformation moduli of the real column will be higher than measured in the calibration chamber due to:

- Higher compaction of installed column than that one reconstituted in laboratory,
- More rigid lateral conditions for a real column related to the presence of surrounding soil,
- Installation effects.

3.2 *Membrane correction*

Additional effect is related to the presence of relatively rigid lateral membrane around the specimen. The observed behavior could be thus closer to that corresponding to the encapsulated column. Such effect was investigated in triaxial tests by Kolymbas & Wu (1990). Due to membrane presence the sample is subjected to additional compressive stress in vertical and horizontal directions:

$$\Delta\sigma_1 = \frac{4Eb}{3D}(5\varepsilon_1 + \varepsilon_v) \tag{4}$$

$$\Delta\sigma_3 = \frac{4Eb}{3D}\varepsilon_v \tag{5}$$

where: E is Young modulus of the membrane, b is the membrane thickness, D is sample diameter, ε_1 and ε_v are axial and volumetric strain, respectively.

The equation 3 can be thus corrected:

$$\phi_{cor} = \arcsin\frac{\sigma_{1\max} - \Delta\sigma_1 - \sigma_3 + \Delta\sigma_3}{\sigma_{1\max} - \Delta\sigma_1 + \sigma_3 - \Delta\sigma_3} \tag{6}$$

For the rubber membrane used in the model tests in the calibration chamber E = 2283 kPa, D = 0.53 m and b = 0.001 m. Additional compressive stress $\Delta\sigma_1$ will reach 0.5 kPa and it will have negligible effect on stress state around the specimen and calculated angle of internal friction. This effect will be higher for larger strains. When the encased gravel columns are considered the influence of geotextile with higher Young modulus should be taken into account.

4 CONCLUSIONS

In this study the calibration chamber was used as a large triaxial apparatus. The behavior of the gravel column segment at different depths was modeled. Analysis of 1 m high segment enables the increase of lateral stress with depth for the real column to be simulated. When the rigidity of the soft soil is small the assumed constant lateral stress boundary condition can be considered as a good approximation of lateral confinement.

The deformation and strength parameters of gravel material can be determined in such kind of test, however, it is troublesome and time consuming. Registered volumetric changes are higher than during typical tests in sands, which makes some experimental difficulties during the operation. To prevent non-uniform displacement on the specimen ends, the use of membranes is limited to relatively small vertical deformation of the specimen up to 2%. The effect of grain penetration into membranes influences the measurements of axial and volumetric strains. This can be attenuated by the application of geotextile sheets of more rigid material in the gravel-membrane interface. Due to all these experimental difficulties the use of large triaxial cell to determine the mechanical parameters of the gravel material is more practical.

The influence of the rubber membrane on the angle of internal friction of gravel was negligible in the present study. When the geotextile encapsulated column is considered, the role of less deformable geotextile membrane will be much higher.

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