Studia Geotechnica et Mechanica, Vol. XXVIII, No. 2–4, 2006

NUMERICAL MODELLING OF DMT TEST IN CALIBRATION CHAMBER

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Abstract: Dilatometric test performed in calibration chamber at Gdańsk UT was modelled with finite element code using Mohr–Coulomb and Hardening Soil Models. The tests were carried out in loose and dense model sands at a given stress level and under boundary conditions. Data from triaxial tests was used to define the model parameters. In parametric studies conducted, among the other things, the angle of internal friction, soil modulus and dilatancy angle were investigated. The values *A* and *B* measured in dilatometric tests were compared to the calculated mean normal stress acting on the dilatometer membrane after the blade insertion and after the inflation of the membrane, respectively.

Streszczenie: Analizę numeryczną badania dylatometrycznego przeprowadzono w komorze kalibracyjnej na Politechnice Gdańskiej z zastosowaniem metody elementów skończonych i modelu Coulomba–Mohra oraz modelu ze wzmocnieniem. Doświadczenia wykonano w piaskach luźnych i zagęszczonych przy zadanym poziomie naprężenia oraz przyjętych warunkach brzegowych. Parametry modelu obliczeniowego określono na podstawie przeprowadzonych badań w aparacie trójosiowego ściskania. W analizie parametrycznej uwzględniono wpływ wartości kąta tarcia wewnętrznego, modułu odkształcenia oraz kąta dylatancji. Wartości *A* i *B* mierzone podczas badania dylatometrycznego porównano z obliczonymi średnimi naprężeniami normalnymi działającymi na membranę dylatometru po wciśnięciu ostrza oraz po przemieszczeniu środka membrany o 1,1 mm.

Резюме: Численный анализ дилатометрического исследования был проведен в калибрационной камере в Гданском техническом университете с применением методов конечных элементов и модели Куломба–Мора, а также модели с укреплением. Эксперименты были проведены в рассыпчатых
и уплотненных песках при заданном уровне напряжения, а также принятых предельных условиях. Параметры вычислительной расчетной модели были приняты на основе проведенных исследований в аппарате трехосного сжатия. В параметрическом анализе было учтено влияние значения угла
внутреннего трения, модуля деформации и угла дилатансии. Значения *A* и *B*, измеряемые во время дилатометрического исследования были сравнены с рассчитанными средними нормальными напряжениями, воздействующими на мембрану дилатометра после вдавления острия, а также после перемещения середины мембраны на 1,1 мм.

1. INTRODUCTION

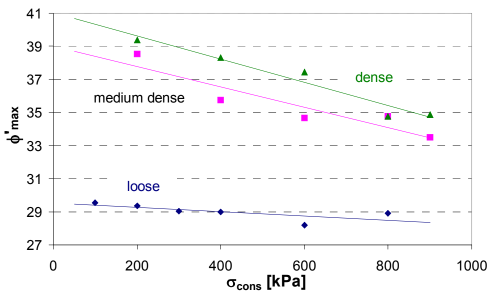
The calibration of device for in-situ measurements is one of a major interest in geotechnics. Calibration chamber tests using CPT and DMT tests have been carried out at the University of Technology in Gdańsk. An extensive series of penetration tests in the calibration chamber has been performed at a wide range of confining pressure, i.e., from 50 to 400 kPa, and loose/dense sand. The results of physical modelling in a calibration chamber filled with a homogeneous soil mass and under appropriately defined boundary conditions present an interesting challenge from a numerical point of view. We can consider the results from cone penetration test and dilatometer test. In cone penetration test, only one independent parameter, i.e., the cone resistance q_c, is measured. The others – the sleeve friction f_s, the pore pressure u – are to some extent dependent on cone resistance. During dilatometer test the two gas pressures measured A and B are independent of each other. DMT with two-parameter test [4], [6] offers an interesting advantage in both physical and numerical modelling.

2. EXPERIMENT DESCRIPTION

A detailed description of the calibration chamber is given in [1]. Soil mass in the calibration chamber is prepared with sand raining. Dense soil mass is obtained with stationary device, while loose soil mass is formed using small travelling sieves at small falling height of the grains. The sand mass was consolidated under K_0 conditions.

2.1. MODEL SAND AND ITS CHARACTERISTICS

Predominantly a uniformly fine quartz sand from the Baltic beach in Lubiatowo is used. In order to obtain the strength parameters for loose, medium dense and dense sand specimens, the sand was tested in triaxial CD tests. These parameters were used to model the soil behaviour in numerical modelling of DMT. The maximum value of an internal friction angle as a function of soil density and stress level is given in figure 1. The values of the deformation modulus corresponding to the deformation level at 50% of the shear strength E_{50} are presented in figure 2, and dilatancy angles – in figure 3.



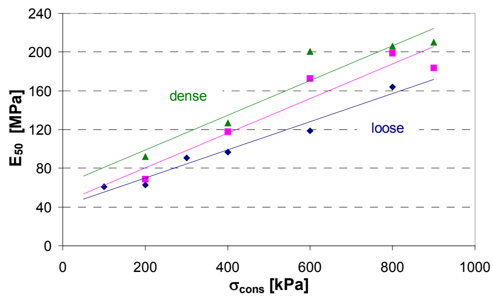


Fig. 1. Angle of internal friction

Fig. 2. Modulus of deformation E_{50}

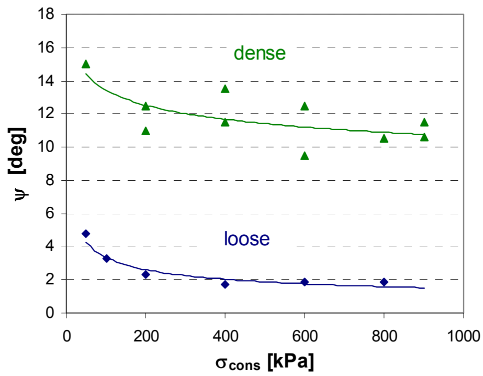


Fig. 3. Dilatancy angle for loose and dense sands

2.2. DILATOMETER TEST

Dilatometer blade was pushed into the soil. Boundary conditions and a constant lateral stress were maintained during blade insertion. At the end of each 5 cm step of penetration the membrane was inflated and the measurements of *A* and *B* were read. An example of readings taken at vertical stress of 100 kPa applied to the upper membrane in a calibration chamber is given for loose and dense sands (figure 4). Relatively uniform distribution of readings with depth is observed, apart from some divergences when the blade is inserted near the upper and lower membranes. High *A/B* ratios, up to 10, are typical of clean quartz sand [2].

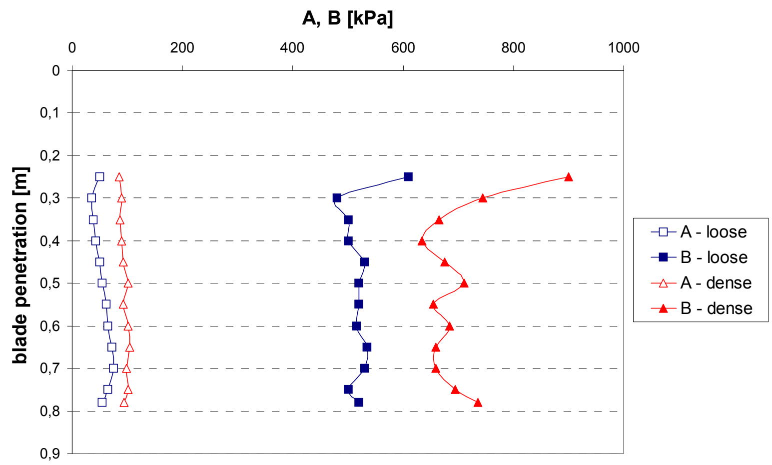


Fig. 4. The measurements of *A*, *B* in loose and dense sands at σ'_v = 100 kPa

3. NUMERICAL MODELLING

3.1. PLANE STRAIN VS. AXISYMMETRIC PROBLEM

The penetration of dilatometer and the inflation of the membrane are very complex, truly three-dimensional phenomena. As the blade is rather flat the penetration stage can be considered as 2D problem. However, the inflation of the circular membrane is truly 3D phenomenon. Taking into account small displacement of the membrane center equal to 1.1 mm, we model both stages of experiment as a plain strain problem.

Two schemes for membrane inflation analysis can be considered (figure 5). In the first one, corresponding to plane strain conditions, membrane can be treated as a simple beam with free supports. In the second scheme, a circular membrane with free supports on the circumference is considered.

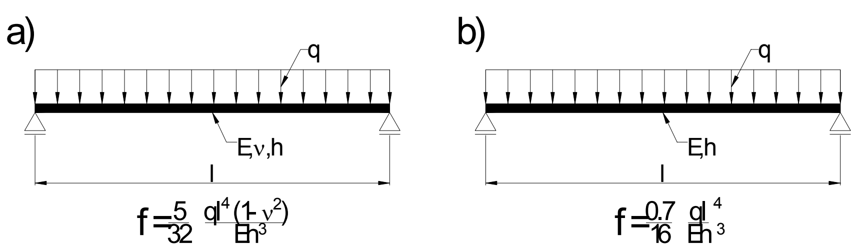


Fig. 5. Schemes for membrane deflection:
a) simple beam in plane strain conditions, b) circular membrane

The formula for membrane deflection under uniform load for both schemes, presented in figure 5, can be given for:

• a simple beam with $v = 0.3$:

$$f = 0.14219\frac{ql^4}{Eh^3}, \tag{1}$$

• a circular membrane:

$$f = 0.04375\frac{ql^4}{Eh^3}. \tag{2}$$

Under the same load the membrane deflection will be thus about 3.5 times more important in plane strain conditions than in axisymmetric ones. In order to model properly the inflation of a circular membrane, one should increase 3.5 times the imposed deflection of the membrane center when calculation is done under plane strain conditions. The problem is however more complex as we should include not only the pressure imposed, but the soil response as well (see figure 6). Additionally some numerical analyses were carried out to verify the membrane response in plane strain and axisymmetric conditions. The blade was placed horizontally on the surface of the box filled with sand. Only a half of the membrane was modelled due to the symmetry axis imposed. A vertical stress of 40 kPa was applied to the box surface to simulate lateral stress in the calibration chamber. Then the membrane was inflated by imposing a volumetric strain on the blade element just behind the membrane. Numerical response corresponding to the reading *B* was evaluated at plane strain and under axisymmetric conditions. Normal stress distribution along the half length of the membrane is given in figure 6. Normal stress calculated under axisymmetric conditions is considerably higher than that under plane strain ones. Normal stress distribution is also given for the 1.1 mm displacement multiplied by 3.5 in plane strain conditions.

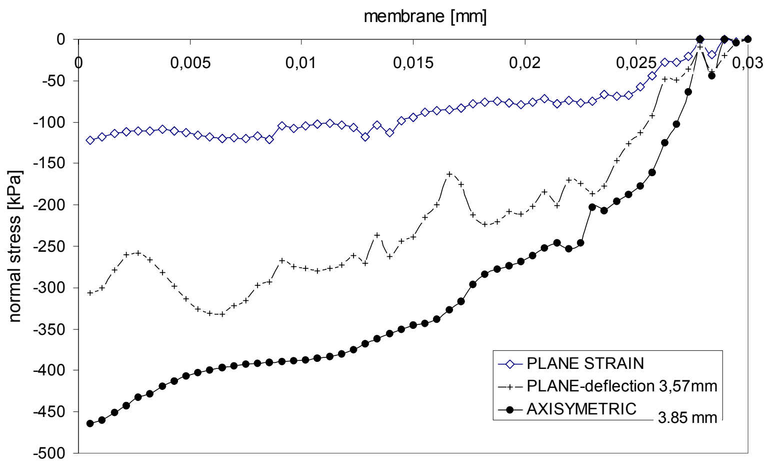


Fig. 6. Calculated normal stress distribution along the dilatometer membrane

3.2. TEST IN CALIBRATION CHAMBER

In the first approximation, the real chamber dimensions were assumed for calculation mesh. The DMT blade was placed in the middle of the chamber. Stage calculations were carried out. The test was conducted under the gravity conditions and at a boundary stress. The blade shape was reproduced by the membrane of 6 cm diameter. An interface separated the membrane and the soil. A fine mesh with 15 node elements was additionally refined near the blade and the membrane. The membrane was included in the mesh. Only one stage of experiment, i.e., blade penetration step followed by the membrane inflation, was modelled numerically. A static (not updated) mesh is considered, since the vertical displacement applied to the top of dilatometer did not exceed several millimeters. The calculations for the penetration of the blade were carried out until the penetration resistance had approached asymptotic value. At this moment the normal stress distribution at the interface was registered, which corresponded to the measurement of *A*. Then a cluster behind the membrane was inactivated and the lateral uniform stress was applied behind the membrane. This stress was increased until the displacement of the membrane center had reached 1.1 mm, corresponding to the measurement of *B*. An example of the shape of the inflated membrane is given in figure 7 for loose and dense sands. One can notice a larger displacement at the edges of the membrane compared to that at the center, which is related to the stress concentration at the membrane edges. Additional calculations performed for the case of circular membrane enclosed in a steel blade placed horizontally on the soil surface and subjected to uniform vertical stress also reveal larger displacement and stresses at the edges of the membrane than at its center. This distribution of stress and of the displacement of the membrane is not due to the procedure of blade insertion. The application of different loading mode instead of applying a constant stress will probably allows us to avoid this effect. Asymmetric shape of the inflated membrane (figure 7) is due to stress distribution at the end of insertion phase and complex stress–strain history, especially for dense sand and near the blade tip.

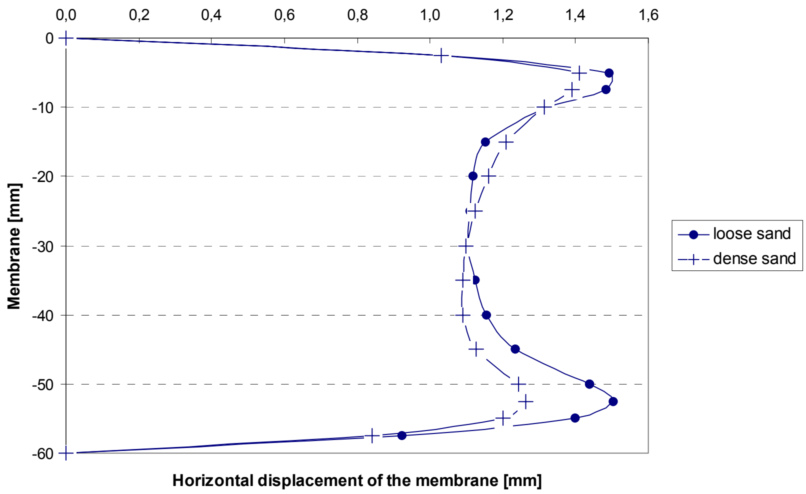


Fig. 7. The shape of the inflated membrane for loose and dense sands

The calculations were done using PLAXIS v.8.2 code and the Mohr–Coulomb (M–C) and Hardening Soil Models (HSM). Preliminary calculation showed a considerable influence of boundary conditions on the calculated values of the pressure *B*. In order to avoid such an effect on the results of numerical analysis, the diameter of the chamber was increased to 2 m. Two types of numerical analysis were carried out. In the first one, the parametric studies included the soil modulus, the angle of internal friction and dilatancy angle. An example of such an analysis is given in figure 8 for dense sand at the angle of internal friction of 42 degrees and the deformation modulus E_{50} = 40 MPa, corresponding to triaxial tests results. We can notice the sensitivity of the model to parametric data. In the second type of the analysis, we compared the results of numerical analysis using the parameters derived from triaxial tests with the pressures *A* and *B* measured in a calibration chamber.

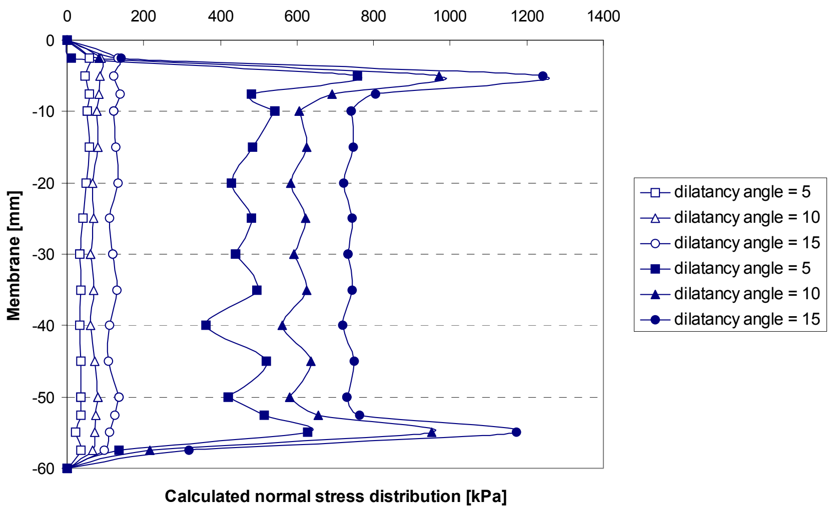


Fig. 8. Parametric studies for the distribution of normal stresses *A* and *B* on the dilatometer membrane

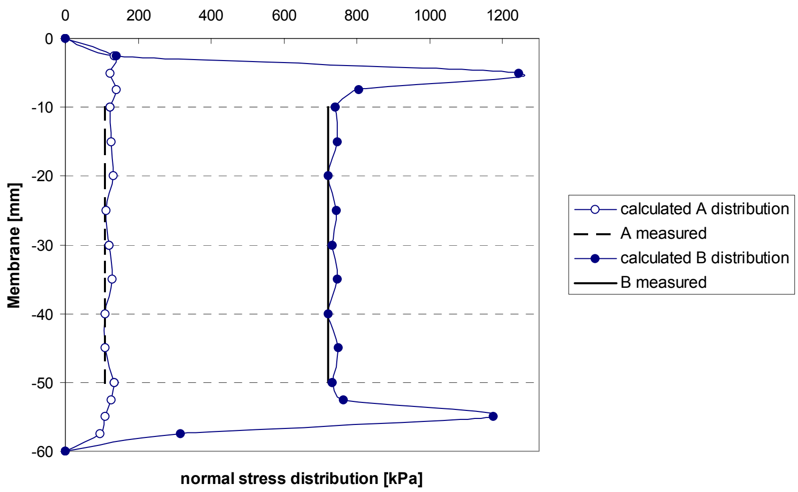


Fig. 9. Normal stress distribution on the membrane for *A* and *B* measurements in dense sand – calculation versus experiment

Dilatometer tests with loose and dense sands at the vertical stress of 100 kPa were carried out and analysed. Normal stress distributions were obtained based on numerical analysis. The distributions of the stresses *A* and *B* in the middle part of the calibration chamber were compared. An example of such a comparison for dense sand is given in figure 9. A very good correlation between numerical and experimental results was found for the central part of the membrane, at the internal friction angle of 42 degrees, the deformation modulus E_{50} = 40 MPa and the dilatancy angle of 15 degrees with MC model. At the edges of the membrane the calculated values of B are considerably higher.

An example of comparison of numerical and experimental results for loose sand is given in figure 10. A very high correlation between numerical and experimental results was found for the reading A and quite lower, apart from some numerical error, for the reading B. At an internal friction angle of 35 degrees, the deformation modulus E_{50} is 40 MPa, and the dilatancy angle is 5 degrees. These parameters are slightly higher than these obtained in triaxial test.

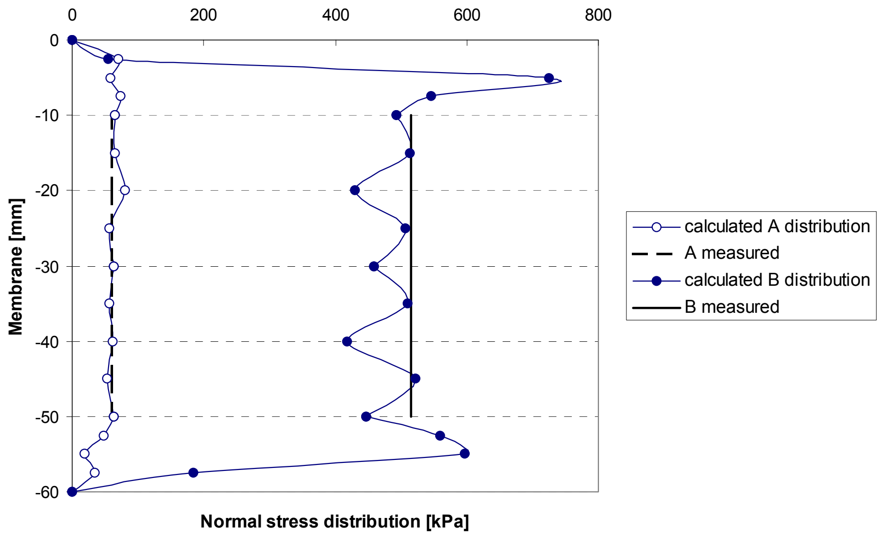


Fig. 10. Normal stress distribution for A and B measurements in loose sand – calculation versus experiment

Comparative analyses for the Mohr–Coulomb and Hardening Soil Models were carried out for dense sand at the same sets of parameters. The values of the results for numerical analysis using HSM (figure 11) are higher than these obtained with M–C and overestimate the measured values of A and B. This is due to the characteristic of the HSM, where the value of the soil modulus E_{50} is a function of the stress level and during the calculation increases with an increase in the actual stress level in the soil. This explains why the values of B of normal stress calculated at the edges are considerably higher than these obtained based on M–C model.

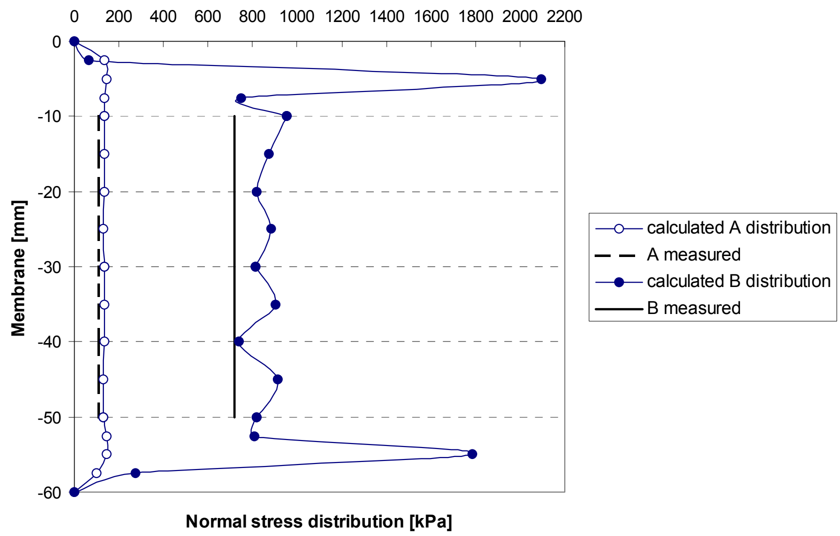


Fig. 11. Comparison of the distributions of the normal stresses *A* and *B* on the membrane, the stresses being measured in dense sand and calculated based on the Hardening Soil Model

4. CONCLUSIONS

It is very interesting to combine the model test whose boundary conditions are appropriately defined using a reference sand and well-known strength parameters with numerical FEM modelling. As in DMT two independent parameters are measured, the results of dilatometer tests in calibration chamber present a real challenge if a numerical analysis is undertaken. It is thus possible to check the validity of the numerical model in two stages of the experiment (i.e., for the readings *A* and *B*). A very good approximation of DMT tests was obtained in numerical modelling of the two pressures *A*, *B* independently. The parametric studies were conducted and the analysis revealed that the calculation performed with the soil parameters obtained in the triaxial tests were compatible with the measurements in the calibration chamber. Refined soil model (HSM) slightly overpredicted the experimental data, because in this model the soil modulus E_{50} was dependent on the stress level. Calculations in plane strain conditions were responsible for underpredicting the response *B* of dilatometer at the membrane deflection imposed.

ACKNOWLEDGEMENTS

Some parametric calculations were performed by two students – Germain Capdevila and Benoît Grossemy – from Université des Sciences et Technologies de Lille during their stay at GUT. The author appreciates the financial support from State Committee for Scientific Research (KBN) in the form of grant 8 T07E 00121.

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