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EFFECT OF PRECONSOLIDATION ON PILE BEARING CAPACITY IN MODEL TESTS

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Abstract: The effect of preconsolidation on pile bearing capacity was studied in model tests performed in the calibration chamber. The tests were conducted on overconsolidated dense fine quartz sand with OCR ratios up to 7. The soil mass was overconsolidated in conditions of no lateral volume changes. Two types of boundary conditions (BC2 and BC3) were applied during pile penetration. The influence of boundary conditions on pile base resistance and lateral friction was analysed.

1. INTRODUCTION

Overconsolidated (OC) sands frequently encountered were formed as a result of glaciations, tides, overloading or compaction process. The overconsolidation, induced by physical overloading, can be reproduced in the soil sample in the calibration chamber. A double-wall calibration chamber constructed in Gdańsk University of Technology permits soil mass consolidation under controlled conditions of vertical stress and lateral strains. A detailed description of the calibration chamber is given in [1], [2]. The tests are made on the Lubiatowo fine sand coming from the Baltic beach. The previous series [2], [3], [7] of model pile tests, carried out in the calibration chamber and concerning normally consolidated sand, forms the database and the reference for the present comparison.

2. RECONSTITUTION OF THE SOIL MASS

Dense soil sample is prepared by sand raining with stationary pluviator to relative density of about 0.75. The sample was subjected to consolidation up to overconsolidation pressure and then this pressure was reduced step by step to obtain 50 kPa of vertical stress in the upper membrane. All process was performed under conditions of no lateral volume changes (BC3). At the same time, lateral stress around the soil sample and water volume changes in the upper and bottom membranes were measured. The maximal vertical stress applied in the upper membrane was 350 kPa, which gave the overconsolidation ratio equal to 7. The vertical stress of 50 kPa in the upper membrane was chosen as reference level, as it enabled us to consider the model piles as deep foundations and to apply quite wide range of overconsolidation ratios. The series of previous tests conducted on normally consolidated sand indicates that the coefficient of a lateral stress at rest deduced from lateral stress measured during consolidation in BC3 condition is generally about 0.4, being slightly larger for low confining pressures. The same was observed in these tests within the range of normal consolidation. In the range of overconsolidation, a classical increase in earth pressure coefficient is observed during unloading as overconsolidation ratio increases. An example of earth pressure coefficient evolution during consolidation to 200 kPa followed by vertical stress decrease to 50 kPa (*OCR* = 4) is given in figure 1. This process is also presented in p'–q space in figure 2.

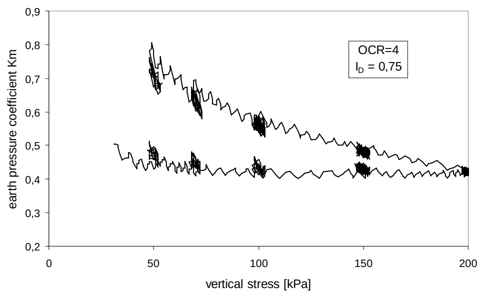

Fig. 1. Earth pressure coefficient during overconsolidation

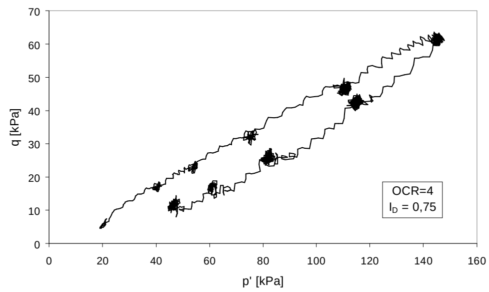

Fig. 2. Stress path during overconsolidation

The values of earth pressure coefficients at rest at the end of overconsolidation $(K_0)_{oc}$ are presented in figure 3 as a function of overconsolidation ratio. All results are given at the vertical stress of 50 kPa applied in the upper membrane, i.e. at the end of overconsolidation process. The recorded results fit quite well empirical correlations.

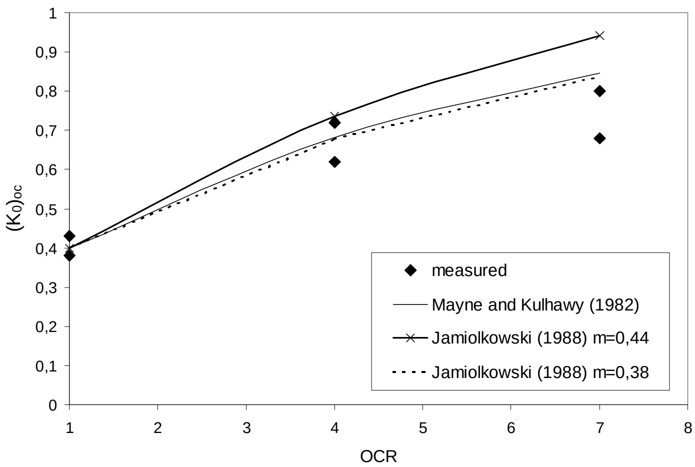

Fig. 3. The coefficient of earth pressure at rest measured in the calibration chamber compared with the coefficients calculated from empirical correlations

The measured values of $(K_0)_{oc}$ are compared with the values from empirical formulae given by Mayne and Kulhawy:

$$(K_0)_{oc} = (K_0)_{nc} \cdot OCR^{1-\sin\phi} \tag{1}$$

and the formula resulted from the calibration chamber tests by Jamiolkowski:

$$(K_0)_{oc} = (K_0)_{nc} \cdot OCR^{m}, \tag{2}$$

where:

$(K_0)_{nc}$ – the coefficient of earth pressure at rest for normally consolidated sands,

ϕ – internal friction angle, assumed here as 38° according to CD triaxial tests,

m – empirical coefficient in the range from 0.38 to 0.44 for medium dense quartz sands.

3. TEST DESCRIPTION

Model pile of 20 mm in diameter was pushed into the mass of overconsolidated sand to reach the pile embedment of about 35 cm and then the pile was unloaded and reloaded. Afterwards, the pile insertion was continued up to 60 cm and then the pile was subjected to tension. During pile loading two types of boundary conditions were maintained:

- BC2 (no volume changes both on vertical and lateral boundaries),
- BC3 (constant vertical stress in the membranes and no volume changes at the lateral boundary).

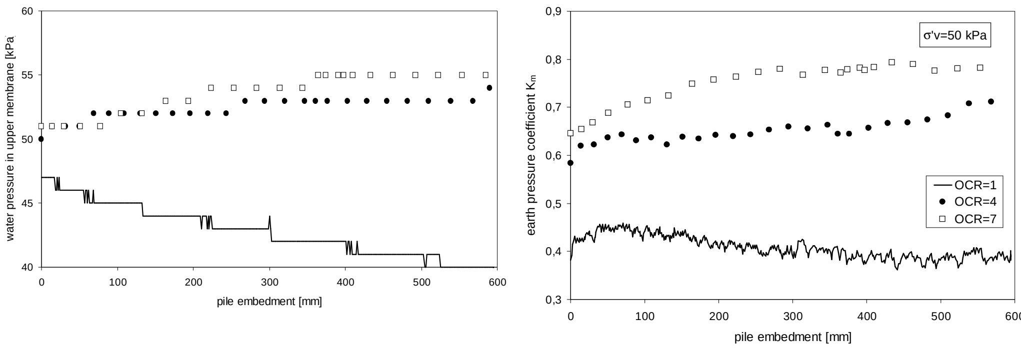

Fig. 4. BC2 condition: evolution of water pressure in the upper membrane and earth pressure coefficient with pile embedment at different *OCR* ratios

In the first case, the water flow from membranes and inner cell was impossible, and vertical and lateral stresses were recorded. In normally consolidated (NC) sands, the pile insertion decreases the water pressure in the upper membrane, i.e. it produces vertical downwards deformations of the upper surface of the soil mass and it induces only small variation of earth pressure coefficient (figure 4). In OC sands, however, both water pressure in the upper membrane and lateral stress acting on the soil mass (earth pressure coefficient) increase during pile penetration. The higher the overconsolidation ratio, the higher the vertical stress and lateral stress induced by pile insertion.

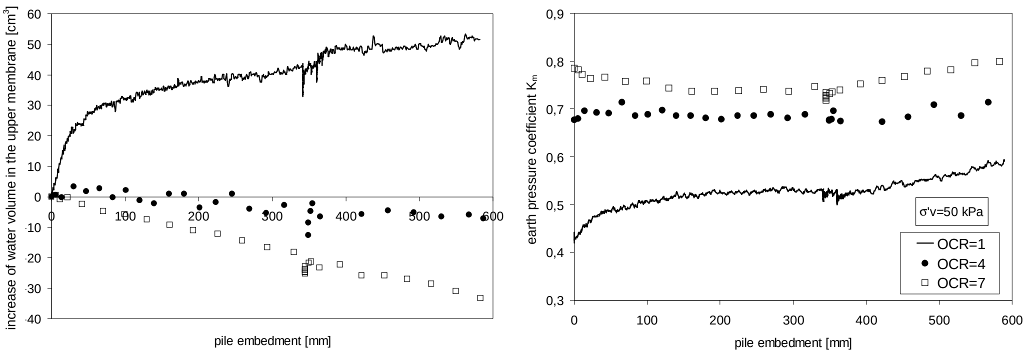

Fig. 5. BC3 condition: evolution of water volume in the upper membrane and earth pressure coefficient with pile embedment at different *OCR* ratios

In BC3 condition, water volume changes were monitored in the upper and bottom membranes and the pressure in the inner cell was recorded. The data recorded for NC sands shows (figure 5) that there is a net increase of water volume in the upper membrane, i.e. vertical downwards deformations of the upper surface of the soil mass. An increase of lateral stress acting on the soil mass (earth pressure coefficient) is observed during pile penetration into NC sands. In OC sands, the water is expulsed from the upper membrane as the pile penetrates soil. Lateral stress acting on the soil mass (earth pressure coefficient) remains nearly constant or even drops during pile penetration. The higher the overconsolidation ratio, the larger volume of water is expulsed from the upper membrane during penetration.

Volumetric deformations of the soil mass, i.e. the sum of water volume changes in the upper and bottom membranes due to pile insertion, are given in figure 6 as volumetric strain. Sand in overconsolidated soil mass displays a clear tendency towards dilatancy. When we consider the volume of the pile itself embedded in the soil mass we will observe a general compressive behaviour of the sand sample in the calibration chamber. Global volumetric strains of the soil mass are given in figure 7. The higher the overconsolidation ratio, the lower the volumetric strains in compression. However, even in a dense overconsolidated sand at low confining pressure the global compressive behaviour is observed.

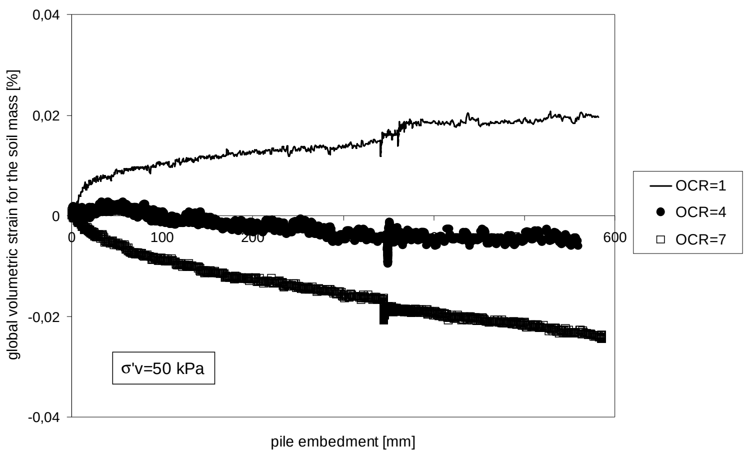

Fig. 6. BC3 condition: evolution of volumetric strain of the soil mass at different *OCR* ratios

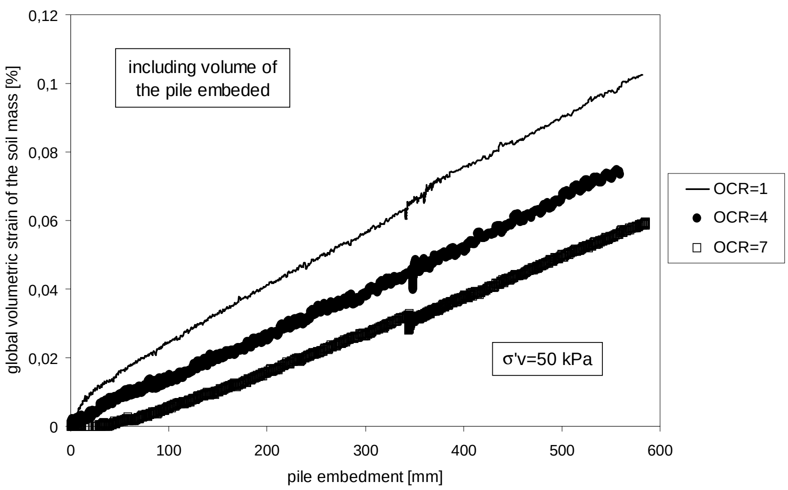

Fig. 7. BC3 condition: evolution of volumetric strain of the soil mass,
including volume of the pile embedded, at different *OCR* ratios

Based on the stress and volumetric deformations induced by pile penetration on the soil mass boundary the following general concluions can be drawn:

- there are important differences in water pressure/volumetric deformations and lateral stress changes at the boundaries of NC and OC sands,
- relatively small changes in stress are recorded for OC sands,
- soil mass of NC sands tends to compress, which is confirmed by water volume increase in the upper membrane and volumetric deformations in BC3 condition or a decrease of water pressure in this membrane in BC2 condition,

• in the case of OC sands, soil mass tends to dilate at the upper boundary, which induces a decrease of water volume in the upper membrane in BC3 condition or an increase of water pressure in the upper membrane in BC2 condition,

• general compressive behaviour of the soil mass is due to pile insertion into a dense overconsolidated sand.

4. MODEL PILE CAPACITY

Evolution of skin friction and point resistance during pile penetration is presented under BC2 (figure 8) and BC3 (figure 9) conditions. One can notice an important influence of overconsolidation on skin friction under both types of boundary conditions. For small embedment, lateral friction generally decreases with pile penetration in BC2 condition, while the opposite is observed in BC3 condition. The measured values of skin friction are quite low and seem to be unrepresentative of a real pile behaviour. They can be explained by soil compression and grain crushing under the model pile base. For further analysis, the values of lateral friction recorded in the middle part of the figure (before unloading–reloading loop) are taken.

Point resistance curves are quite different under both types of boundary conditions. For BC2 a large difference in point resistance is observed at small embedment. This is due to vertical strain restraint and vertical stress increase/decrease. The first factor seems to play a dominant role. Maximal point resistance recorded at BC3 assumes similar values irrespective of overconsolidation. For further analysis, the maximal recorded values of point resistance are taken.

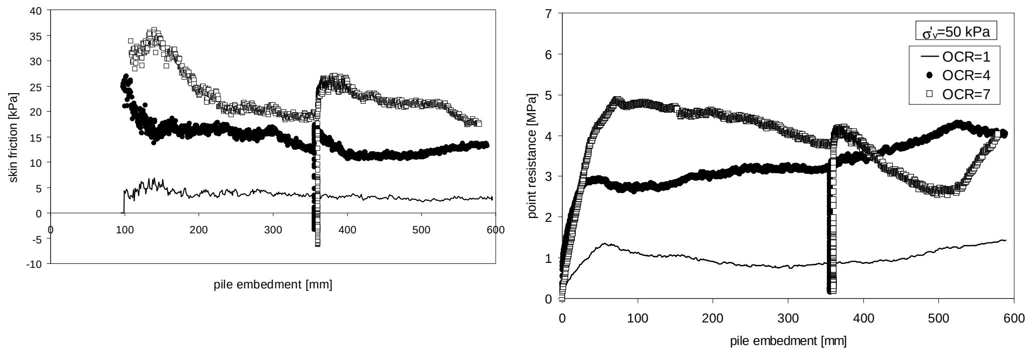

Fig. 8. BC2 condition: evolution of skin friction and point resistance with pile embedment at different *OCR*

The ratios of point resistance for piles in OC and NC soil masses are given in figure 10. The ratios of skin friction for OC and NC soil mass are summarized in figure 11. The following conclusions can be drawn from the analyses of these figures:

• There is an important effect of boundary condition at upper and bottom surfaces of the soil sample. Vertical strain restraints, i.e. application of BC2 condition, produce larger changes in point resistance and skin friction than BC3 condition.

• Under BC2 and BC3 conditions the lateral stress at the boundary does not change practically for OC soil mass during pile penetration (see figures 4, 5), so the boundary effect is primarily due to restraints (strain/stress) at the upper and bottom soil mass boundaries.

• Point resistance and skin friction in OC sands are more affected under BC2 than under BC3 conditions.

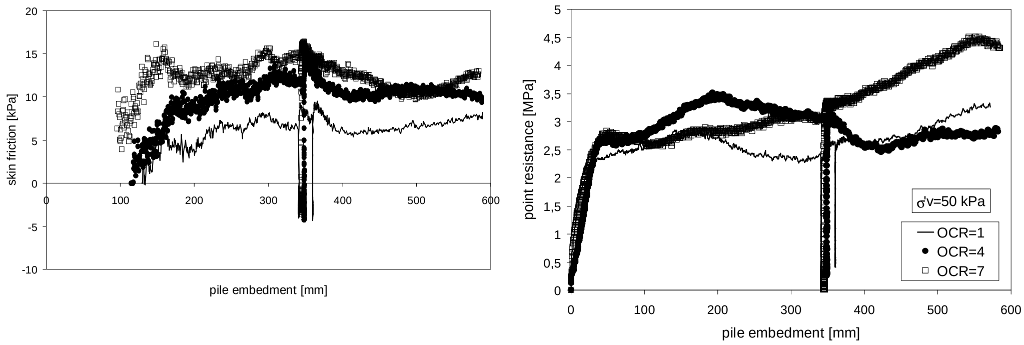

Fig. 9. BC3 condition: evolution of skin friction and point resistance with pile embedment at different *OCR*

The results obtained can be compared with database previously recorded in NC sand. Such figures as a function of vertical stress are shown for point resistance (figure 12) and skin friction (figure 13). For the purposes of comparison, the values of point resistance and skin friction of NC sands concern BC3 condition. *OCR* values are printed above (BC2) or below (BC3) the corresponding results for OC sands.

The values of point resistance for NC Lubiatowo sand [2], [3] seem to be practically independent of boundary conditions (BC1, BC3). The size effect of calibration chamber, when considering the model pile, 20 mm in diameter, seems to be relatively small, at least for high confining pressures. At present series of tests on dense overconsolidated sand under low confining pressure one should theoretically expect the highest possible magnitude of boundary effect. However, general compressive behaviour of the sand tested recorded during pile penetration (see figure 7), even for overconsolidated soil mass, together with grain crushing exclude classical boundary effect, i.e. measured point resistance lower than theoretical one. Overconsolidation increases the point resistance due to the coefficient of earth pressure at rest higher than that for NC Lubiatowo sand. Significantly lower value of the point resistance for the pile in NC sand in BC2 condition can be considered as a result of boundary effect.

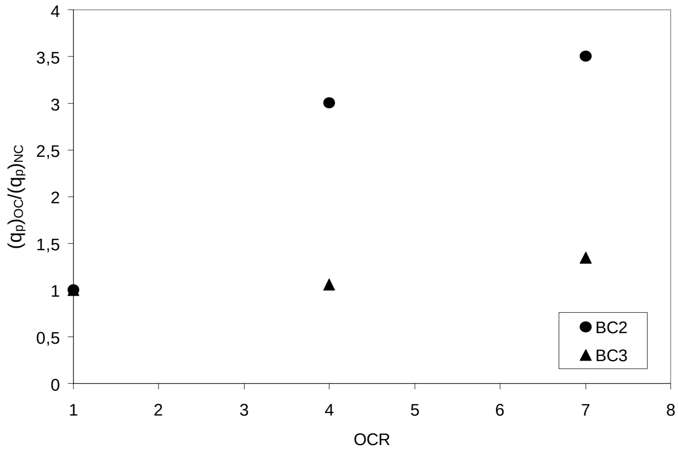

Fig. 10. Ratio of point resistance for OC and NC sand under BC2 and BC3 conditions (σ'_v = 50 kPa)

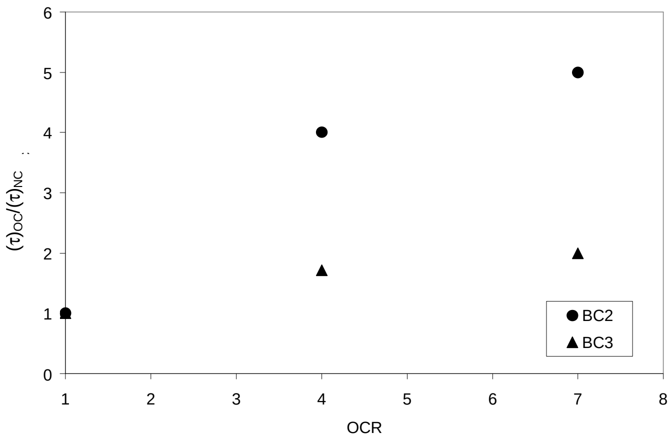

Fig. 11. Ratio of skin friction for OC and NC sand under BC2 and BC3 conditions (σ'_v = 50 kPa)

As we consider skin friction in NC Lubiatowo sand [2], [3], its value depends on calibration chamber size and boundary conditions. It is generally higher in BC3 than in BC1 condition due to a lateral stress increase. Under the same boundary conditions in the calibration chamber, reduced size and boundary effect for the skin friction in OC sands should be expected [6] compared to NC sands, which is due to higher normal stiffness of the interface. Nonnegligible boundary effect for skin friction in OC sand is observed, being higher in BC2 condition. One should notice that the recorded values of skin friction at low stress level are considerably smaller than those generally admitted for piles in silica sand. This is probably due to a general compressive behaviour and grain crushing, which can modify the interface friction.

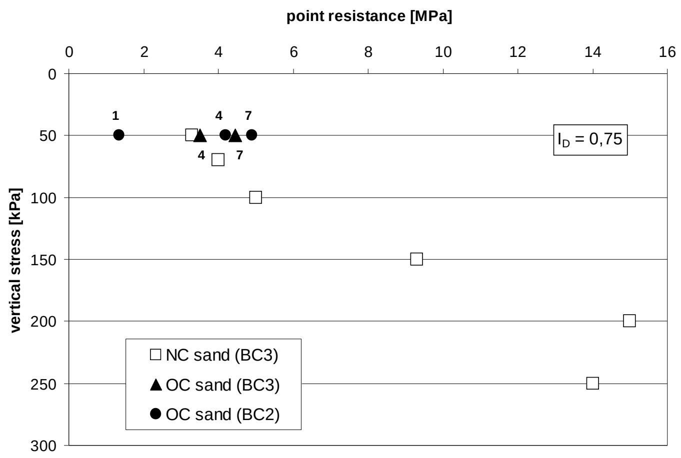

Fig. 12. Point resistance for the piles in NC and OC sand (the values of *OCR* given)

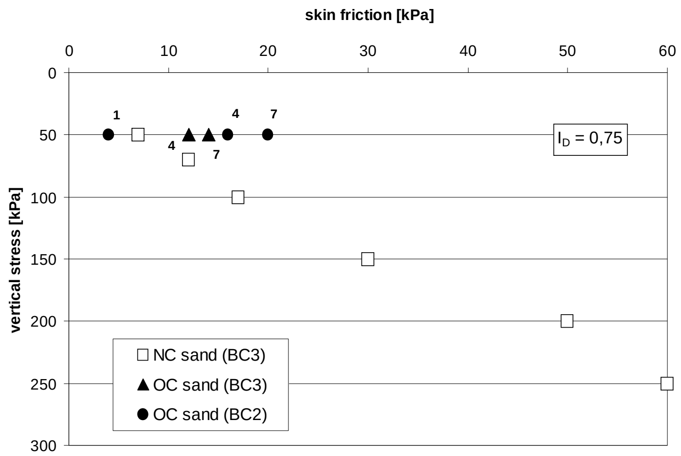

Fig. 13. Skin friction for the piles in NC and OC sand (the values of OCR given)

5. CONCLUSIONS

The coefficient of earth pressure at rest for OC sand, measured for reconstituted soil in a calibration chamber, is in agreement with the empirical correlations analysed.

A series of pile penetration tests on overconsolidated soil in the calibration chamber was performed under two boundary conditions (BC2 and BC3) at an initial vertical stress of 50 kPa. Contrary to expectations, global compressive behaviour of the Lubiatowo sand was observed while pile penetrated dense overconsolidated soil mass at low confining stress. Boundary effect in OC sand was found to be more important for skin friction than for point resistance. Boundary effect is higher under BC2 than BC3 conditions.

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