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Experimental and numerical investigations of the guided caisson method

Recherches expérimentales et numériques sur la méthode du caisson guidé

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ABSTRACT
The conventional caisson construction method has already been in use for a long time. A drawback of the procedure is the irregular lowering process of the caisson and that the final position of the caisson cannot be achieved precisely. To achieve a higher accuracy, the "guided caisson technique" was developed within a Vienna tunnelling project. Thereby a steel frame that is positioned at the surface is used as guidance during the lowering process and prevents the conventionally occurring pendulousness of the caisson. This method of construction works for single objects as well as for successive lowered elements in shallow tunnelling. This paper shows the results of a large-scale laboratory test and for the first time numerical simulations of the lowering process of a caisson using the Particle Flow Model especially to simulate the penetration of the cutting edge into the soil.

RÉSUMÉ
La méthode de construction du caisson est utilisée depuis longtemps. Un des inconvénients de la procédure est le processus irrégulier d'abaissement du caisson, qui pénètre le sol en provoquant un effondrement de terrain en proximité de la lame. A cause de ce mouvement, la position finale du caisson dans le sol ne peut être déterminée avec précision. Cet article montre les résultats d'essais en laboratoire effectués à grande échelle, et pour la première fois des résultats d'études numériques. Des analyses avec la méthode des éléments particulaires furent menées pour simuler la pénétration de la lame.

1 INTRODUCTION

The caisson technique has been known for hundreds of years. Caissons were already built in ancient times for the establishing of foundations (Arz et al., 1991). Beyond this they are also used as autonomous buildings (shafts, underground car parks, pumping stations).

The advantage of the caisson technique is that there is no influence in groundwater and environmental conditions. It is not necessary to lower the ground water table. Also the lowering process is widely free of shocks. The method mostly gets profitable when the construction is under the ground water table, when the soil is homogenous and not cohesive.

During the lowering process of the conventional caisson irregular sinking of the caisson and with it tilting occurs as a result of the asymmetric excavation process. Furthermore also non horizontal layers or locally varying compactness of the soil can cause tilting. During the whole lowering process tilting occurs in varying directions.

A new option of the caisson method is the guided caisson technique which permits a relatively precise lowering of the caisson by means of a steel frame similar to a gantry crane. This procedure is particularly of interest if several caissons are to be lowered next to each other, as it was intended for the shallow 4 lane road tunnel "Rannersdorf", south of Vienna, with 2 km of length. During the design phase a large-scale laboratory test was developed and carried out at the Institute for Soil Mechanics and Foundation Engineering of the Graz University of Technology. The conducted test provided information about the optimal sequence of the lowering process of a guided caisson, the most suitable geometry of the cutting edge and the establishing of the impermeability of the joints between two caissons (ARGE Planung Tunnel Rannersdorf, 2002).

On the other hand numerical investigations with the Particle Flow Model were conducted to simulate the penetration of a cutting edge into the soil.

2 LABORATORY TEST

2.1 *Test procedure*

Nearly no experience with the guided caisson technique is available. Only a small scaled laboratory experiment was already carried out (Savidis et al., 1987).

The main aim of the new developed experiment at the Graz University of Technology was to simulate the lowering process of the caisson. For that purpose basic components of the caisson and of the appropriate steel frame were built in scale 1:10 (Fig. 1). The lowering process itself was carried out in a box with the dimensions width/length/depth = 2,85/2,85/3 m filled with soil and water to a height of 1,6 m. In the start position the caisson is hanging on a steel frame which is situated at the surface of the soil.

2.2 *Execution of the laboratory test*

The self weight of the caisson leads to a penetration into the soil. With the increasing resistance of the soil, the tension forces between the steel frame and the caisson change into compression forces. In this phase the weight of the steel frame is used as an abutment to push the caisson into the soil by jacks. The steps of the excavation inside of the caisson are orientated on the measured amplitude of the compression force. Under observance of the forces the lowering process can be done either simultaneously or alternating to the excavation.

2.3 *Test results*

The tests showed that at the start of the lowering process the passive earth pressure at the inner side of the caisson is higher than the earth pressure from the outer side. The horizontal earth pressure at the inner side of the caisson is caused by the incline

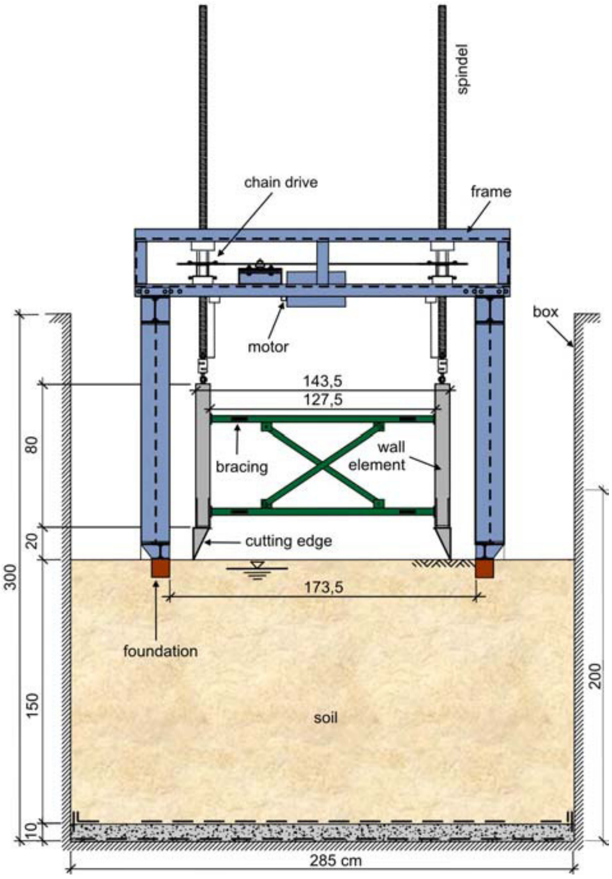

Figure 1. Cross section of the laboratory test equipment

of the cutting edge. The cutting edge pushes the earth away and causes the earth pressure. For very low lowering depths the horizontal earth pressure is larger than the earth pressure from the outer side. If the caisson gets deeper into the soil, the earth pressure on the outer side increases while the earth pressure on the inner side of the caisson stays the same, because inside the caisson the soil is excavated (Fig. 2). The forces are measured in the bracings of the caisson.

The evaluation of the conducted laboratory tests point out that it was possible to establish reproducible conditions. With the results of the tests the main differences between the conventional and the guided caisson technique could be evaluated. A sharp shape of the cutting edge for the guided caisson is more appropriate than an obtuse or a stepped one. Tilting can be avoided by the use of a steel frame. Therefore, also in soft ground conditions it is not necessary to use obtuse cutting edges.

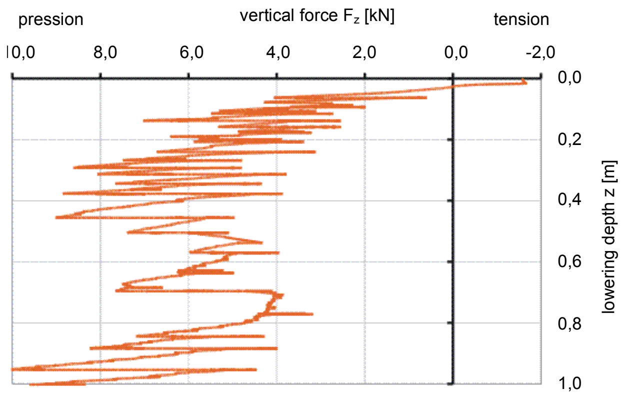

Figure 2. Measurement of vertical forces versus lowering process

Nevertheless the tendencies for tilting and canting are also given by the guided caisson technique. This is clearly to be seen in every experiment. Despite the homogeneous soil at the measuring points, different vertical forces occur. They have to be transferd by the steel frame into the ground.

The execution of the test showed that the excavation should not start in the edges as it is the standard procedure with conventional caissons. With guided caissons the excavation should be started where the resistance against penetration of the cutting edge is the maximum. The conducted tests show clearly that the measurement of the occurring forces are similar to reality for a successful lowering process.It’s necessary to get information about the stresses at the cutting edge and the forces at the equipment.

If predefined limit forces are reached, it can be reacted by an aimed excavation step or via stopping of the lowering process. The lowering of the caisson is conducted by the pushing of the caisson while the occurring forces are measured. The excavation can be done either parallel or alternating to the lowering process.

A significant difference to the conventional caisson technique is that the force which is applied to the ground should be higher than the weight of the caisson. In this manner the foundation of the steel frame is getting unloaded and the risk that the forces on the walls of the caisson and with that the friction angel increases are reduced. The lower the forces on the foundation the lower are the potential occurring differential settlements. From the measured data it can be clearly seen, that caused by the non uniform occurring forces different loads on the foundation are to be expected. Differential settlements can be compensated with the help of a ride control system in the steel frame. At any time of the lowering process it has to be possible to assure the horizontal alignment of the caisson.

3 NUMERICAL SIMULATION

3.1 *Basics*

The Particle Flow Model (PFM) is a procedure for numerical modelling of discrete elements on basis of the discontinuum mechanics.

The Particle Flow Code (PFC) is a software for two (PFC2D) and three dimensional (PFC3D) problems. It is developed by Itasca Consulting Group in Minneapolis, USA (Itasca 2002). Discrete elements with the shape of round disks, respectively spheres, allow to simulate the behavior of granular materials, for instance non cohesive soil.

The two dimensional version of PFC was used because of calculation reasons. This is basically accurate for the simulation of the cutting edge, but not for the soil. The problem with the soil is, that in a two dimensional simulation there is no possibility of grain movements into the third dimension.

3.2 *Calibration of the model*

In a first step simple soil mechanic tests (shear test, oedometer test) have been simulated and the results of the simulations were compared with the results of laboratory tests. For these tests the particles were generated 1:1 to a grain size distribution of a coarse sand. Therefore a previously defined number of particles were generated with half of their final radius in the testing box, afterwards the radius is extended. With this procedure, every required compactness of particles can be established.

The simulated oedometer tests show that it is possible to fit the results relatively well to the laboratory tests. But the simulation of an unloading and reloading loop showed the limits of the used model. The numerical simulation of the soil structure showed a widely linear elastic behaviour. This is caused by the linear elastic model of the contact constitutive model of the contact between the grains. The inclination and the shape of the stress strain curve are primarily controlled by the chosen contact stiffness. In the laboratory tests ductile deformations occur and a non linear behavior of the sample is observed.

The simulation of the shear tests showed that the achieved friction angle φ is basically dependent on the compactness of the packing and the friction angle between the single contacts φ_p. The numerical simulations of the shear test showed that the friction angle between the single contacts φ_p is correlating with the friction angle φ, but the interrelation is not linear.

3.3 *Upscaling*

A maximum of 6000 particles were used for the numerical simulation of the laboratory oedometer and shear tests. For the simulation of soil mechanic problems the number of required particles would increase enormously. Followed by the increasing numbers of particles the calculation time would also rise equally. One method to reduce the calculation time for the numerical simulation is the upscaling technique. This means that the grain size distribution of the soil is increased multiple in the model without changing the properties of the particles. This multiplier is called scale factor S. In so doing, the numbers of particles can be reduced signifcantly and with that a much lower calculation time is reached. If the grain size distribution of the soil should be increased, it has to be assured that the properties of the original material stay the same. To verify the behaviour of the sample of particles after the upscaling, the oedometer and the shear tests were conducted with the increased grain size distribution (Fig. 3).

It could be shown that the properties of the sample of particles due to the upscaling stayed nearly the same for the different used scale factors. Out of the conducted oedometer tests it could be derived that the scale factor has only a very small influence on the strains and the stiffness of the soil structure. The conducted shear tests showed that in the observed area the macro mechanic friction angle of the particle sample is not dependent on the scale factor.

As the executed tests showed that the porosity and also the friction angle had not been influenced by the scale factor S, it is assumed that the properties of the material will not be influenced importantly for further larger scale factors.

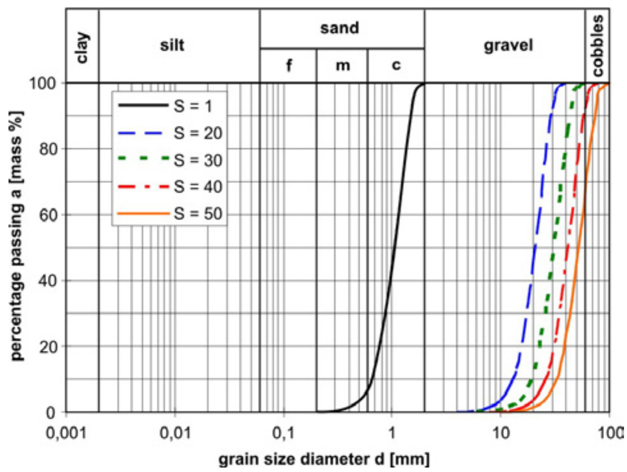

Figure 3. Parallel shifting of the grain size distribution by upscaling

3.4 *Simulation of penetration of a cutting edge*

For the design process of a caisson the occurring normal and shear stresses at the cutting edge are very important.

For the calculation a section of 11 x 10 m was chosen. The technique of upscaling was adapted in a way that in the area close to the cutting edge the scale factor was relatively low, with respect to the relatively high stress gradient, equivalently to the generating of a mesh in finite element calculations. In the outer areas a larger scale factor was used. With this system the number of particles could be reduced significantly (Fig. 4). With the used approach the number of particles is held quite low but in the area of the cutting edge there are still enough contacts between the cutting edge and the soil.

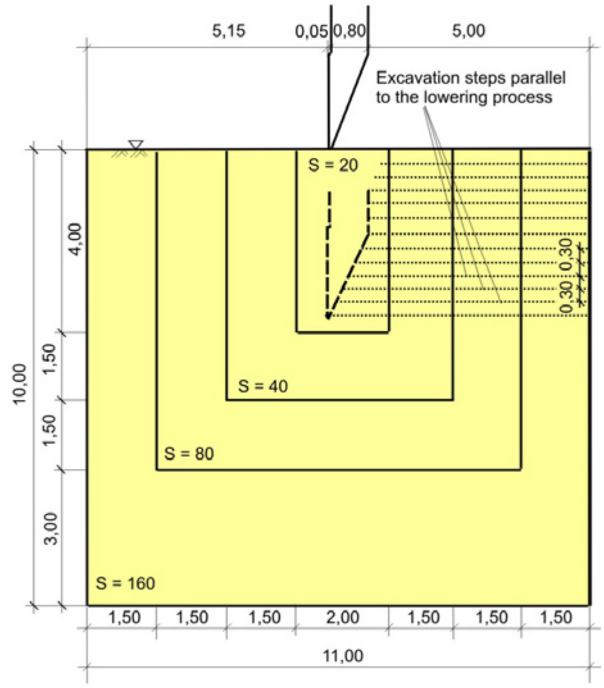

Figure 4. Numerical model with areas of different upscaling factors

The simulation of the penetration process works in the following way. The cutting edge is driven into the soil with a constant velocity. Parallel to the penetration process at the inner side of the cutting edge the soil is excavated in layers of 30 cm. During the penetration process the occurring forces at the inner and outer side of the cutting edge are calculated (Fig. 5).

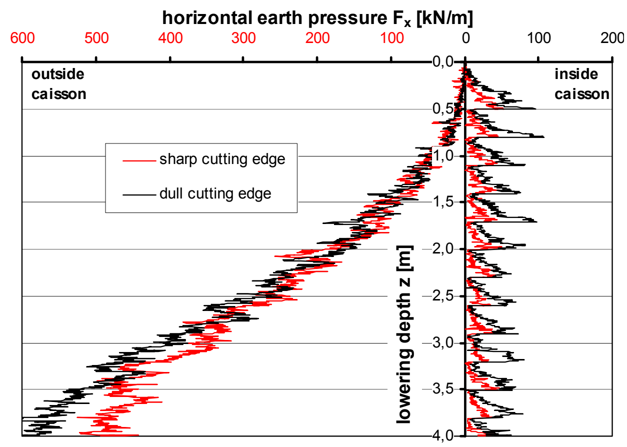

Figure 5. Horizontal earth pressure versus lowering process

For the simulation of the penetration process two different types of cutting edges, a sharp and an obtuse one were used. The simulation showed that on the inner side of the cutting occurred a shear failure. Also at the outer side of the cutting edge displacements occurred. Furthermore it turned out that the declination of the cutting edge had no significant effects on the behaviour of the particles on the outer side of the cutting edge.

It could be shown that the earth pressure trend at the inner and outer side of the cutting edge, which is to be expected from the laboratory tests and the conventional calculations, can be reproduced qualitatively. As a result of a large dilatancy and an only two dimensional possibility of the particles to move, the numerically calculated earth pressure is significantly higher than the conventionally calculated forces.

The behaviour of the soil during the penetration of the cutting edge showed a kind of shear failure for both types of cutting edges at their inner side. At the outer side of the cutting edge a kind of sliding wedge is visible (Fig. 6).

4 CONCLUSION

The laboratory tests as well as the numerical investigations showed that the shape of the cutting edge is not really important for the lowering depth of the caisson. Furthermore it is to say that for the guided caisson technique an obtuse cutting edge is not reasonable in opposition to the conventional caisson technique. The numerical calculation with PFC showed that the gradient of the earth pressure on the caisson qualitatively agrees with the conventional calculations.

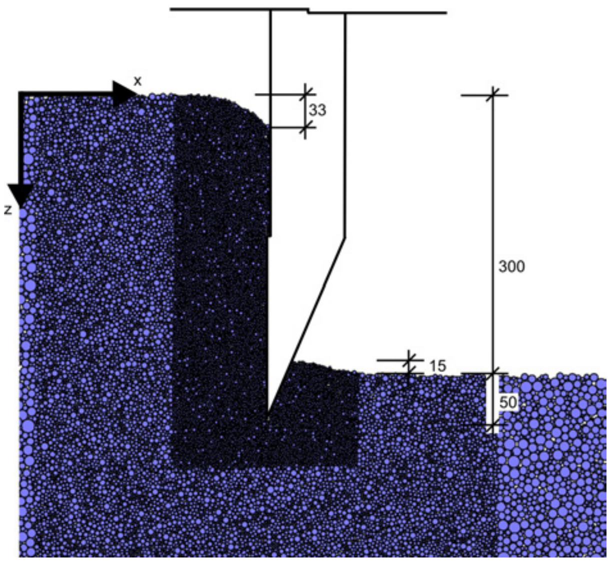

Figure 6. Particle displacements at lowering step z = 3,50 m and excavation step z = 3,00 m

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