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# Mechanical behaviour of sand in three-dimensional state

## Comportement mécanique du sable dans l'état tridimensionnel

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**SYNOPSIS** The results of triaxial tests and plate loading tests carried out in the laboratory are presented in the article. The triaxial tests were done with both common and so-called true triaxial apparatus. The loading tests were carried out with circular and rectangular steel plate. Test material was uniform, medium to coarse sand. The calculated settlement and bending moment of the rectangular test plate are compared with the results measured in the loading test.

### INTRODUCTION

The laboratory of Soil Mechanics at the Helsinki University of Technology is developing a mechanical soil model for frictional and cohesive soils. The model is of an elastoplastic, strain hardening and non-associative type. The model will be used in the geotechnical and structural planning of soil and foundation structures. The model has been tested with triaxial and plate loading tests in the laboratory, and in addition to this with long-term settlement observations of various structures. This article presents the results of laboratory tests done with Ojakkala sand in order to test the basic equations of the model.

### TRIAXIAL TESTS

The results of studies with the Ojakkala sand and other Finnish soils have shown the equations (1) and (2) to be so reliable that they can be used as the basic equations of the model (Korhonen 1979, 1984). The equations have been formulated for calculating plastic deformations.

$$\frac{\tau}{\tau_f} = \frac{\tau_0}{\tau_f} + \left(1 + \frac{\tau_0}{\tau_f}\right) \left(\frac{\gamma}{\gamma_f}\right)^\alpha \exp\left(\alpha \left(1 - \frac{\gamma}{\gamma_f}\right)\right) \quad (1)$$

$$\frac{\tau}{p} = \tan \phi_\mu - \frac{dv}{dp} \quad (2)$$

$\tau$  octahedral shear stress  
 $\tau_0$  octahedral shear stress when  $\gamma = 0$   
 $\tau_f$  octahedral shear stress at failure  
 $\gamma$  octahedral shear strain  
 $\gamma_f$  octahedral shear strain at failure  
 $p$  octahedral normal stress  
 $v$  volume change  
 $\alpha, \tan \phi_\mu$  soil parameters

Equation (1) is said to be the deformation function and it has been used to determine the strain hardening parameter for the mechanical soil model. Equation (2) is the flow-rule of the stress-dilatation theory (Frydman 1976) and it is used in the model to determine the plastic potential. The suitability of equation (1) as a deformation function can be verified with the aid of the test results shown in figure 1. One can find that equation (1) can be used to approximate the results of both common and true triaxial tests.

### PLATE LOADING TESTS

Loading tests have been carried out in a test pit with both circular and flexible rectangular plate. The results are shown in figures 2 and 3. Tests have been done in order to find out the reliability of the methods that are commonly used to determine the deformation modulus  $E$  and the modulus of subgrade reaction  $K$ . Figure 2 presents the result of the plate loading test made with circular plate (dia 30 cm). The relationship between the plate pressure and the settlement has been approximated with equation (3).

$$s = p/E_{di} D I + c (p/\sigma_0)^m \quad (3)$$

$s$  settlement  
 $p$  plate pressure  
 $E_{di}$  initial deformation modulus  
 $I$  shape factor  
 $D$  plate diameter  
 $c$  and  $m$  soil parameters

According to figure 2 it can be found that equation (3) describes the test results of rigid circular plate with moderate accuracy. Pietseh (1981) has approximated the relationship between settlement of structure and foundation pressure with a hyperbolic function. However, hyperbola is not suitable for describing the

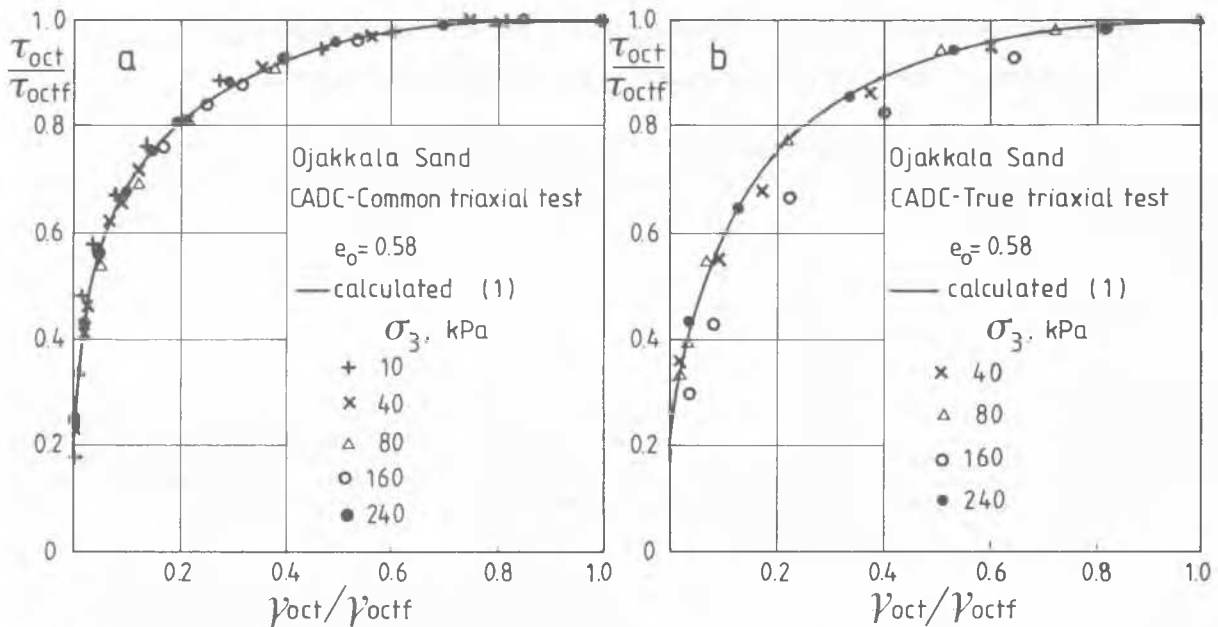


Fig. 1 Triaxial test. The relationship between normalized shear strain and shear stress. The test results have been approximated with equation (1).

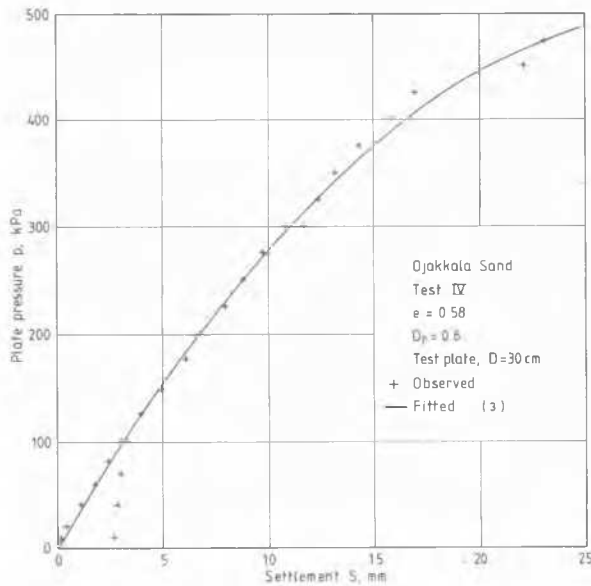


Fig. 2 Plate loading test with rigid circular plate. The relationship between the plate pressure and the settlement. The test results have been approximated with equation (3).

case presented in figure 2.

Figure 3 presents the settlement and the bending moment distribution of the loading test made with the rectangular plate. Strain gauges were used to determine the moments. Figure 3 shows also the theoretical settlement and moment distribution calculated using the modulus of subgrade

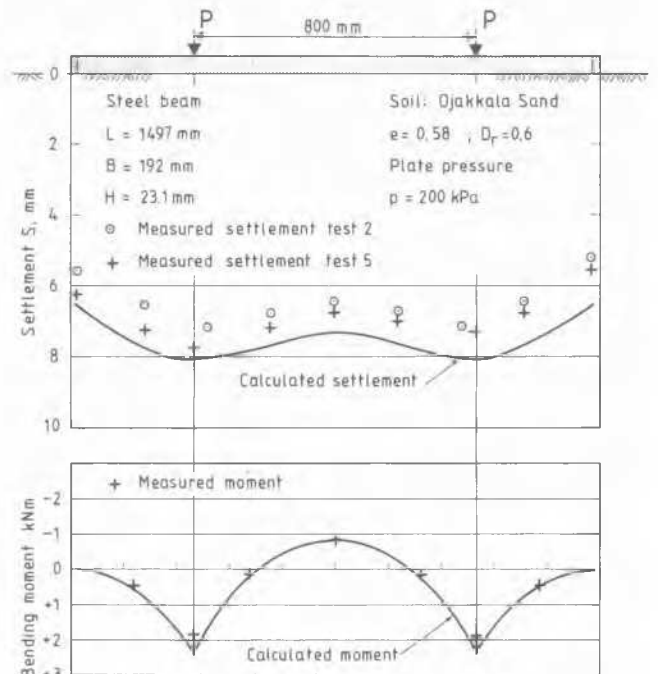


Fig. 3 Plate loading test with flexible rectangular plate. Measured and theoretical settlement and bending moment.

reaction. The tables made by Grasshof (1978) were utilized in these calculations.

The modulus of subgrade reaction  $k_s$  has been determined from the results of the loading test

made with circular plate. On the basis of figure 3 it can be seen that the settlement and the bending moment calculated using the modulus of subgrade reaction are close to those measured values.

The use of the modulus of subgrade reaction for structural dimensioning has been criticized (for example Kany (1974)) due to illogicalities of the initial hypothesis. It is however, obvious that with the modulus of subgrade reaction it is possible to calculate the settlement and the bending moment of a beam founded on the soilbed, if point loads lie far from each other and if one succeeds in determining the modulus of subgrade reaction well enough. The above-mentioned conditions have been valid in tests made with steel plate.

In this case the area of the circular plate is  $A_t = 707 \text{ cm}^2$  and the corresponding area of the rectangular plate is  $A_s = 2874 \text{ cm}^2$ . The ratio of areas  $A_s/A_t$  between the structure or steel plate and circular plate is about four. In real structures the ratio  $A_s/A_t$  is considerably larger. In these cases the modulus of subgrade reaction can not be determined with the same accuracy as in the circumstances described in figure 3.

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