USING DEM FOR THE ASSESSMENT OF K_0 IN SOILS

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This paper explores the possibility of using DEM for gaining further understanding of the evolution of K_0 in soils. In spite of the inherent approximations involved when using numerical methods, the results appear to lie within the scatter produced by experimental results. In addition, micro-scale analyses of the evolution of soil fabric demonstrate that the evolution of K_0 is related to the observed macro-scale response.

INTRODUCTION

The in-situ state of stress in soils is of major significance in geotechnical problems. While the vertical effective stress (σ'_v) is easily estimated from the soil profile, the horizontal stress (σ'_h) is highly dependent on depositional history. Normally, the at-rest coefficient ($K_0 = \sigma'_h / \sigma'_v$) is used. Numerous laboratory and in-situ tests can be performed to estimate the magnitude of these stresses.

As pointed out by Mayne & Kulhawy (1982), numerous researchers have addressed this issue achieving varying degrees of success as many factors are involved in the experimental K_0 data that cannot be quantitatively analysed. For example: different test methods, equipment and personnel, sample disturbance effects, time and aging effects, inherent anisotropy, etc. It is expected that an additional difficulty in such analysis is provided by the particulate nature of soils.

The Distinct Element Method (DEM) was proposed by Cundall & Strack (1979) and uses and explicit finite difference approach to solve the dynamic equilibrium of individual particles. DEM has been extensively used in order to simulate laboratory testing of soils. Although some difficulties have been found possibly due to particle shape effects (i.e. Ji et al, 2009; Barreto, 2009), DEM results have been validated with experimental results on spherical particles (e.g. Cui et al 2007).

In this study, a set of three-dimensional DEM simulations on assemblies of spheres were used to study the evolution of the K_0 value. Consequently, the adverse effects caused by different testing methods, personnel, as well as those related to sample disturbance, time effects, etc. can be isolated. Furthermore, the effects of inherent anisotropy were quantified.

STRESS HISTORY AND THE K_0 COEFFICIENT

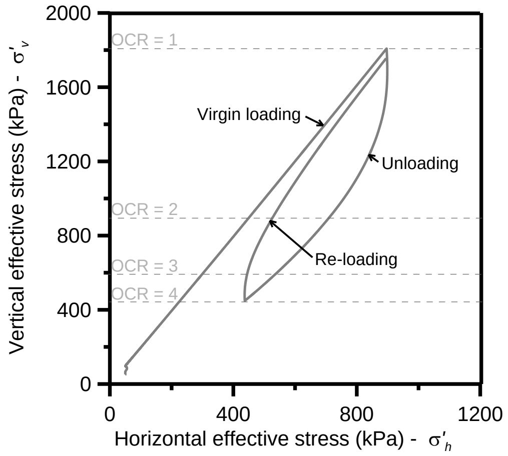

Fig 1. Typical stress path for soil under K_0 conditions

Consider a homogeneous soil deposit with horizontal ground surface. Fig. 1 illustrates a typical stress path. The virgin loading portion is associated with sedimentation and normal consolidation. Any reduction (unloading) in the effective overburden stress caused by erosion or excavation results in over-consolidation of the soil. Clearly, during unloading the over-consolidation ratio ($OCR = \sigma'_{vmax}/\sigma'_v$)

has a significant effect on the value of K_0. If the soil is reloaded the stresses will evolve as shown in Fig. 1.

Several expressions can be found in the literature to calculate the value of the K_0 coefficient. Mayne & Kulhawy (1982) collected and analysed a database comprising tests from over 170 soils and extended Jaky's relationship ($K_0 = 1 - \sin\phi$) in order to estimate the at rest coefficient during virgin compression, unloading and subsequent reloading:

$$K_0 = (1 - \sin\phi)\left[\left(\frac{OCR}{OCR_{\max}^{(1-\sin\phi)}}\right) + \frac{3}{4}\left(1 - \frac{OCR}{OCR_{\max}}\right)\right] \quad (1)$$

where ϕ is the angle of shearing resistance and the OCR is calculated as:

$$OCR = \frac{\sigma'_{v_{\max}}}{\sigma'_{v_{current}}} \quad (2)$$

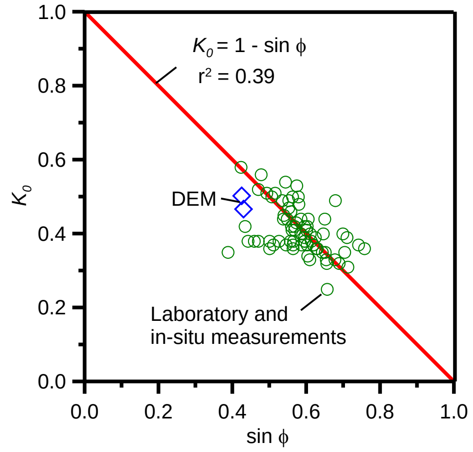

Fig 2. Observed relationship between K_0 and $\sin\phi$ for cohesionless soils during virgin compression (modified after Mayne & Kulhawy, 1982)

The accuracy of Equation (1) can be assessed if only the data for granular materials and virgin loading is considered. Fig. 2 illustrates that the scatter of the results is significant. Note that for over-consolidated conditions the reliability of the expression reduces due to the even more limited data available.

With the recent advances in computational systems a vast amount of information can be collected without major difficulty if DEM is used. Fig. 2 also shows the results of two DEM simulations presented in the following section. Clearly the numerical results lie within the scatter of the experimental data available. Therefore, the potential of using numerical methods to provide further understanding into the particle scale interactions affecting the K_0 value is evident.

DEM SIMULATIONS

A series of simulations involving different stress histories were performed on polydisperse assemblies of spheres using periodic boundaries. The behaviours of two assemblies with different initial fabrics but identical initial solid density were evaluated. The first assembly was isotropically compressed to 50 kPa using a servo-control algorithm. The second assembly was initially compressed isotropically as the first one, but then it was pre-sheared under axi-symmetric compression before being re-consolidated back to an isotropic stress of 50 kPa. These procedures created an assembly with isotropic and anisotropic fabrics (with a bigger proportion contacts in the vertical direction), respectively.

Macro-scale response. After specimen generation, both assemblies were then subjected to identical combinations of virgin loading, unloading and re-loading (while $\varepsilon_2=\varepsilon_3=0$), as illustrated in Figure 3a. Note that unloading and re-loading cycles were simulated starting from different *OCR* values. Interestingly, Fig. 3a shows that the difference in the K_0 value caused by having a different initial fabric is of the same order of magnitude as the difference between the isotropic specimen and the empirical relationship. Therefore, the effects of inherent anisotropy that were impossible to quantify from experiments might be responsible for a significant part of the scatter in the results available.

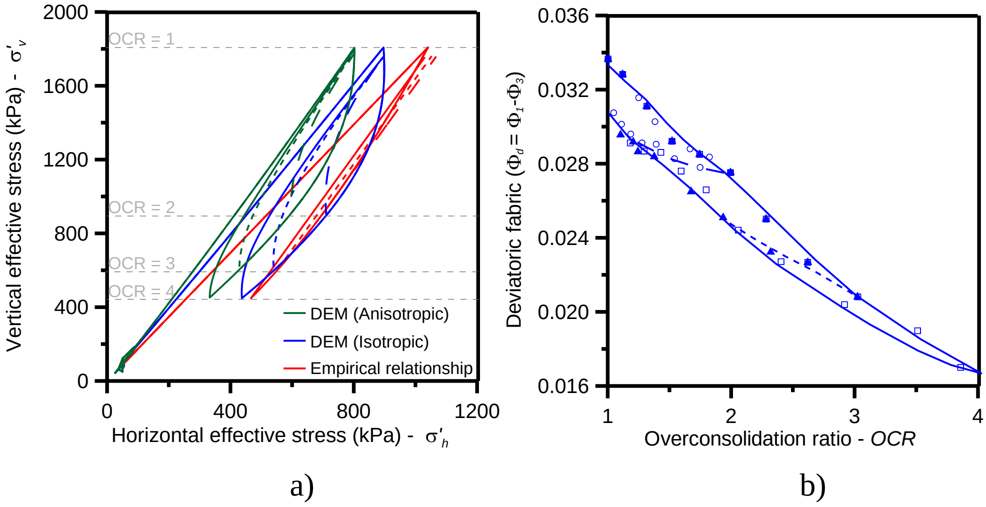

Fig 3. a) Macro-scale results for different stress histories on inherently isotropic and anisotropic fabrics and b) micro-scale response for isotropic specimen

Micro-scale response. The evolution of soil fabric for these different stress histories was also monitored. As means of quantifying the evolution of soil fabric, the fabric tensor (Φ_{ij}) was evaluated:

$$\Phi_{ij} = \frac{1}{N_c} \sum_{k=1}^{N_c} n_i n_j \tag{4}$$

where N_c is the number of inter-particle contacts in the assembly $n_i = n_j$ are the Cartesian components of the unit contact normal between the two particles in contact. In particular the deviatoric fabric (Φ_d) defined by Thornton (2000) as the difference between the major and minor eigenvalues of the fabric tensor was calculated and it is presented in Fig. 3b for the isotropic specimen.

In Fig. 3b only the over-consolidated states are presented, therefore after initial virgin loading the fabric of the specimen has increased from 0 to about 0.034 (i.e. it has become anisotropic. Then after unloading the fabric tries to become isotropic before increasing its anisotropy during re-loading. It can be observed that the evolution of Φ_d against *OCR* is somehow similar and inversely proportional to the evolution of the macro-scale response shown in Fig. 3a.

CONCLUSION

The results presented in this study demonstrate that the scatter available from experimental measurements of K_0 can be partly explained by the evolution of soil fabric. Furthermore, it has been demonstrated that the observed macro-scale behaviour can be also explained by this evolution of fabric.

The success of K_0-*OCR* relationships is demonstrated by the success of existing geotechnical structures and extensive additional research is needed to further understand the factors affecting such relationships. This would immediately lead to the use of lower factors of safety and perhaps more economical geotechnical designs. However, the biggest challenge still remains in how to reconstruct the geological stress history of soils in-situ.

REFERENCES

1. Barreto, D. ‘Numerical and experimental investigation into the behaviour of granular materials under generalised stress states’. PhD thesis, Imperial College of Science, Technology and Medicine. Univeristy of London, 2009.
2. Cui, L., O'Sullivan, C. and O'Neill, S. ‘An analysis of the triaxial apparatus using a mixed boundary three-dimensional discrete element model’, Géotechnique, **57**, No. 10, 831-844, 2007.
3. Cundall, P. A. & Strack, O. D. L. ‘A discrete numerical model for granular assemblies’, Géotechnique, **29**, No. 1, 47-65, 1979.
4. Ji, S., Hanes, D. M. & Shen, H. H. ‘Comparisons of physical experiment and discrete element simulations of sheared granular materials in an annular shear cell’. Mechanics of Materials, **41**, No. 6, 764-776, 2009
5. Mayne, P. W. & Kulhawy, F. H. ‘K_0-OCR Relationships in Soil’. Journal of the Geotechnical Engineering Division, ASCE, **108**, No. 6, 851-872, 1982.
6. Thornton, C. ‘Numerical simulations of deviatoric shear deformation of granular media’, Géotechnique, **50**, No. 1, 43-53, 2000.