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ANISOTROPIC SMALL STRAIN STIFFNESS IN MULTILAMINATE SOIL MODELS

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SUMMARY

A multilaminate constitutive model for soils is presented, which can account for cross-anisotropy in small strain stiffness. Even though the anisotropic stiffness of soils is well documented by experimental data, this effect is usually neglected in practice due to a lack of appropriate soil models.

The stress-strain behaviour of soils at very small strains is much stiffer than in the strain range applied in standard laboratory tests and almost fully recoverable. Elastic moduli of coarse grained soils at very small strains depend on the axial stresses, which magnifies the inherent anisotropy due to deposition and fabric. At load reversal the high initial stiffness gets at least partially reactivated.

These effects have been incorporated into a multilaminate constitutive model, which is based on formulating the stress-strain behaviour on predefined planes. Stress dependency of stiffness, stiffness degradation with strains and stiffness recovery at load reversal are taken into account. The model also accounts for plastic strains in the medium to large strain range.

The model was applied to a finite element calculation of a simple strip footing. A wide range of cross-anisotropic small strain stiffness parameters were considered. Settlement proved to be governed by the mean stiffness of the soil, and not, as might be expected, by the vertical stiffness.

REFERENCES

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Seed, H.B., Idriss, I.M. (1970) *Soil moduli and damping factors for dynamic response analyses.* Earthquake Engineering Research Center, Berkeley, California, USA, Report No. 70-10.

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INTRODUCTION

Soils exhibit much higher stiffness at very small strains (< 10^{-5}) than in the strain range typically applied in laboratory tests. After a small initial range of constant high stiffness, shear stiffness decreases rapidly with accumulating strains. The stiffness of soils at very small strains has been studied in laboratory and field investigations since the early 1970ies, and its anisotropic nature has been recognized not much later. However, in most numerical simulations soil is still assumed to behave isotropically, even though extensive experimental research was devoted to anisotropic soil stiffness in the last two decades. This can be primarily attributed to a lack of appropriate constitutive models which can take anisotropy in small strain stiffness into account.

MULTILAMINATE MODEL WITH CROSS ANISOTROPIC SMALL STRAIN STIFFNESS

The multilaminate model used in this study is based on approximating the 3D material behaviour by formulating constitutive equations on a number of planes with fixed orientation. Strains are calculated on these planes and the macroscopic strain increment is obtained by summation over all planes. Elasticity governs the behaviour at very small strains, and consequently local elastic parameters are required for the calculation of strains on each integration plane. For cross-anisotropic material these stiffness parameters differ among the planes. However, local parameters can be related to the global stiffness parameters analytically by the spectral decomposition of the global compliance matrix (Schädlich & Schweiger 2012).

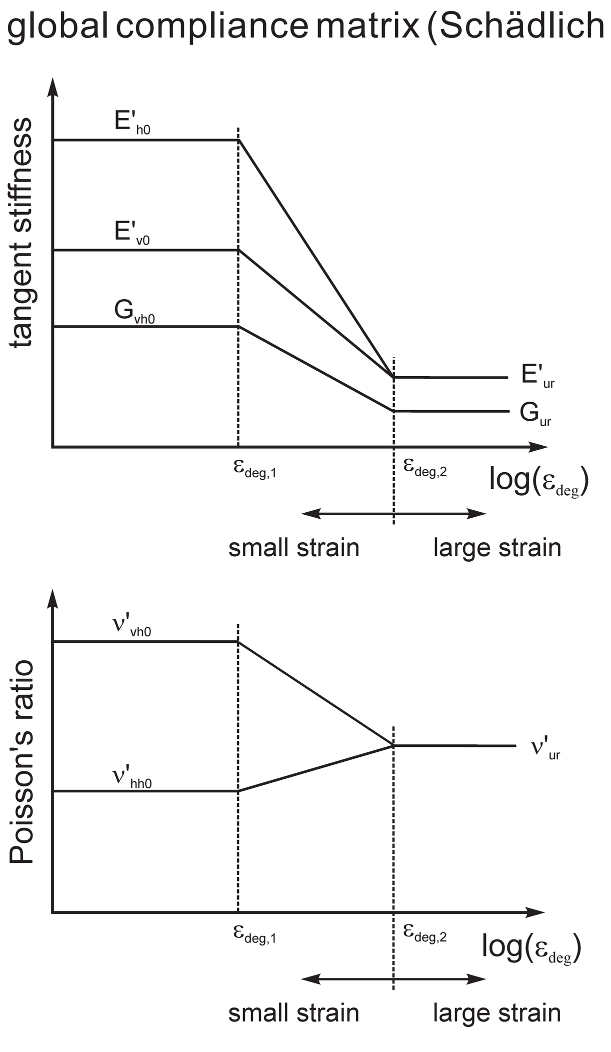

Figure 1: **Degradation of stiffness**

Degradation of small strain stiffness is governed by the local deviatoric strain $_{deg}$, which is different on each integration plane (Figure 1). It is assumed that the initially anisotropic material reaches an isotropic state at large deviatoric strains.

The axial Young's moduli of coarse grained soils strongly follow the stresses applied in the corresponding direction (Figure 2). This behaviour is taken into account in the model for the initial stress state by varying the initial ratio of anisotropy E'_{h0}/E'_{v0} with the stress ratio $'_{h0}/\ '_{v0}$ according to a power law.

Once the very small strain range is exceeded, the model gradually allows for plastic strains, which are calculated separately on each plane according to classical strain hardening plasticity. Shear stresses are limited by a Mohr-Coulomb failure criterion, defined by the strength parameters ' and c'.

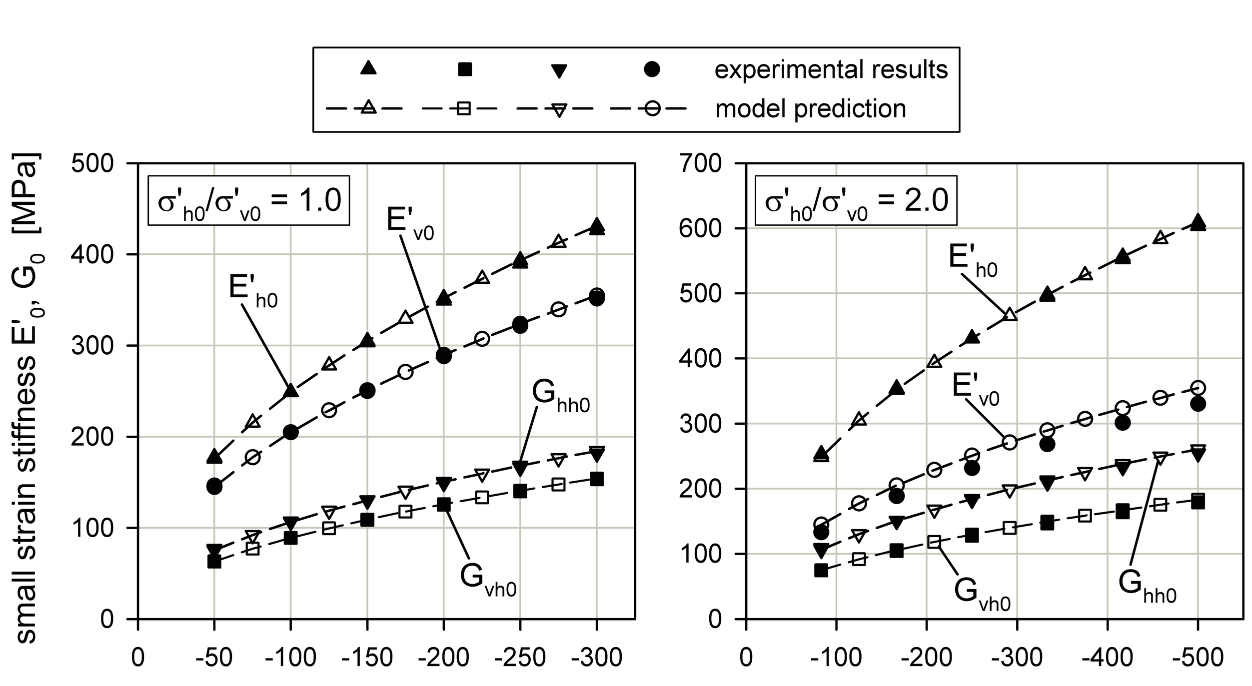

Figure 2: **Anisotropic small strain stiffness moduli of Ticino sand for different stress ratios (experimental results from Bellotti et al. 1996)**

INFLUENCE ON SETTLEMENT PREDICTIONS

The influence of anisotropic small strain stiffness on settlement predictions was evaluated for a simplified strip footing model (Figure 3). Fully drained, plane strain conditions were assumed, and the load on the rigid footing was gradually increased to 300 kPa. Large strain parameters typical for a dense sand were chosen, and different sets of isotropic and anisotropic small strain stiffness moduli (Table 1) were considered which cover the range of experimental results on various coarse grained soils. The stiffness degradation curve was calibrated against experimental data of coarse grained soil (Figure 4, Seed & Idriss 1970).

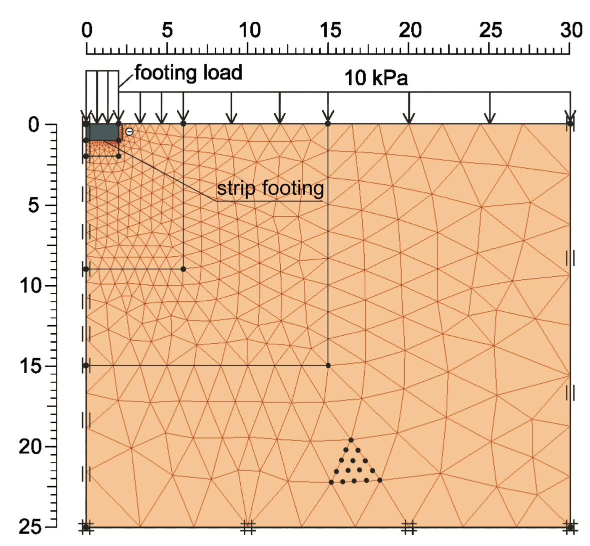

Figure 3: **Strip footing model [m]**

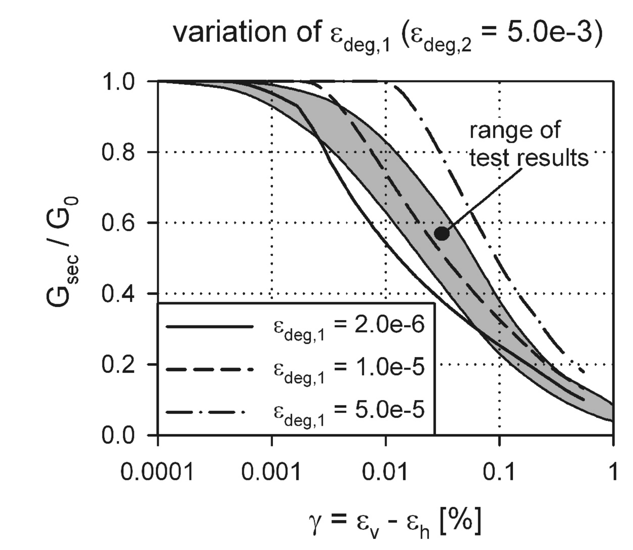

Figure 4: **Stiffness degradation curve**

	isotropic	anisotropic 1	anisotropic 2	anisotropic 3	anisotropic 4	anisotropic 5	anisotropic 6	anisotropic 7	anisotropic 8	anisotropic 9	anisotropic 10
$E'_{h0,ref}$	270	116	463	116	270	135	270	540	202	324	270
$E'_{v0,ref}$	270	417	417	417	135	270	540	270	405	162	270
E'_{h0}/E'_{v0}	1.0	0.28	1.11	0.28	2.0	0.5	0.5	2.0	0.5	2.0	1.0
$G_{vh0,ref}$	112	115	115	77	115	115	115	115	115	115	115

Table 1: **Isotropic and anisotropic small strain stiffness parameter sets [MPa]**

Plotting the ratio of current stiffness with regard to the initial and residual elastic stiffness (Figure 6) shows, that parts of the soil body below the footing still remained at the high initial stiffness even at the final loading stage. Consequently, load-settlement curves did not reach a constant inclination (Figure 5). Final settlements varied from 28 mm to 40 mm for the different parameter sets and did not correlate with neither the horizontal nor the vertical axial stiffness.

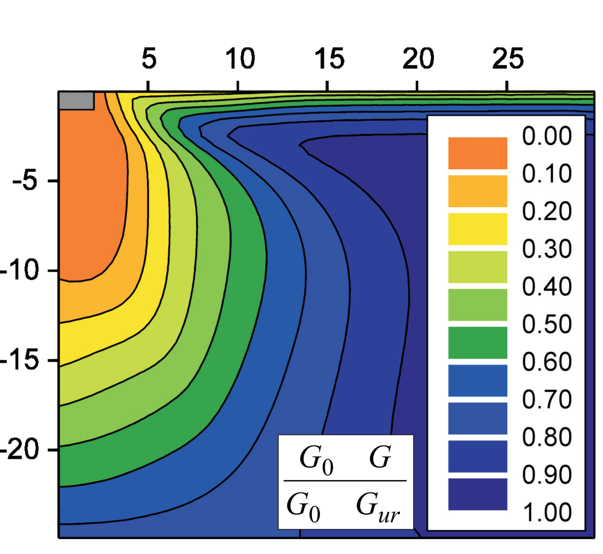

Figure 5: **Small strain stiffness degradation at 300kPa**

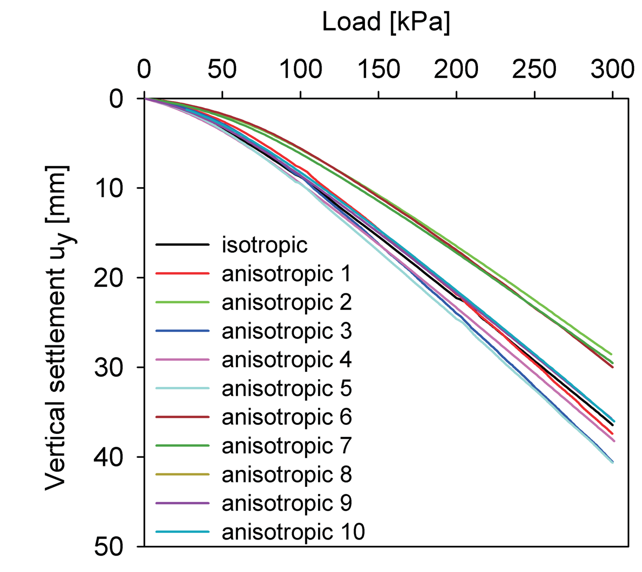

Figure 6: **Load-settlement curves**

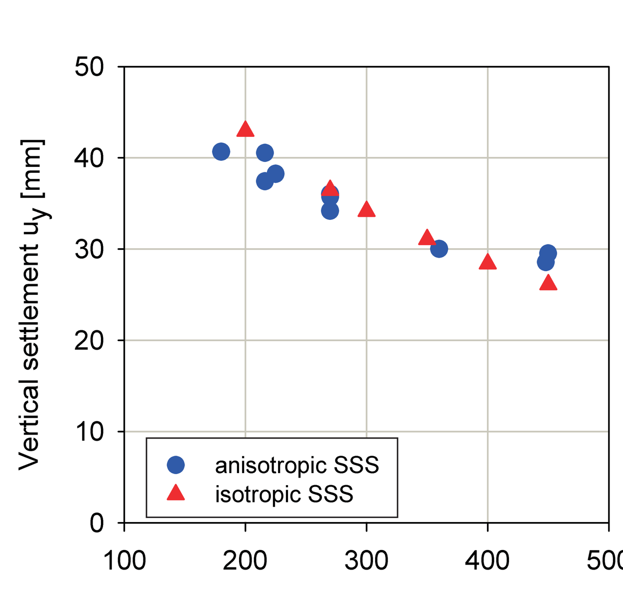

Figure 7: **Final settlement vs. mean axial stiffness**

Settlements of all isotropic and anisotropic calculations, however, formed a unique line if plotted against the mean axial stiffness (Figure 7). Anisotropy in small strain stiffness hence had a clear influence on the load-settlement behaviour of the strip footing, but could be accounted for by performing isotropic calculations with the mean axial stiffness.

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