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A Study of the Influence of Anisotropy on the Response of Foundation of Multi-storey Building

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SUMMARY The linear elastic cross-anisotropic model was used to model the behaviour of soil deposits manifesting anisotropic stress-strain characteristics. Based on this this model, the effect of anisotropy on predicted raft settlement and the contact pressure developed between the raft and the supporting soil was examined with a soil-structure interaction analysis. A typical case is exemplified by a multi-story office building in Shanghai supported on a raft 7m below the ground level.

1 INTRODUCTION

It is generally recognized that natural clay deposits exhibit some degree of stiffness anisotropy. Recognizing that there is symmetry of stiffness about the vertical axes σ_z for Shanghai Clay, the cross-anisotropic elastic model (Atkinson 1975, Baladi 1978, Graham & Houlsby 1983) can be used to model the stress-strain response of Shanghai Clay. Denoting the material axes by X-Y-Z (Fig 1), the cross anisotropic elastic model (sometimes referred to as transverse isotropic elastic model) is described by eqn (1).

$$\begin{pmatrix} d\epsilon_x \\ d\epsilon_y \\ d\epsilon_z \\ d\gamma_{xy} \\ d\gamma_{yz} \\ d\gamma_{zx} \end{pmatrix} = [C]. \begin{pmatrix} d\sigma_x \\ d\sigma_y \\ d\sigma_z \\ d\sigma_{xy} \\ d\sigma_{yz} \\ d\sigma_{zx} \end{pmatrix} \qquad (1)$$

$$[C] = \frac{1}{E_z}. \begin{pmatrix} 1/n & -\mu/n & -\mu_z & 0 & 0 & 0 \\ -\mu/n & 1/n & -\mu_z & 0 & 0 & 0 \\ -\mu_z & -\mu_z & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & E_z/G & 0 & 0 \\ 0 & 0 & 0 & 0 & E_z/G_z & 0 \\ 0 & 0 & 0 & 0 & 0 & E_z/G_z \end{pmatrix}$$

where n $= E/E_z$
E = Young's Modulus in O-X-Y plane
E_z = Young's Modulus in Z-direction
μ = Poisson's ratio in O-X-Y plane
μ_z = Poisson's ratio for any plane parallel to Z-axes
G = Shear modulus in O-X-Y plane
$= 0.5E/(1+\mu)$
G_z = shear modulus for any plane // OZ

Eqn (1) gives equivalent properties in all directions in the O-X-Y plane but properties in the OZ direction differ. Thus plane O-X-Y is the plane of isotropy and corresponds to the horizontal plan in Shanghai Clay whereas OZ corresponds to the vertical direction. Only five independent elastic parameters are required by eqn (1) Values of the parameters have been recorded for various soils, and, for example, Gazetas (1981) has summarized soil data from several sites.

Analytical solutions for the stress and strains developed in a cross anisotropic layer of semi-infinite extent have been determined, for example, by Zhang et al (1982) for an arbitrary load system and Zai et al (1985) developed a soil-structure interaction programme which considered the soil anisotropy.

The present paper reports the anisotropic stiffness parameters determined from laboratory test for Shanghai Clay.

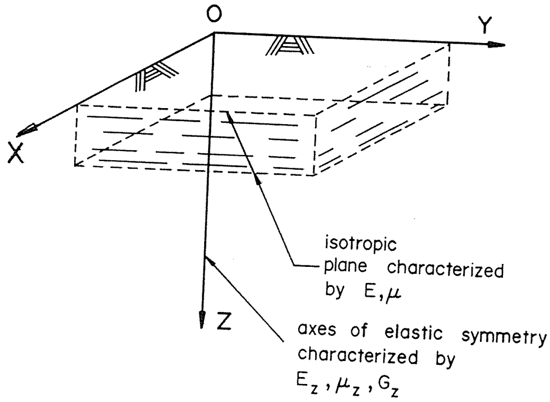


Figure 1 Cross-Anisotropic Model

These parameters are then inputted in a soil structure interaction analysis to examine the influence of anisotropy on predicted settlement and contact pressure of a raft supporting a multi-story building. A sensitivity study using a range of reported anisotropic stiffness parameters was also conducted.

2 LABORATORY TESTS

Although it is possible to determine the five independent elastic parameters using the multi-axial compression tests, a simpler procedure by conducting conventional triaxial compression tests on undisturbed "vertical" and "horizontal" samples was adopted.

TABLE I

Shanghai Clay

Description	Water Content	Void Ratio	Specific Gravity	Degree of Saturation
Clay with fine sand	37%	1.010	2.7	100%

At the Shanghai site, undisturbed block samples were retrieved from a depth of 6m - the preliminary excavation depth for the raft. Typical properties of Shanghai Clay are given in Tab. I. Consolidated drained tests were conducted on these samples which were initially consolidated under a K_0 stress state. Three vertical and three horizontal samples were tested. Deviator stress-axial strain relation- ships are included as Fig. 2, where V and H referring to the "vertical" and "horizontal" samples, respectively. Equations used to interpret the test results are discussed in Section 3.

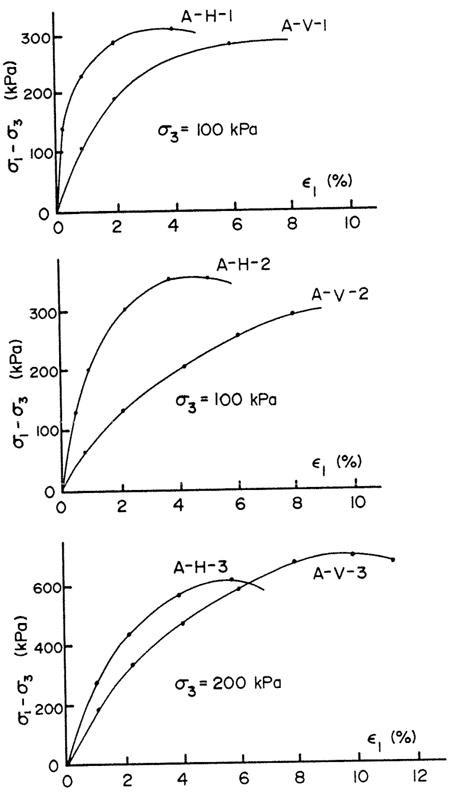


Figure 2 Stress-Strain Curves

Further data for the Shanghai soils was obtained from another construction site. Samples of the soft, laminated clay were taken from a depth range of 9m to 13m. Based on the stiffness data obtained in consolidated drained compression tests, empirical expressions were derived for the moduli of the cross isotropic model (Zhao and Qiao, 1987).

$$E_v(0.5) = 34.30p_a(\sigma_3/p_a)^{0.955} \quad (1)$$
$$E_h(0.5) = 36.23p_a(\sigma_3/p_a)^{1.033} \quad (2)$$
$$E_v(0) = 58.03p_a(\sigma_3/p_a)^{1.016} \quad (3)$$
$$E_h(0) = 59.50p_a(\sigma_3/p_a)^{1.050} \quad (4)$$

where $E_v(0.5)$ = secant modulus at 50% mobilized
= strength using vertical samples
$E_h(0.5)$ = ditto but using horizontal samples
$Ev(0)$ = initial tangent modulus using
= vertical samples
$E_h(0)$ = ditto but using horizontal samples
p_a = atmospheric pressure in consistent unit

3 INTERPRETATION OF TEST DATA

It is appropriate to consider the determination of the stiffness parameters from the test data. For the consolidated drained tests the relevant expressions for E_z, E, μ_z, μ are (Atkinson 1975),

(i) for vertical samples

$$E_z = \delta\sigma_A/\delta\epsilon_A$$
$$D = 2\mu_z \quad (6)$$

(ii) for horizontal samples

$$E = \delta\sigma_A/\delta\epsilon_A$$
$$D = \mu + n.\mu_z \quad (7)$$

where $D = 1 - d\epsilon_v/d\epsilon_A$ and subscript "A" refer to the axial direction. For vertical samples, axes "A" is along the Z-direction whereas for horizontal samples, axes "A" is in the O-X-Y- plane.

The shear modulus G_z cannot be determined from conventional triaxial testing and needs to be computed by the approximate eqn (8) proposed by Carrier (1946).

$$\frac{G_z}{E_z} = \frac{d_1.d_4 - d_3^2}{d_1 + 2d_3 + d_4} \quad (8)$$

where $d_1 = a.n(1 - n^3.\mu_z^2)$
$d_3 = a.n^2.\mu_z(1 + \mu)$
$d_4 = a.(1 - \mu^2)$
$a = \frac{1}{(1+\mu)(1-\mu-2n^3.\mu_z^2)}$

TABLE II

Anisotropic Elastic Parameters for Shanghai Clay

Parameter	drained	Undrained
E_Z(MPa)	13.6	14.83
n	2.5	1.82
μ	0.0	0.09
μ_Z	0.23	0.5
G_Z/E_Z	0.58	0.49

The equations relating the drained (effective stress) and undrained (total stress) parameters are given by Uriel and Canizo (1971). Denoting the undrained parameters by subscript "u", we have

$$n_u = 2(n - n.\mu - 2n^2.\mu_z^2)/d \quad (9)$$
$$E_u/E = (2 + n - 4n.\mu_z - 2\mu)/d \quad (10)$$
$$G_u = G \quad (11)$$

where d $= (2 + n - 4n.\mu_z - 2\mu) - (1 - \mu - n.\mu_z)^2$
$n_u = Eu/E_{z,u}$

The condition of $d\epsilon_v = 0$ for undrained loading leads to (Atkinson, 1975).

$$\mu_{z,u} = 0.5 \quad (12)$$
$$\mu_u = 1 - n_u/2 \quad (13)$$

Combining eqns (10), (12) & (13) leads to

$$E_u = \frac{4 - n_u}{2(1 + \mu)}.E \quad (14)$$

Thus using the conventional triaxial compression test results of vertical and horizontal samples leads to Tab. II.

4 ANALYSIS OF STRUCTURE-FOUNDATION

The structure is analysed by using the double extended substructure method and the cross-anisotropic soil by the finite layer (element) method.

Frictionless contact is assumed at the foundation base. The flexibility matrix $[F_s]$ of the soil continuum is established using the finite layer method (Zhang, Zhao and Zai, 1982), in which the elasticity matrix [D] for any cross anisotropic soil element is obtained by inverting the matrix of eqn (1). The stiffness matrix $[K_s]$ of the soil continuum was then obtained by inverting $[F_e]$. Let $\tilde{w}$ and $\tilde{p}$ represent the settlements and contact pressures on the interfacial nodes, then,

$$[K_e].\tilde{w} = \tilde{p} \qquad (19)$$

For the cross-wall-frame structure, the sub-structure method method can be extended plate by plate and storey by storey. Finally, the boundary stiffness matrix $[K_b]$ and boundary load vector $\tilde{R}_b$ of the super-structure are obtained. Hence the equilibrium equations for the whole structure (super-strcture plus raft/box foundation) can be written in a partitioned form as

$$\begin{pmatrix} [K_{bb}+[K_b] & [K_{bs}] \\ [K_{sb} & [K_{ss}] \end{pmatrix} \cdot \begin{pmatrix} \tilde{u}_b \\ \tilde{u}_s \end{pmatrix} = \begin{pmatrix} \tilde{Q}_b + \tilde{R}_b \\ \tilde{Q}_s - \tilde{p} \end{pmatrix} \qquad (20)$$

where $[K_{bb}], [K_{bs}], [K_{sb}], [K_{ss}]$ are the partitioned stiffness matrices for the box/raft foundation
$\tilde{u}_b, \tilde{u}_s$ are partitioned displacement vectors
$\tilde{Q}_b, \tilde{Q}_s$ are partitioned applied load vectors
subscript 'b' - boundary
subscript 's' - soil

Considering the compatibility of vertical displacements on the contact surface, ie $\tilde{w} = \tilde{u}_s$, eqns (19) & (20) can be solved by partial inversion. Such a method of analysis will automatically account for the interaction between the super-structure, the raft, and the soil continuum.

5 CASE STUDY AND SENSITIVITY ANALYSIS

A detailed study was made of the influence of anisotropy on predicted settlements and contact pressure distributions of a raft supporting a 13 storey office building in Shanghai. The building is a 51.8m high, cross-wall, structure with a double basement. The structure was founded on a box foundation of plan dimensions 57.60m by 16.50m located at a depth of 7m below the average level of the ground surface - as shown in Fig 3. The box type foundation is utilized to diminish the differential settlements developed in the foundation system. The longitudinal settlement profiles for the structures in Shanghai showed that the system was very effective, with differential settlements reduced to about 30 % of the maximum settlement.

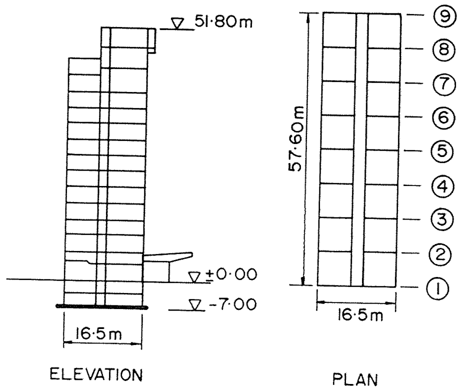


Figure 3 Building Analysed

Fig 4 shows the average longitudinal settlement profiles and contact pressure distributions for the actual soil properties (Tab. 2) at the Shanghai site. It is seen that the effect of the stiffness anisotropy is a reduction of the settlement compared with an isotropic soil with the same vertical Young's modulus. However, the magnitude of the settlement reduction associated with n = 2.5 was only of the order of 10 per cent. Differences between the contact pressure distributions were negligible as evidenced by the plot in Fig. 4.

To investigate the sensitivity of the predicted values to the degree of anisotropy it is first necessary to establish realistic ranges of the parameters. In the present study the decision was made to use the data summarized by Gazetas (1981) that is, it was imagined that the Shanghai building was constructed on each type of soil. Thus, a further five long term cases (see Tab. III) were analysed by the interaction programme. These analyses gave the combined effects of changes in horizontal stiffness and Poisson's ratios, but for a constant vertical modulus of 13.6 MPa, and enabled a comparison to be made between the isotropic and anisotropic soil conditions. The predicted settlement and contact pressure profiles are shown in Fig. 5. All settlement profiles were convex, and the difference in maximum final settlement between the anisotropic soil and the "corresponding" isotropic soil was of the order of 10 per cent. Contact pressure distributions were essentially independent of the deformation properties within the (typical) ranges considered in the analyses.

TABLE III

Parameters for Sensitivity Study - Drained Condition

Case Reference	E_Z (MPa)	$n=\frac{E}{E_Z}$	μ_Z	μ	$\frac{G_Z}{E}$
D1–a	13.6	1.00	0.19	0.19	0.42
D1–b	13.6	2.00	0.19	0.0	0.54
D2–a	13.6	1.00	0.12	0.12	0.44
D2–b	13.6	1.60	0.12	0.16	0.69
D3–a	13.6	1.00	0.20	0.20	0.42
D3–b	13.6	1.38	0.20	0.27	0.52
D4–a	13.6	1.00	0.48	0.48	0.34
D4–b	13.6	1.20	0.48	0.39	0.44
D5–a	13.6	1.00	0.35	0.35	0.37
D5–b	13.6	0.62	0.35	0.20	0.19

Note "a" refers to isotropic
"b" refers to cross-anisotropic

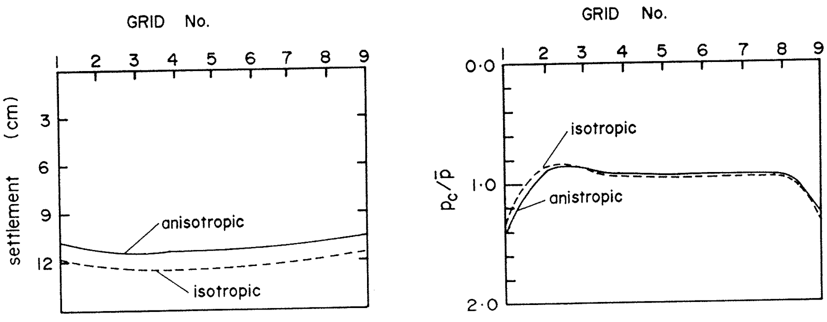
Two short term cases (see Tab. IV) were also analysed. These corresponded to an undrained state since the two Poisson's ratios satisfy eqns (12),(13). For computational and comparative purposes it was convenient to maintain the vertical stiffness at 13.6 MPa. The analyses indicate that the immediate settlements are quite sensitive to the combined effects of the stiffness anisotropy and the associated changes in Poisson's ratio. Fig. 6 shows a reduction in the theoretical immediate settlement of about 50%. Contact pressure distributions are not greatly affected but the differences are greater than in the drained state.

TABLE IV

Parameters for Sensitivity Study - Unrained Condition

Case Reference	E_Z (MPa)	$n=\frac{E}{E_Z}$	μ_Z	μ	$\frac{G_Z}{E_Z}$
U1–a	136	1.0	0.5	0.5	0.33
U1–b	136	1.8	0.5	0.08	0.46
U2–a	136	1.0	0.5	0.50	0.33
U2–b	136	1.36	0.50	0.32	0.38

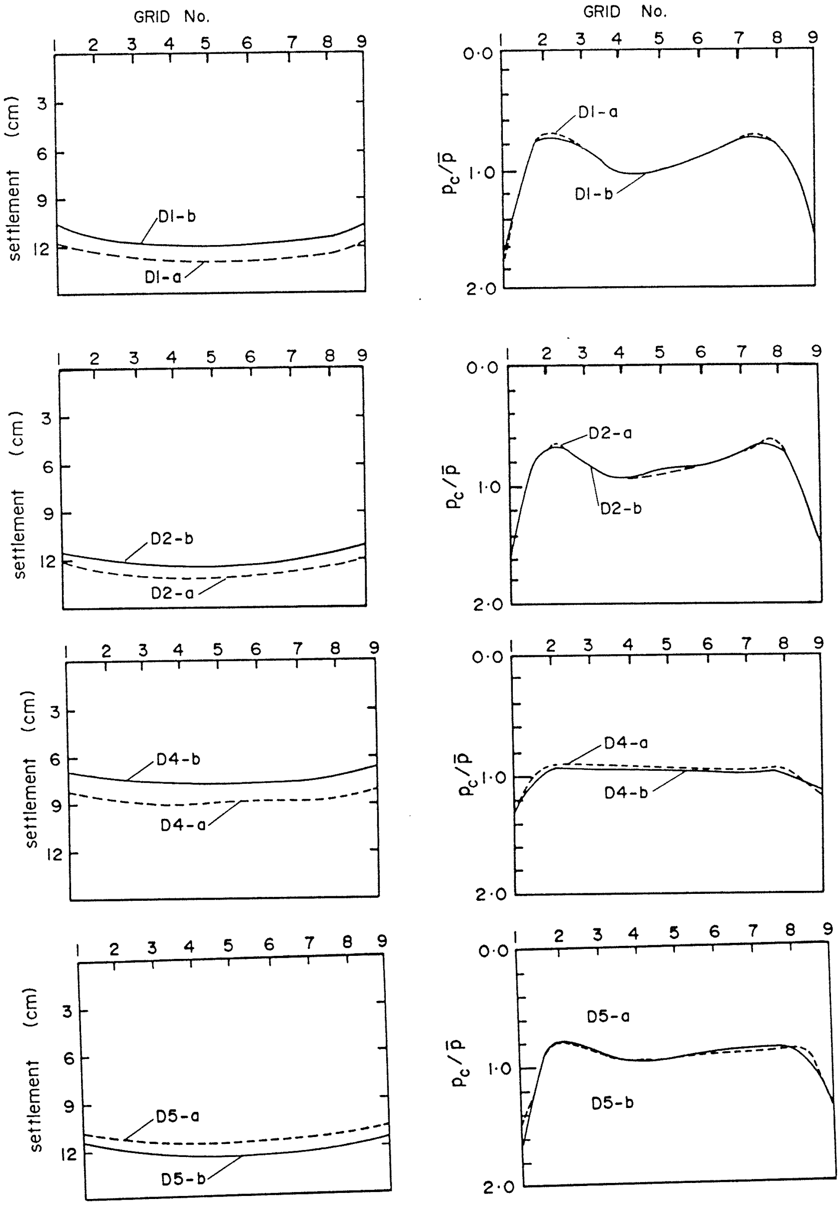
Note : "a" refers to isotropic soil
"b" refers to cross-anisotropic soil



Based on properties of Shanghai Clay, Tab. III

p_c — contact pressure $\bar{p}$ — average bearing pressure

Figure 4 Predicted Settlement and Contact Pressure Distributions



p_c - contact pressure; $\bar{p}$ - average bearing pressure

Figure 5 Influence of Anisotropic Parameters on Prediction - Drained

6 CONCLUSIONS

Theoretical studies suggest that the neglect of anisotropy in long term settlement prediction may lead to discrepancies of "secondary importance" (of the order of 10%). Under undrained conditions, the relative effect of anisotropy is much greater and it may be necessary to model the anisotropy of the soil in order to reliably predict short term settlement. The influence of anisotropy on contact pressure distributions between a raft and the supporting soil is small in a practical design situation for both short term and long term conditions. However, stiffness anisotropy leads to a reduction of the concentration of contact pressure at edges of the raft, thus decreasing the error of a linear analysis due to local yielding.

7 ACKNOWLEDGMENTS

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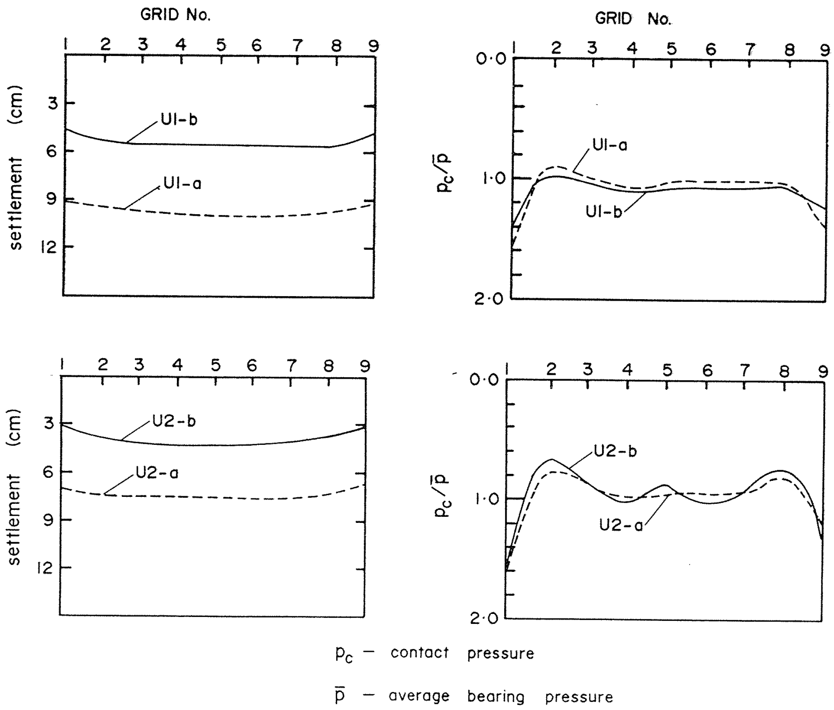

Figure 6 Influence of Anisotropic Parameters on Prediction - Undrained