Figure 4: Application of the computer model to the prediction of the surge capacity of a building collection drain serving a 4 storey vertical stack.

Figure 5: Validation of the computer model at the National Bureau of Standards, Centre for Building Technology, plumbing tower facility.

Computer Aided Design of Time Depending Structure-Soil Interaction

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KEYWORDS
Geomechanics, Structure-Soil Interaction, Non-linear, Time Dependant, Deformation Analysis.

ABSTRACT
The paper presents graphical interpretation of non-linear time dependant interaction between elastic structure and high flexible non-homogeneous (layered) soil. The use of program has been shown on space reinforced concrete frame structure on a layered halfspace. Time dependant displacements were evaluated successively by computer as to load path and the consolidation process in soil of viscous unequal thickness clay layers on a rock basis. The program uses deterministic analysis on a theoretical Kelvin's rheological model. An incremental iterative method is used: skeleton structure is presented by linear finite elements but the soil is described using analytical function defining non-linear and time dependant relations. Rheological soil characteristics were determined with slow, drained triaxial tests and monotonously increasing (decreasing) load.

A graphic simulation of structural displacements during the construction and after it has been built up enables better, faster, more economical design and higher safety in everyday engineering practice.
CONCEPTION INFORMATISÉE DE L’INTERACTION CONSTRUCTION-SOL DÉPENDANT DU TEMPS

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MOTS-CLEFS

SOMMAIRE
L’article présente l’interprétation graphique de l’interaction non-linéaire dépendant du temps entre une construction élastique et un sol non-homogène (avec des couches) de haute flexibilité. L’applicabilité du programme est démontrée sur une construction 3-dimensionnelle à soutelet en béton armé fondée sur des couches semi-espaces. Les déplacements dépendant du temps ont été successivement évalués à l’aide de l’ordinateur; il s’agit du chemin de la charge et du procès de la consolidation dans le sol consistant des couches d’argile viergeuse d’épaisseur indéterminée reposant sur une base rocheuse. Le programme utilise l’analyse déterministe suivant le modèle théorique et rhéologique de Kelvin. Une méthode incrémentale et itérative est employée: la construction à soutelet est présentée au moyen des éléments finis linéaires, mais le sol est décrit par la fonction analytique qui définit les relations non-linéaires et dépendantes du temps. Les caractéristiques rhéologiques du sol ont été déterminées par des épreuves 3-axiales sur des échantillons chargés d’une manière monotone croissante et décroissante. Ces expériences sont lents et drainés.
La conception informatisée des déplacements de la construction pendant la construction et après celle-là nous permet de mieux projeter et en même temps de projeter d’une manière plus rapide, plus sûre, et plus économique. Tout cela est très important en pratique quotidienne des ingénieurs.

INTRODUCTION
We are dealing with several practical cases of structure-soil interaction where a dependence between structure and soil can be given with uneven loading on the structure and with non-linear rheological soil characteristics. A numerical solution is given by levelling layered soil and structural foundation displacements:

\[ dP_r = \Delta_r \frac{\text{d}Q_r}{\text{d}Q_r} - I \text{d}u_{or} = S_r \text{d}p_r \]

where \( \Delta_r \) represents a soil flexibility matrix, 1 is a unit matrix, \( S_r \) is a structure flexibility matrix and \( \text{d}u_{or} \), \( \text{d}P_r \), \( \text{d}p_r \) represents vectors of increments of unknown foundation contact pressure, translation and rotation of foundation contact surface, foundation relative displacements, and structure loads respectively.
A stress-strain relationship in general non-linear but in addition a viscous flow has to be taken into account at uncharged stress state. Previous studies determined rheological dependencies for coherent soils on the basis of slow, drained triaxial test with monotonously increasing load.

A non-linear and time dependant relationship for soils in the range of secondary consolidation branches is given by analytical expressions in a form of elastic-viscoplastic model. This solution enables sufficiently exact analytical determination of stress-strain state for practical engineering problems, i.e. where primary hydrodynamic effects can be neglected.
The paper presents calculation and graphic interpretation of the non-linear time dependant interaction between elastic structure (skeleton) and highly flexible layered soils. The incremental concept has been taken into account with monotonously changing load and experimentally determined rheological relations for soils in the form of a non-linear Kelvin's model and well-known Hook's model for structure.

Rheological relationships for soils
On the basis of slow, drained and monotonously loaded and unloaded triaxial tests, one can determine volumetric dilatation \( \varepsilon(V) \), axial strain \( \varepsilon_L \) and their corresponding elastic components \( \varepsilon(V) \), \( \varepsilon_L \). Strains \( \varepsilon(V) \), \( \varepsilon_L \) and \( \varepsilon \) can be divided into spheric, distortional and viscous components, which are expressed analytically by stress invariants:
\[ p = \frac{\sigma_{ij}^{'}}{3}, \quad q = \frac{(3/2)\sigma_{ij}^{'2}}{\sigma_{ij}^{'2}}, \quad \sigma_{ij}^{'2} = \sigma_{ij}^{'2} - \delta_{ij}\sigma_{kk} \]  
\[ (2), (3), (4) \]

where \( \sigma_{ij}^{'} \) means effective stress tensor and \( \delta_{ij} \) is Kronecker symbol. Subtracting corresponding elastic \( (\epsilon^{(e)}) \) and viscous \( (\epsilon^{(v)}) \) components from \( \epsilon^{(v)} \) an \( \epsilon^{(e)} \), one can get plastic strain:
\[ \epsilon^{(p)} \text{ and } \epsilon^{(e)} \]

In general the strain tensor consists of 36 constants, determined experimentally. Due to the elimination of some constants the solution can rapidly deduce to Sekiguchi (1977), Shibata (1963) or Roscoe (1963) models.

The stress and displacement increments calculation

If a contact pressure \( d Q_r \) is continuous and smooth and applied on polygonally shaped foundation contact surface \( \sigma_r \), \( k \) being a number of discrete surface to a non-homogeneous soil halfspace with known stress and time dependent spheric \( (K_r) \) and distortion \( (G_r) \) deformation moduls at each point \( t \) then stress and displacement can be determined at these points using the following equations:

\[ (d \sigma_{m}^{(m)})_r = \int_{S} \left( k \left( \sigma_{m}^{(ep)} \right)_r + (d \sigma_{m}^{(v)})_r \right) \text{dS} \]  
\[ (6) \]

\[ (d u_{m}^{(m)})_r = \int_{S} \left( \sigma_{m}^{(ep)} \right)_r + (d u_{m}^{(v)})_r \text{dS} \]  
\[ (7) \]

\[ (d \sigma_{m}^{(ep)})_r = \int_{S} \left( k \left( \sigma_{m}^{(ep)} \right)_r + (d u_{m}^{(e)})_r \right) \text{ds} \]  
\[ (8) \]

where \( \sigma_r = \sigma_{r-1}^{+} \sigma_r, \quad u_r = u_{r-1}^{+} + (d u)_r, \quad \sigma_{r-1}^{+} \sigma_r = \sigma_r = \sigma_{r-1}^{+} \sigma_r \]  
\[ (9) \]

The calculation is performed in two successive iteration loops: in the first loop we solve elastic and plastic relations between structure and soil while in the second a viscous (i.e. time dependent) relation of soil consolidation is evaluated.

The iteration loop is repeated using equations (1), where matrix \( A_r \) and incremental vector of foundation relative displacement \( d Q_r \) are changing, until the following conditions are satisfied:

\[ d Q_r = d Q_{r-1} + \delta Q_r \]  
\[ (10) \]

where \( n \) represents iteration cyclus and \( \delta Q_r \) takes desirable small value. After the iteration the following values are known: \( d Q_r, K_r \) and \( G_r \) (or \( A_r \)). Substituting these values into Eq. (5) or (8), using Eq. (9) we get at first the stress increments \( (d \sigma_r) \), displacements \( (d u_r) \) and finally we find stress-displacement state using:

\[ \sigma_r = \sigma_{r-1}^{+} \sigma_r, \quad u_r = u_{r-1}^{+} + (d u)_r, \quad \sigma_{r-1}^{+} \sigma_r = \sigma_r = \sigma_{r-1}^{+} \sigma_r \]  
\[ (11), (12), (13) \]

**NUMERICAL EXAMPLE**

The computer program was written by M. Jeler on the basis of the above equations. The test was performed on the example shown in Fig. 1, Fig. 2, Table I. and Table II. Triaxial Tests of constitutents were performed in the laboratory (See Ref. 3 and 4).

The space frame structure of reinforced concrete with rectangular shaped foundation is founded in under the ground level. The load \( F_r \) is continuous at the upper level of the structure and time increasing to the final value within 18.5 months. (The program allows also any non-continuous load as applied in practice).

Fig. 3 shows few sensitive results of the numerical analysis: foundation settlements and frame displacements.

**DISCUSSION**

Numerical calculations using finite element methods for space problems tend to be too expensive considering non linear and time dependent constitutive laws (owing to slow, high compressibility and non homogeneous soil halfspace).
The paper presents joint solution of structure-soil interaction given by a numerical method for structure and analytical functions (based on experiments) for soil, which in practice design is sufficiently exact and economical. The given solution is straightforwardly applicable for the determination of foundation settlements and stress-deformation state of structure.

ACKNOWLEDGEMENT

The author wishes to thank Mr. S. Skrabić, Mr. D. Reboj and Mr. M. Jeler (University of Maribor) for elaborating the numerical example. The study was financially supported by the Research Council of Slovenia (Raziskovalna skupnost Slovenije).

REFERENCES


Table I. Time dependant loading data for skeleton structure

<table>
<thead>
<tr>
<th>Relative time $t$ (days)</th>
<th>Increments of time $dt$ (days)</th>
<th>Load $P$ (kN)</th>
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<tr>
<td>$t^0$</td>
<td>1</td>
<td>$P_0$ 0</td>
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<tr>
<td>$t_1^*$</td>
<td>36</td>
<td>$P_1$ 200</td>
</tr>
<tr>
<td>$t_2^*$</td>
<td>102</td>
<td>$P_2$ 400</td>
</tr>
<tr>
<td>$t_3^*$</td>
<td>204</td>
<td>$P_3$ 600</td>
</tr>
<tr>
<td>$t_4^*$</td>
<td>213</td>
<td>$P_4$ 800</td>
</tr>
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</table>

Fig. 1 Geometrical (See Fig. 2), physical and loading data for skeleton structure.

Table II. Basic physical soil characteristics

<table>
<thead>
<tr>
<th>Clay $^a$</th>
<th>Characteristics</th>
<th>Symbol $^b$</th>
</tr>
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<tr>
<td></td>
<td>$w$ (%)</td>
<td>$w_L$ (%)</td>
</tr>
<tr>
<td>CI</td>
<td>29</td>
<td>39</td>
</tr>
<tr>
<td>CH</td>
<td>60</td>
<td>35</td>
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<tr>
<td></td>
<td>$\gamma_s$ (kN/m$^3$)</td>
<td>$\gamma_c$ (%)</td>
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<tr>
<td>CI</td>
<td>27</td>
<td>20</td>
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<tr>
<td>CH</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>$e$ (%)</td>
<td>$S_r$ (%)</td>
</tr>
<tr>
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<td>96</td>
</tr>
<tr>
<td>CH</td>
<td>100</td>
<td>100</td>
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<tr>
<td></td>
<td>$k$ (cm/s)</td>
<td>$c'$ (kPa)</td>
</tr>
<tr>
<td>CI</td>
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</tr>
<tr>
<td>CH</td>
<td>$2 \times 10^{-3}$</td>
<td>0</td>
</tr>
</tbody>
</table>

$^a$ AC classification. 
$^b$ ISSMFE classification.
Fig. 2: Stratigraphical data and basic physical characteristics of non-homogeneous soil halfspace (See Table II.).

Fig. 3: Time ($t^*$) and load ($P^*$) dependent (See Table I.) displacements and settlements (increased 15 times) of skeleton structure.