
22 3D modelling system for ground engineering

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22.1 Introduction

Three-dimensional geo-information systems (3D GIS) provide the tools for enabling interactive construction of volumetric models of the ground profile. These permit analysis and interpolation of geological characteristics, facilitating appraisal of the engineering problem to hand (Turner, 1992, Orlic and Hack, 1994).

However, 3D GIS are not well suited to decision support. There is a need to combine the powerful visualisation technologies with decision analysis and artificial intelligence software. 3D subsurface modelling applications are discussed from a decision making perspective for two case studies which typify ground engineering.

22.2 Case Study 1: Foundations

The selection of foundation type is determined by the regional estimation of soil settlement, aided by geometrical modelling, visualisation and geostatistical analysis. Finite Element Modelling (FEM) enables surface or volumetric representation through the use of nodes generated from control data (boundary conditions).

The goal is to correctly select the foundation type and design a cost effective and safe foundation. The basic need for this decision-making problem is access to appropriate information regarding the subsurface conditions and the ground-structure interaction. These can be listed as geological information (depth, extent, thickness of layers), geotechnical information (soil/rock engineering properties, unit weight, cone resistance), and information regarding the behaviour of the ground when subject to a change in equilibrium.

The present 3D GIS technology provides tools and techniques to model the structure but treats the subsurface as a continuous distribution within the volume of interest. Traditional design practice assigns an averaged sample value using the statistical mean, leading to a somewhat conservative design and consequently higher foundation cost.

The foundation engineer uses soil/rock mechanics models to predict the reaction of the ground subjected to loading. The 3D geological and geotechnical models provide the ground parameters to the soil mechanics models.

Saturated soils undergo a volume change under application of a steady load (due to the weight of overlying earth material or manmade structures, or from the lowering of the water table). The volume change (a decrease in volume) in the soil mass is the result of dissipating water to restore an equilibrium stress state.

A settlement model may be based on the modified Terzaghi equation (Koopejan equation, CUR, 1996) and uses the following relationship:

$$S = \frac{H}{C'} \ln \frac{\sigma'_v + \Delta p}{\sigma'_v} \quad [1]$$

Where,

- S = settlement (m)
- H = thickness of the compressible layer (m)
- C' = the coefficient of compressibility
- σ'_v = the initial vertical effective stress at the mid-height of the compressible layer (kPa)
- Δp = increase in vertical effective stress (kPa).

The total settlement is thus a direct result of the subsurface geometry and the geotechnical properties of the soil masses. The vertical displacement is calculated at the mid-height of the compressible layer (the centre of the 3D grid cell). By adding the individual displacements from bottom to top (3D grid column), the total settlement at any depth is obtained.

The geometrical modelling of the ground is based on cross-sections derived from the geological map, boreholes and CPT soundings (Orlic, 1997). The Lynx geoscience modelling system has been used for the modelling tasks (Houlding, 1994). Using Lynx, data is stored in a 3D database projected to user-selected planes to delineate polygonal boundaries of each geological unit. These are connected by links to form solid volumes. Subsequent 3D model building based on the surfaces is tedious and time consuming, and impossible where the geology is complex or discontinuous.

To overcome the drawbacks, a measure of certainty (confidence level) can be assigned to the user-interpreted boundaries. This sort of functionality allows the user to incorporate his belief regarding the model.

The 3D geotechnical model is constructed in a comparable manner, as a continuous distribution utilising grid cell dimensions of 10 m x 10 m horizontal (N-S and E-W) and 1 m vertical (depth). This grid is intersected with the volume model of soil units to provide the data structure suited to spatial analysis and geotechnical characterisation (Figure 22.1). The 3D grid data structure supports the geological controls on the interpolation and calculation routines and provides a continuous distribution of the parameter of geotechnical interest.

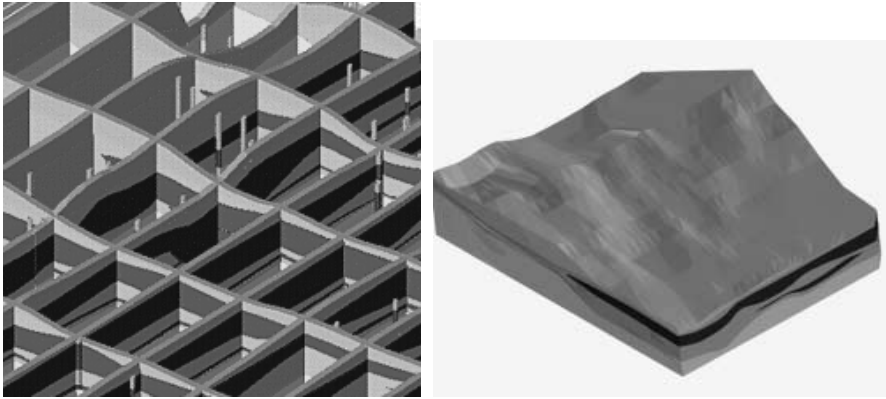


Figure 22.1. Geological modelling; fence diagram (left) and solid volume model (right) of soil profile

Using the geostatistical modelling routines in Lynx, the distribution of cone resistance values within the modelled volume may then be predicted. The prediction is made using ordinary volume kriging on log-transformed sample values. The geostatistical modelling process first involves a statistical analysis of measured sample values in terms of primary statistics, histogram and probability analysis. The anisotropy, directional trends and data transformations are then tried and the variography conditions tested. If a measurable spatial variability of sample values is identified then the variogram models can be constructed. The details of variography and the geostatistical interpolation techniques are contained in standard texts (e.g. Myers, 1997).

The 3D settlement may then be calculated at the centre of each cell by applying a volume weighted average algorithm. The procedure is illustrated in Figure 22.2.

The major problem experienced concerned the data exchange between the 3D modelling and FEM packages. The number of nodes in the exported file was too high for the FEM package to effectively generate a finite element mesh. In addition, the thin layers and lenses modelled in the 3D system could not be regenerated in the FEM geometry especially when the length to depth ratio of the section is high.

The analysis of settlement using 3D GIS resulted in a realistic picture of settlement predictions (Figure 22.3).

22.3 Case Study 2: Tunnels

The second case study concerns ground characterisation for tunnelling in soft soils. The engineering requirements are to determine the volumes of each soil type to be encountered and to estimate their geotechnical properties, water pressures and likely surface settlements. The first two requirements are satisfied with the available 3D modelling functions with little use of external routines. The third requirement could only be partially satisfied with extensive use of external routines.

A multi-attribute dynamic functional analysis capability is required on vertical grid-sections of predefined thickness.

The geological modelling was based on a site investigation comprising 62 Cone Penetration Tests (CPTs) and 11 boreholes with associated sampling. Lynx was again employed, but the geological complexity meant that only manual modelling could be used (Lynx, 1997). Two main sets of cross sections were drawn to define the geological unit boundaries, aided by fence-diagrams linked to form a solid volume model (Figure 22.4). The accurate volume modelling had decisive impact (Figure 22.5). The inclusion of geological semantics facilitated provision of technical advice delineating each unit's polygonal boundaries.

Geotechnical modelling was based on the site investigation data and the results of laboratory tests on soil samples. The data scarcity restricted the use of geostatistical interpolation as an option. Only the inverse distance interpolation of a few geotechnical variables could be achieved. In most instances the assignment of geotechnical parameters was done by using a knowledge-based system, i.e. reasoning on the basis of engineering geological knowledge by an expert (preferences and rules) (Attewell and Toll, 1990).

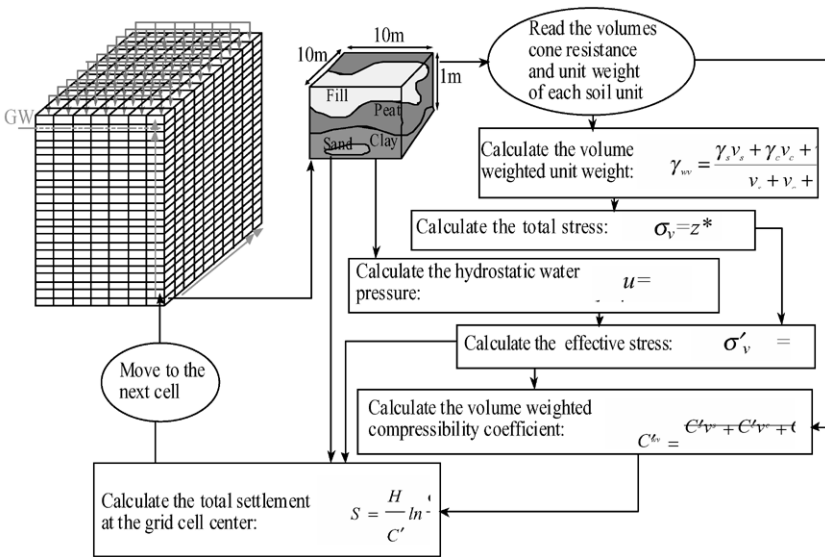


Figure 22.2. The conceptual diagram of settlement modelling system

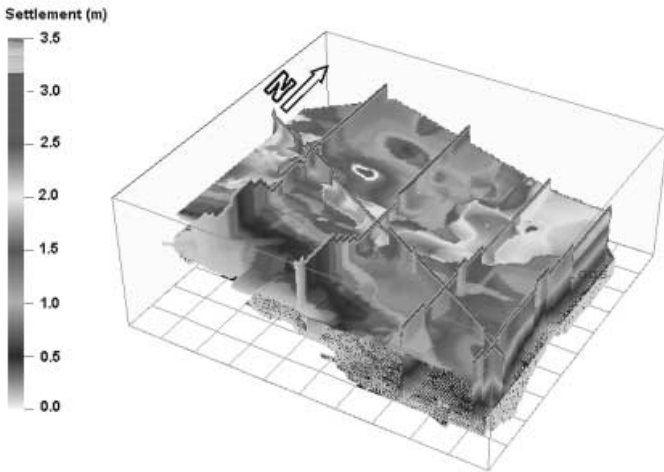
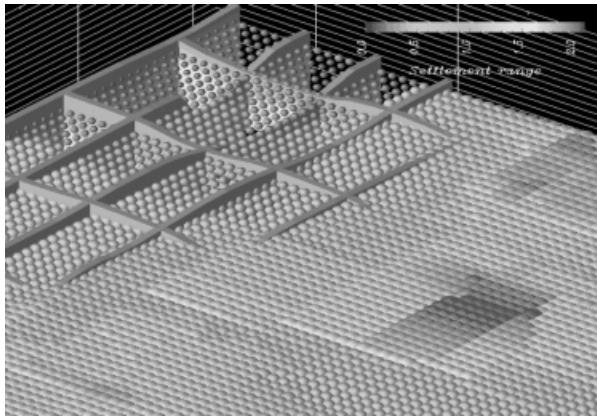


Figure 22.3. The 3D visualisation of settlement ; settlement glyphs (upper) and iso-volumes of settlement range (lower)

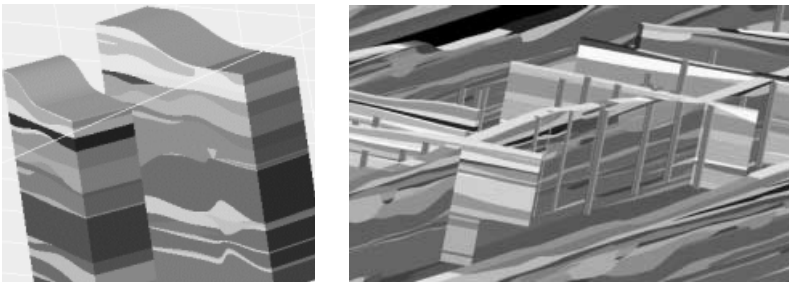


Figure 22.4. Geological modelling: interpreted cross-sections (left) and fence diagram with soundings (right)

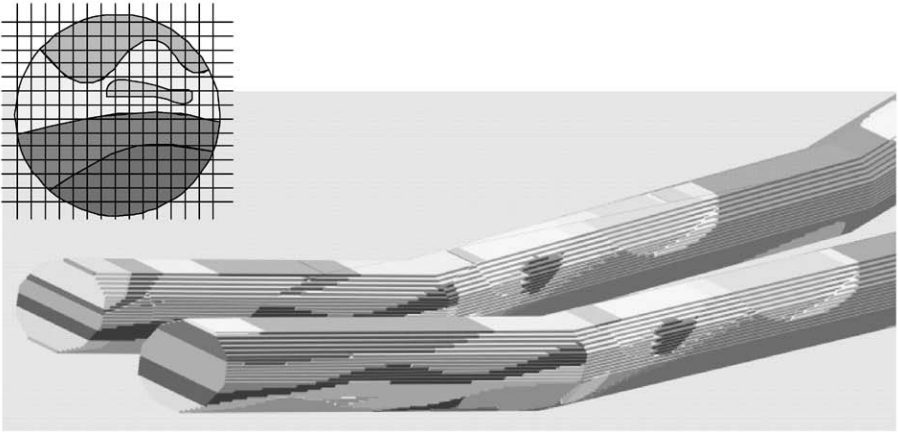


Figure 22.5. Intersection of the tunnel structure with the volumetric model displaying the geology, with an inset to show a single element to be excavated or considered for settlement analysis

The representation of expert knowledge can be accomplished with rules and symbolic functions. LispWorks-KnowledgeWorks (1997), a commercial Lisp-based system, was used for the application. An example of an expert rule assigning values to project variables follows, updating the information-base, and interfacing the user with other applications:

```
(defrule settlement_risk_10 : priority 2
  (voxel ?grid-object soil_type ?soil_type, tbm_type ?tbm_type,
  tunneling_depth, ?tunneling_depth, tunnel_diameter ?tunnel_diameter,
  surface_surchage ?surface_surchage, water_table ?water_table)
  (Test (equal ?soil_type clay))
  (Test (equal ?tbm_type EPBS))
  (Test (>= ?tunneling_depth 16)) .....
->
  (assert (voxel ?grid-object "settlement likely"))
  (update-information-base ?grid-object) (capi:confirm-yes-or-no "Do you want
to visualize the results now"))
```

Such algorithms are used for decision tree generation and knowledge extraction from the available data (Figure 22.6). These include inductive learning, back-propagation, Bayes classification, and case-based reasoning. Details are provided by Quinlan (1993), Taylor et al. (1994), and Kohavi et al. (1996). The algorithms spot patterns or relationships in the data, and then extract knowledge in terms of rules and decision trees (Table 22.1).

22.4 Conclusions

The two case studies have demonstrated some of the capabilities of 3D GIS as a modelling and problem-solving tool for civil engineering projects. The current state of 3D GIS technology nevertheless has shortcomings. In terms of volume representation and property analysis, the detail required in the shallow subsurface characterisation for construction and the efficiency in handling such detail have not yet reached a desirable level. Moderately complex mathematical calculations and the incorporation of accepted rock/soil mechanics models are not yet supported. The ease of exchange of model structures between 3D GIS and FEM applications is limited to simple situations, but can nevertheless facilitate the effective use of subsurface information in the design and construction stages. An integrated system of tools and techniques from 3D GIS, improved visualisation and artificial intelligence components will bring the necessary power and functionality to support effective decision making in large ground engineering projects.

Table 22.1. Categorical attributes for training the knowledge-based system

<i>a) a simplified table of categorical attributes (structure)</i>			
ATTRIBUTE		POSSIBLE VALUES	
Geology		sand, clay, peat	
Permeability		unknown, low, medium, high	
CPT		unknown, range A, range B, range C, range D	
<i>b) a simplified table of training set [When the structure (a) and the training set are provided, the complete test set (unclassified data) including millions of instances can be induced]</i>			
GEOLOGY	PERMEABILITY	CPT	CLASS
Sand	Unknown	unknown	class 1
Peat	Medium	range A	class 6
Peat	High	range C	class 4
Clay	Unknown	unknown	class 2
Peat	High	range B	class 3
Peat	High	range D	class 5
<i>c) a decision tree model for the training set in (b)</i>			

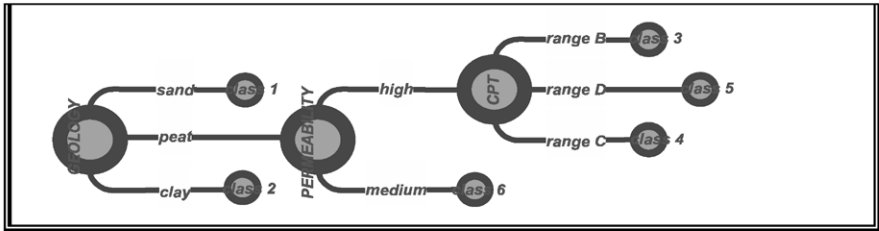


Figure 22.6. Stages of machine learning and the rule induction process

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