Unlocking the potential of digital 3D geological subsurface models for geotechnical engineers

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ABSTRACT

Within any construction project the most significant factor in controlling the cost and feasibility is the subsurface ground conditions. This is particularly the case in underground construction. Geological modelling in three-dimensions (3D) can provide a detailed definition of sub-surface conditions. Such modelling requires the extension of traditional GIS methods to handle the volumetric representations. Over the past two decades, a series of sophisticated 3D modelling technologies have been developed to address this need. However, the adoption of these techniques in the geotechnical industry has lagged behind technological advances.

Two contrasting approaches to 3D geological modelling are presented: a) the Thames Gateway Development Zone (TGDZ) in London, UK and b) subsurface characterisation studies in Boston, USA. The TGDZ studies used 'GSI3D' software, while the Boston studies involved geostatistical evaluations of the field data and the Environmental Visualization System (EVS) for model creation and visualisation. Both studies have created 3D geological models attributed with physical and mechanical property data, but this has been achieved in two different ways. The TGDZ study provides a single uniform property attribution to individual geological units, whereas the Boston studies used geostatistical methods (kriging) to interpolate borehole sample data onto a 3D structured mesh. This 'discretisation' allowed the development of volumetric models that quantified the variability of the data used to build the property model.

These different modelling methods provide solutions to two very different problems. In the TGDZ, the requirement was for regional scale information for ground investigation design, for assessing water management strategies, and as a tool for communicating information to non-geo-specialists. In this situation, the best approach was a system for model building that did not require a specialist modeller, the use of bulk attribution, and the ability for modelling to be carried out quickly using a desktop computer. However, in Boston, a more specialist solution was required to provide a detailed understanding of the natural variability of the complex geology, thus discretisation and spatial interpolation of sample data values was necessary.

The 2001 EuroConference in Spa, Belgium, that addressed characterisation of the shallow subsurface, identified four major constraints on the use of 3D digital geological data: This paper shows that these constraints are being overcome with the use of new modelling software and techniques and, more importantly, with an understanding of the needs of the client.

Keywords: Geological modelling, subsurface digital information, geotechnical engineering

1 INTRODUCTION

Geology has always been concerned with the presentation and interpretation of three dimensional (3D) information about the ground. When William Smith developed the first modern geological map the challenge was to present a 3D representation of the strata beneath the ground surface using a medium (paper) that was two dimensional in form. This led to increasing sophistication in the way geology was presented but also to ever increasing complexity. Some of the engineering geological maps discussed by Anon. (1976) are testimony to this complexity. However, with the development of computer technology, modelling in 3D became increasingly possible. At first, this required powerful computers and was expensive. As a result, much of the development took place to meet the needs of the hydrocarbon industry. It was not until 3D modelling became possible on smaller computers and at lower cost that the geotechnical industry began to take an interest. A landmark was reached with the holding of a Euro-Conference in Spa, Belgium in 2001 (Rosenbaum & Turner 2003). At that conference, Rosenbaum (2003) identified four impediments, at that time, to greater use of 3D geological models:

- a lack of 3D/4D mathematical, cognitive and statistical spatial tools;
- a lack of cheap modelling tools designed for the shallow subsurface that can be operated without specialist personnel;
- the inability of models to depict natural variability of geological systems;
- a shortage of case histories.

This paper briefly describes some of the latest developments in 3D modelling in the shallow subsurface and, in particular, the new ways being developed in the UK and the USA to model the variation in geotechnical properties in the urban environment. These advances are illustrated with two case studies, one from the Thames Gateway Development Zone to the east of London, which includes the 2012 main Olympic site, and one from Boston, Massachusetts. The paper shows that if these case histories are viewed against Rosenbaum's (2003) four impediments, it can be seen that, in the seven years since the Spa conference, we have advanced a considerable way towards overcoming them.

2 DEVELOPMENTS IN THREE-DIMENSIONAL GEOLOGICAL MODELLING

The demand for subsurface geological models is growing. This has posed a challenge for geological surveys that have to acquire the skills and tools to meet this demand. Until recently, the tools available for geological modelling have been aimed mainly at the hydrocarbon and mining industry and, therefore, often only dealt with specific geological scenarios and data types. CAD and GIS tools were also customised to deal with geological environments but this often led to a convoluted multi-software solution which became hard to use and implement as a single work flow (Kessler *et al.* 2008)

Another 3D geological subsurface modelling problem is the lack of sufficient factual data. Field observations are usually very widely spaced and the creator of an acceptable model must interpolate between these widely-spaced data points. This interpolation process usually requires geological knowledge to successfully replicate actual geological environments. Simple geometric algorithms frequently produce unacceptable results; thus, iterative methods involving assessments and progressive refinements by qualified experts are required. These procedures add considerable time and cost to the creation of subsurface models (Turner 2006). Furthermore, as Perrin *et al.* (2005) commented, all current modelling methodologies "do not allow the use of a knowledge-driven approach" and are not conducive to rapid model updating and revision.

2.1 *Three-dimensional geological modelling at the British Geological Survey*

After considerable research, the British Geological Survey has now implemented GSI3D (Geological Surveying and Investigation in 3 Dimensions) as its core software to carry out systematic 3D geological modelling of the UK. The methodology and the associated GSI3D software tool were developed by INSIGHT GmbH over the last 16 years, initially in collaboration with the Geological Survey of Lower Saxony (Germany). The software is written in Java and data are stored in extensible mark-up language XML.

For the past six years the British Geological Survey has been acting as a test bed for the accelerated development of the system and is now further developing the software to cope with complex bedrock environments. The methodology is based on the philosophy that the construction of geological subsurface models has to proceed with an understanding of the complete geological sequence and the likely geomorphological evolution of the study area (Fookes 1997). GSI3D uses the morphological data in the form of Digital Terrain Models (DTM), geological linework, downhole borehole data and geophysical data. It enables the construction of user-defined cross-sections by correlating boreholes and the outcrops to produce a geological fence diagram. Mathematical interpolation between the nodes along the drawn sections and the crop lines of the units produces a stack of triangulated objects each corresponding to one of the geological units present (Kessler *et al.* 2008). The software interface comprises four, interactively-linked windows, representing the geologist's familiar view to a geological system. These are: borehole, map, section, and 3D windows (Figure 1). This enables the real-time verification of all datasets used during the modelling process. Geologists draw their sections based on facts such as borehole logs correlated by intuition - the shape 'looks right' to an experienced geologist (Kessler & Mathers 2004). Previously, this tacit and implicit knowledge was left uncaptured in the transformation of the model onto a two-dimensional media such as paper or GIS.

The resulting geological models describe the arrangement of lithostratigraphic units in the subsurface in their real position and full extent. These models are the extensions of 2D maps into the third dimension and, therefore, could also be referred to as 3D geological maps (Culshaw 2005). By logical extension of this concept, these models can only be attributed with properties that extend to the whole unit. These properties can be many-fold, but have to share common boundaries, in effect replicating the traditional process of creating derived maps from geological maps. Section 3 describes how a standard model from the Thames Gateway, to the east of London, has been attributed with applied parameters to aid decision making. This method of attribution has the advantage of being relatively simple and can be provided for large study areas with little effort.

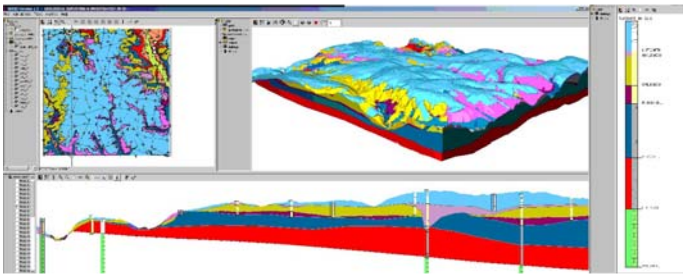

Figure 1. The four windows comprising the GSI3D interface.

2.2 *Discretisation to allow for spatial distribution of property values*

Discretisation involves the subdivision of spatial objects into a series of small elements. There is a considerable body of theory concerning the design and construction of meshes appropriate to different modelling requirements (Knupp & Steinberg 1994). There are two broad classes of meshes – structured and unstructured (Turner 2006).

Most commercial geological modelling products use regularly-spaced structured meshes to divide the volume into discrete cubical 'volume elements,' or 'voxels.' Voxels provide a data structure upon which more specialized applications can be built fairly rapidly and, thus, offer commercial advantages. However, unless the cell dimensions are very small, the discretisation process may destroy important geometric details. Very large data files may result, since a very low resolution 3D model involving only 100 x 100 x 100 cells results in 1 million cells. Many projects require much higher resolutions, so that many applications may require tens or hundreds of millions of cells.

Consequently, various methods of variable-sized voxels have been proposed, including 'octree' and 'geocellular' representations (Turner 2006). Octrees provide greater sampling frequencies in areas of rapid change and larger cells in areas of uniformity and also rapid indexing of the individual cells within the database, but octrees require model re-computation whenever the overall framework geometry is changed and so may hinder iterative model construction. Since sedimentary strata typically have greater property variations between than within strata, some commercial products developed for petroleum exploration (for example, Stratamodel) offer partly deformable 'geocellular' voxels (Denver & Phillips 1990). Figure 2 provides an example of such a model.

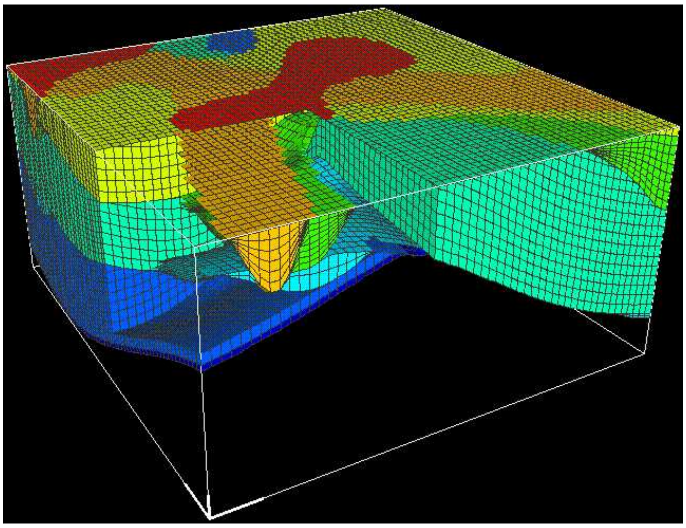

Figure 2. A geo-cellular model with multiple stratigraphic geo-objects.

Visualisations of voxel or octree models often display rough blocky surfaces reflecting their cellular structure; this may be a distraction. To avoid this, some products (such as EarthVision by Dynamic Graphics) convert a voxel data structure into a three-dimensional isosurface prior to display (Smith & Paradis 1989; Belcher & Paradis 1991).

Three-dimensional unstructured meshes, based on a variety of fundamental elements, including tetrahedrons, hexahedrons, and dodecahedrons, can link with finite element models to evaluate fluid-flow or stress/strain relationships (Gable *et al.* 1996). Unstructured meshes can accurately and efficiently accommodate complex subsurface geometries, but this flexibility comes at a price: added computational demands and very slow model construction unless sophisticated 'mesh builder' software is developed and employed. Because unstructured meshes are particularly useful in modelling fracture discontinuities, a number of research teams have invested considerable effort in developing unstructured 3D mesh systems and 'mesh builders' (Gable *et al*. 1996). Figure 3 illustrates a tetrahedral unstructured mesh developed to study the unsaturated zone at the proposed Yucca Mountain nuclear waste repository in Nevada.

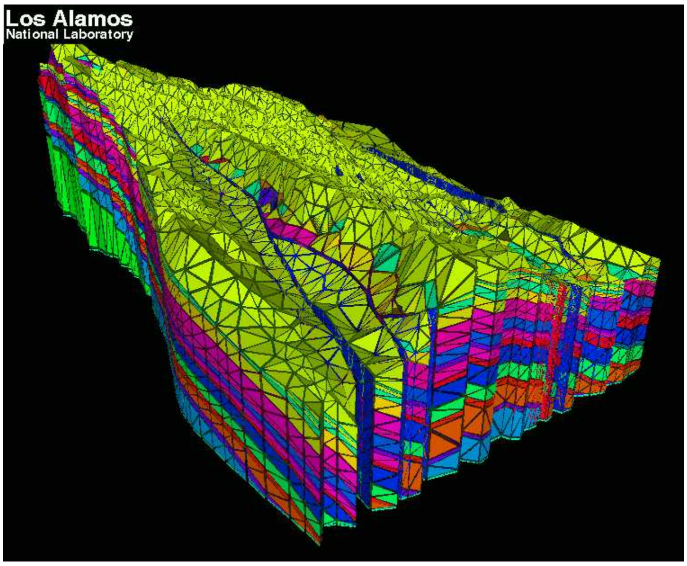

Figure 3. Tetrahedral unstructured mesh model of Yucca Mountain unsaturated zone. (Source: Carl Gable, Los Alamos National Laboratory).

3 ATTRIBUTION OF THE THAMES GATEWAY 3D GEOLOGICAL MODEL

To gain full value from the 3D geological model in the urban environment, attribution of the model with engineering geological and hydrological data is necessary. Particularly at a regional scale, bulk attribution provides a way of visualising the property characteristics of each geological unit modelled and their spatial relationships (Figure 4). The Thames Gateway Development Zone (TGDZ) model has been attributed with several datasets including lithostratigraphy, engineering geological classification, ground water productivity and, maximum and minimum permeability (Royse *et al.* in press).

For geotechnical information, this is achieved by developing an engineering geological classification scheme. In this case, the geological units were primarily divided in terms of engineering 'rocks' and 'soils'. These primary divisions were further subdivided into coarse grained (sand and gravel), fine-grained (clay and silt), organic soil (peats) and mixed soils. Secondary subdivisions further classify the modelled units on the basis of general strength or density. These subdivisions are based on log descriptions, undrained shear strength values and standard penetration test results, plus any other appropriate parameters included in site investigation reports.

3.1 *Thames Gateway Development Zone (TGDZ) model*

At 1 800 km^2 the Thames Gateway Development Zone is the biggest urban development project in the UK for over 50 years. For that reason, and to meet sustainability requirements, developers and planners need to understand the implications of such large-scale urbanisation on the environment. This has resulted in a growing demand for geo-environmental information to be provided in more accessible, relevant and understandable forms.

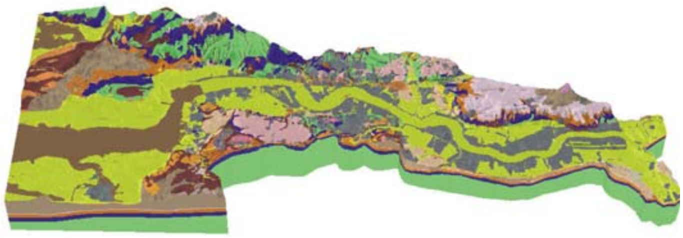

Figure 4. 3D geological model of the Thames Gateway Development Zone from Stratford in the west to Canvey Island in the east. Areas of peat (brown) are revealed beneath deposits of alluvium (yellow), river terrace deposits (orange) and anthropogenic deposits (grey). Bedrock is composed of Palaeogene deposits (orange, blue and pink) underlain by Chalk (green).

The geological model of the TGDZ was constructed using proprietary software GSI3D (Hinze et al. 1999; Sobisch 2000; Kessler *et al.* 2008), described above. The main reason why many professionals do not use 3D modelling routinely is because many modelling packages are too complex (Hack *et al.* 2006). GSI3D gets around this problem by using traditional techniques of cross-sections and fence diagrams, together with a generalised vertical section. The model was built from over 4000 boreholes and over 200 north-south and east-west trending cross-sections.

The method of attribution described above is not able to take into account the heterogeneity within a modelled geological unit (Group, Formation, Member or Bed) but rather it provides the user with bulk attributes for a given unit. This was done for two reasons: first, so that file sizes were manageable on a standard desktop PC and second, because there was insufficient data for detailed variability modelling. To model property variation within a geological unit without an unfeasibly high level of uncertainty, it is essential that geoscientific data is of a high density and quality throughout the modelled area, which was not the case for the whole of the TGDZ (Royse *et al.* in press).

3.2 *Applications and uses of the attributed 3D geological model*

Engineers and geologists can use the attributed geological model to assist in the recognition and identification of problematic ground conditions, to help design more appropriate ground investigations and contribute to the most efficient foundation design. The model can be used to provide information on the depth to founding material, its properties and the variability of these properties. For instance the depth to the top of the gravel formations and Chalk beneath the alluvium in the TGDZ can be exported from the 3D model and displayed as depth or thickness (isopach) contour plots in a GIS. It is then possible to combine the 3D surfaces with other spatially rectified data (be that geotechnical, geochemical, or geographical etc) which, when combined together, provides a way of assessing the suitability of sites for a variety of construction techniques.

The attributed 3D model can be used to generate synthetic geological cross-sections and borehole logs along a specified route enabling the interpretation of the subsurface geology beneath the route. For example, a synthetic section can be generated along a given linear route such as railway track. In the TGDZ, the geological model was characterised using particle size distribution and standard penetration test data, held in the National Geotechnical Properties Database (maintained by the British Geological Survey). Ten engineering geological units were distinguished and consequently applied to the synthetic geological cross-section producing an engineering geological section (Figure 5). Visual inspection of Figure 5 allows zones of potentially difficult ground conditions to be identified. The 3D modelling of the TGDZ is described in detail by Royse *et al.* (2008).

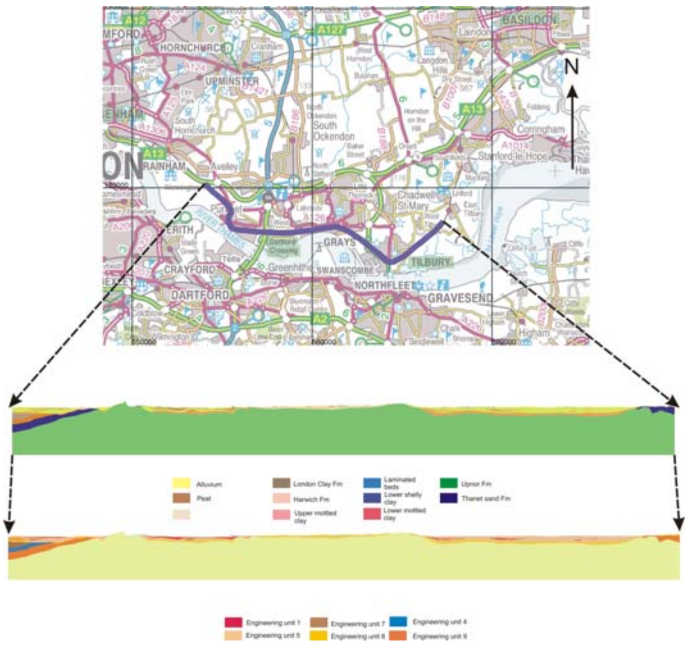

Figure 5. 3D geological model of a railway route from Purfleet to East Tilbury, London with automatically generated geological and engineering geological cross-sections.

4 SITE CHARACTERISATION MODELLING IN BOSTON, MASSACHUSETTS

Boston was first settled on and around Beacon Hill, a drumlin which formed an island at high tide. Urban growth, especially between the mid-1800s and early-1900s, led to the infilling of many tidal marshes, estuaries, and bays with non-engineered artificial fill. The area also has a historical record of several earthquakes with M6.0.

A rich heritage of geotechnical investigations was supplemented, in recent years, by investigations in connection with the construction of the Central Artery/Tunnel (CA/T) project that traverses the entire central Boston area. A digital geotechnical borehole database containing approximately 3 000 borings was assembled (Baise *et al.* 2004; Brankman & Baise 2008). This database was used to support regional liquefaction susceptibility studies (Brankman & Baise 2008) and a number of site-specific modelling studies (Baise *et al.* 2004, 2006; Balfe *et al.* 2005).

Several studies compared 2D areal mapping of vertically averaged SPT values to 3D volumetric representations of the same SPT data. Because there is often considerable variation of the SPT values with depth, corresponding to changes in material characteristics, even within a single artificial fill unit, the true 3D interpolations and models are always found to be superior and to provide predictions with higher levels of confidence. The Boston studies involved geostatistical evaluations of the field data and the Environmental Visualization System (EVS) for model creation and visualisation (C-Tech Development Corp 2008).

4.1 *Liquefaction potential study*

The South Boston area was one of eight sites where artificial fill was evaluated by 3D geostatistics (Baise *et al.* 2004). The site contains 407-hectares of filled land and 232-hectares of original land. Most of the artificial fill was placed in the late 1800s and early 1900s by hydraulic dredge and consists of fine silty sand and some clay. The South Boston site had the highest liquefaction potential; it also demonstrated the greatest degree of lateral spatial continuity and consistency in SPT values. Thus, it produces some of the clearest visualisations.

Figure 6 is a 3D visualisation of standardised SPT blow count values along a cross-section that approximates the route of the CA/T tunnel. Low blow count values, shown as blue colours in the figure, represent high liquefaction susceptibility and are concentrated in a layer that is 4-5 m below the ground surface. Indicator kriging was used to further characterise the liquefaction potential. Each sample was coded '1' if it was considered liquefiable, and '0' if it was considered not liquefiable. Figure 7 shows the probability of liquefaction along the approximate trace of the CA/T tunnel. Areas where the liquefaction probability is at least 80% appear as a light coloured zone in Figure 7. Analysis of the full volumetric model defined a zone approximately 3-10 m thick, 500 m long and 100 m wide that exhibits a probability of liquefaction of 0.7 or better, with a safety factor of 1.2 (Baise *et al.* 2004).

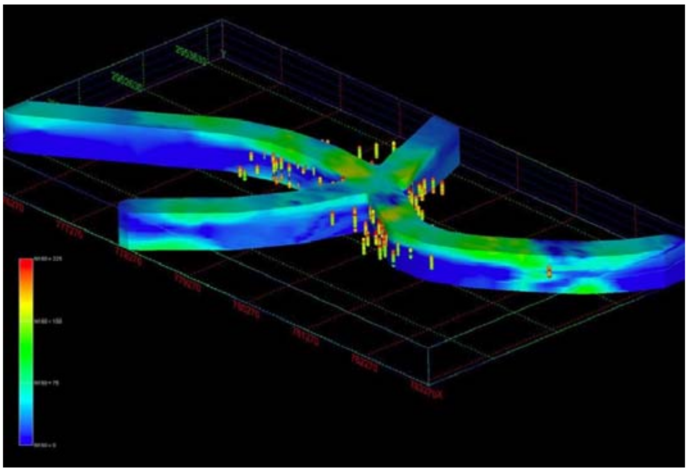

Figure 6. Figure BOS-1. 3D visualisation of standardized SPT blow count values along a cross-section that approximates the route of the CA/T tunnel in South Boston. Low blow count values, shown as blue colours, represent high liquefaction susceptibility (after Baise *et al.* 2004).

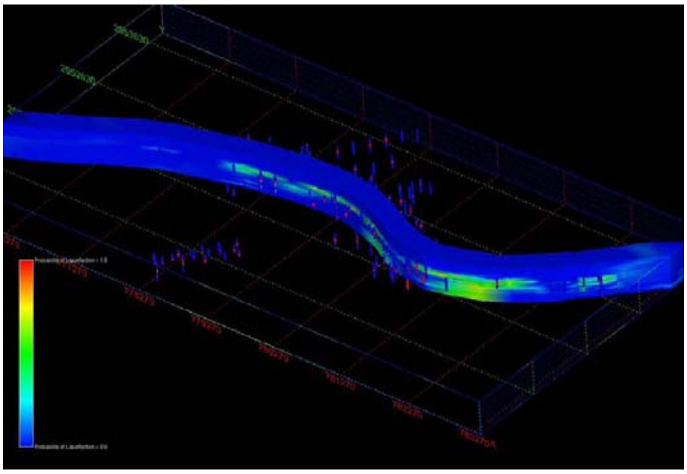

Figure 7. Slice through South Boston model of probability of liquefaction, created by indicator kriging. Light colours represent high liquefaction probability. (after Baise *et al.* 2004).

4.2 *Variation in geotechnical properties of till*

A subsequent study (Balfe *et al.* 2005) evaluated the properties of till underlying a 10-hectare site in central Boston. The site includes several structures over 25-stories, two transit tunnels and about 300 m of the CA/T project tunnel. Figure 8 shows the 3D stratigraphy of the area. Varying amounts of artificial fill, highly organic materials, and clay overlie the till, which is the primary load-bearing layer for buildings within the site. Also, the CA/T tunnel is located within the till. Consequently, substantial numbers of boreholes were located in the area and are included in the geotechnical database – the study used 79 test borings (containing 423 SPT samples) completed prior to 1988, and 33 additional deeper borings (containing 305 SPT samples) collected for the CA/T project.

Several approaches to creating 3D property models were compared. As would be expected, a model based only on the 33 CA/T boreholes showed much lower levels of confidence in the SPT property prediction, compared to a model developed using all 112 boreholes. Although the CA/T boreholes were deeper, and so provided additional information about the deeper portions of the till, the extended spatial coverage provided by the older boreholes created a more stable volumetric property prediction. This finding illustrates the importance of relating site-specific investigation observations to a larger regional perspective.

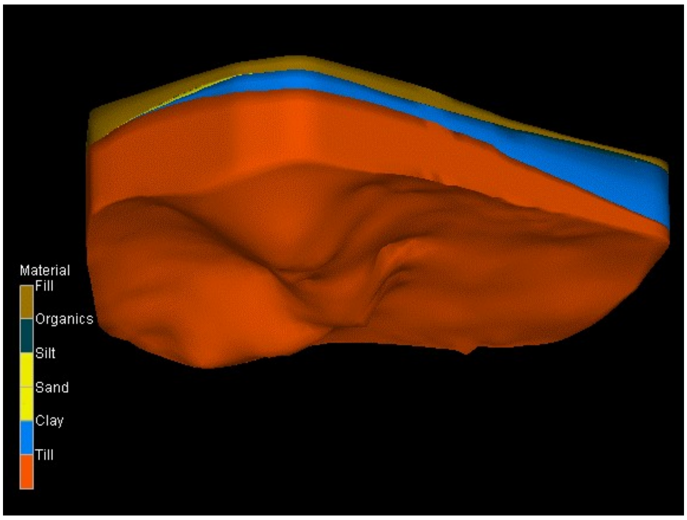

Figure 8. 3D visualisation of the stratigraphy within the central Boston site (after Balfe *et al*. 2005).

Figure 9 illustrates the 3D volumetric distribution of the standardised $(N_1)_{60}$ SPT blow count values within the till, based on all 112 boreholes and 728 SPT samples. This 3D interpolation incorporates both vertical and horizontal anisotropy; thus, the resulting predictions more clearly represent the natural variability of the till and can be used with higher confidence. Balfe, *et al.* (2005) compared the 3D results to simple 2D spatial interpolations that used average SPT values in each borehole, thus ignoring vertical variability, and to a series of 2D interpolations after subsetting the till into a series of six thin zones. Neither 2D approach produced a prediction model with as high a degree of confidence as the 3D model shown in Figure 9.

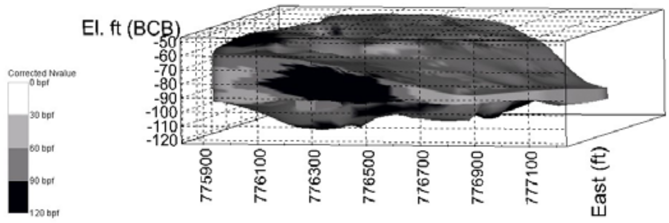

Figure 9. 3D volumetric distribution of the standardised $(N_1)_{60}$ SPT blow count values within the till underlying central Boston (Balfe *et al*. 2005).

5 CONCLUSIONS

The development and attribution of 3D geological subsurface models for geotechnical engineers involves two stages: 1) the creation of a 3D geological framework model, and 2) the attribution of this framework with desired geotechnical properties. Experience gained at the British Geological Survey demonstrates that the GSI3D approach efficiently develops geological framework models because it parallels the traditional interpretive work flow of the geologist and allows incorporation of tacit and implicit geological knowledge.

The simplest approach to attribution of quantitative properties, such as permeability, strength, or compressibility, to an existing geological framework model is to assign a single 'typical value' and 'typical variability' (represented by the mean and standard deviation) for the property in question to each geological volume element in the framework model. This 'bulk attribution' approach has been successfully applied in the Thames Gateway Development Zone and is appropriate for regional ground investigations.

More detailed site specific design applications require discretisation of the geological framework model. Finite-difference and finite-element methods may be used to model fluid flows, or stresses and strains, loadings, or deformations, and the chosen method often dictates the appropriate discretisation approach. Discretisation also permits the spatial interpolation of property values or conditions from known observation locations (boreholes, outcrops, or samples) to entire 3D volumes,while retaining property variations and identifying confidence level in the predicted values at all locations. Geostatistical methods, as utilized in the Boston studies, offer one method for spatially predicting property values, but other techniques have also been considered and may be better in some situations.

Regardless of the specific discretisation approach adopted, 3D geological framework models, combined with a 3D spatially distributed prediction of properties, have been demonstrated to provide superior characterisation of the subsurface for geotechnical applications. Also, 3D characterisation and prediction of properties is improved when project-specific investigation data are combined with models based on pre-existing data that provide a regional context.

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